



The Hazardous Materials Vehicle Routing Problem

Literature Review, Risk Analysis and Heuristic Solution Procedures

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Abstract

Hazardous materials (hazmat) have become important goods for satisfying the industrial and customer demand in our modern society. The transportation of these materials is always associated with safety, security and environmental concerns due to the dangerous nature of the cargo. To improve the safety of the transportation process hazmat transportation problems have become a popular research topic in the field of operations research. This thesis contributes to the ongoing research on the hazmat transportation problem. It provides an extensive overview of the existing literature on the hazardous materials transportation problem and offers a new classification extending the existing ones. With particular focus on the hazardous materials vehicle routing problem (HMVRP), this thesis compares different risk models and analyses their influence on the problem outcomes. Additionally, heuristic and meta-heuristic solution procedures are proposed for handling the NP-hard nature of the problem.

For this purpose, four different studies are conducted. Study 1 presents a state of the art literature review including over 300 contributions to the hazmat transportation problem. The historical development of the research field is analyzed and the most important journals are identified. A detailed classification focusing on hazmat transportation on public roads is provided. Furthermore, the study identifies research gaps and presents new research opportunities. Study 2 and 3 investigate the effects of path generation in a realistic urban network on the outcomes of the HMVRP. Additionally, different risk models for the HMVRP are compared and their influence on the problem solutions is analyzed. Study 2 proposes a simple but effective heuristic algorithm to solve the HMVRP with load-independent risk models. Study 3 extends the focus and includes load-dependent risk models. The influence of six different risk models on the solution outcomes of the HMVRP is compared and the tradeoff between risk minimization and the minimization of traveled distance is investigated. For this purpose, more than 1,700 problem instances are solved to optimality using CPLEX.

In study 4 a hybrid genetic algorithm (HGA) for solving the HMVRP with a load-dependent risk model is proposed. The HGA aims to find pareto-optimal solutions for the bi-objective HMVRP when risk and travel distance are addressed simultaneously. The structure of the HGA is explained and experimental findings are presented.

In conclusion, this thesis contributes to an improved understanding of the general development in the research field of hazmat logistics and the influence of different risk models on the solution outcomes of the HMVRP. Additionally, heuristic solution methods are proposed and tested for finding compromise solutions when the bi-objective case of risk and distance minimization is addressed. Furthermore, this thesis helps new researchers the access to the field of hazmat logistics as it provides a structured overview of the research field while pointing out research gaps. To address some of the identified research gaps, the thesis provides an extensive analysis of the risk modelling approaches. Thereby, it provides new insights to the basic research on risk modelling for the HMVRP. Finally, to overcome the long computation times of large problem instances heuristic solution approaches are proposed.

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List of Abbreviations

DPP	Dissimilar path problems
GA	Genetic algorithm
GGBefG	Gefahrgutbeförderungsgesetz
HGA	Hybrid genetic algorithm
HMVRP	Hazardous materials vehicle routing problems
LD	Load-dependent
LI	Load-independent
LPG	Liquefied petroleum gas
NDP	Network design problems
NP-hard	Non-deterministic polynomial-time hardness
RAP	Risk assessment problems
RLP	Routing and location problems
RSP	Routing and scheduling problems
SPP	Shortest path problems
ToSP	Toll setting problems
USDOT	United States department of transportation
VRP	Vehicle routing problems

I

Introduction

1. Relevance and challenges for hazardous materials transportation

The worldwide economic growth and the rise of individual welfare lead to an increase in the global demand of materials and goods. It also includes the demand of hazardous materials (hazmat) or dangerous goods. Hazmat, such as nuclear, toxic, explosive or highly flammable materials and chemicals, are needed for various production processes in different industries. Furthermore, hazmat such as gas, petrol or heating oil, have become an essential consumable in our daily life. However, in contrary to non-hazardous goods, hazmat are emitting a potential danger to their environment when they are transported and handled wrongly. The consequences of hazmat incidents can vary extremely and can easily lead to a catastrophic event. Therefore, the definition, classification and handling of hazmat are regulated in most countries by law. In Germany, any materials or objects are considered as hazardous materials that by their very nature, characteristics or state, when transported, pose risk to public safety or order, in particular, to the general public, the patrimony, the life and health of persons, animals and objects (GGBefG, 2015). The United States department of transportation (US DOT, 2016) provides a similar definition.

Hazardous materials are strictly associated with risk. While the term “hazardous materials” is uniquely defined, the definition of risk is not so clear. Depending of the research field, a large variety of definition approaches exists. In the field of hazmat transportation risk is often expressed as the product of consequences and the probability of an unwanted incident (Covello and Merkhofer, 1993). This definition also corresponds to the “traditional risk model”, a popular risk model for hazmat problems. However, risk models that are solely

focusing on the accident probability or solely on the consequences are also common (Erkut and Verter, 1998). In general the risk for hazmat transportation can be considered as low probability but high consequences risk (Sherali et al., 1997). The probability is almost always represented by the probability of a hazmat accident with a release of the cargo. However, multiple measuring approaches for the consequences are possible. In most cases the consequences are measured by the amount of people affected in case of a hazmat spill. In addition, approaches assessing the damages to the infrastructure or the natural environment are possible, but less common (Holeczek, 2019). Of course, the dangers emitted by hazmat strongly depend of the category of hazmat considered. Based on their specific risk producing chemical characteristics, hazardous materials are divided into nine classes and various subclasses (UN, 2009). Laws and regulations for each class of hazmat, aim to ensure the safety of the transportation process. International treaties and recommendations like the “*European Agreement concerning the International Carriage of Dangerous Goods by Road*” (UNECE, 2017) or the “*Recommendations on the Transport of Dangerous Goods*” (UN, 2009) target to improve the safety on a global and transnational scale. Thanks to these regulations, the number of unintended hazmat releases during the transportation process is very small compared to the number of shipments of such materials. Furthermore, the accident rates of hazmat transportation are relatively smaller than the accident rates of shipments of non-hazardous materials (Bianco et al., 2013). Nevertheless, the complete safety is not possible and the residual risk will always remain.

To underline the global importance and the catastrophic consequences, three recent hazmat incidents that received a lot of international media attention are provided as examples. In May 2019, the explosion of a tank-truck in Niamey, Niger, lead to over 55 casualties and over 37 heavy injuries (Tagesschau, 2019). In August 2018, the explosion of a tank-truck on the highway of Bologna, Italy, caused one casualty and over 145 injuries (RP-Online, 2018). In August 2015, in Tianjin, China, the explosion of a hazmat storage side lead to over 165 casualties and to over 700 injuries (Spiegel Online, 2015; Fischer, 2016).

For further safety improvement of the transportation process, hazmat transportation has become a popular research topic in the field of operations research. Over the last 50 years, researchers all over the world have contributed various papers, books and conference articles to the hazmat transportation problem. Especially, contributions focusing on risk assessment and route planning decisions received plenty of attention. The first risk assessment and risk evaluations problems appeared in the 1970s, e.g. Shappert et al. (1973). The first approaches

to optimize the routing process followed a little later, e.g. Kalelkar and Brooks (1978). Truck routing problems became popular in the 1980s, e.g. Saccomanno and Chan (1985) and Cox and Turnquist (1986). Since then, the hazmat transportation problem has known a growing number of contributions and various problem extensions.

To differentiate between the varieties of problems in the research field of hazmat transportation, different approaches are possible. However, two main classification clusters have been established in the common literature, first to classify the problem by the considered mode of transportation and then by the goal of the optimization problem.

The classification according to the transportation mode is easily understandable and mostly self-explanatory. The different modes for hazmat transportation are air, marine, pipeline, rail and road. When more than one transportation mode is included, approaches are considered as intermodal (Erkut et al., 2007; Verma and Verter, 2010) or as multimodal (Reniers et al., 2010; Xie et al., 2012). Road is by far the most important transportation mode. The total amount of hazmat transported on roads is over 49% in Germany (Destatis, 2019), over 80% in China (Zhong et al., 2018) and over 90% in the USA (Erkut et al., 2007). This underlines the importance of road as the prime transportation mode and justifies the focus of this thesis on the hazmat transportation by truck on public roads.

The differentiation between problem categories is not as definite as the one for the transportation mode. Overall, hazmat problems are mostly assigned to five different problem categories (Erkut et al., 2007; Bianco et al., 2013). The problem categories have grown historically and are referred as risk assessment problems (RAP), network design problems (NDP), routing and scheduling problems (RSP), routing and location problems (RLP) and toll setting problems (ToSP). Further sub-classifications are possible. For this thesis, RSP are further divided in different categories of shortest path problems (SPP), dissimilar path problems (DPP) and vehicle routing problems (VRP). An extensive literature overview and a more detailed classification are provided by study 1 of this thesis.

2. Research scope and structure of the thesis

The goals of this thesis are to contribute toward a better understanding of the hazardous materials transportation problem, to give new and detailed insights into the risk modelling for the hazardous materials vehicle routing problem (HMVRP) and to provide heuristic solution approaches with a particular focus on the bi-objective risk-cost conflict. For this purpose four different studies have been carried out with focus on three different aspects. The first aspect is the exploration of the existing basic research as well as the development and trends in the research field of hazmat logistics. For this purpose in study 1 an extensive literature review is conducted to improve the understanding of hazmat logistics and to reveal research gaps. The second aspect lies in a further exploration of risk modelling for the HMVRP. Consequently, different risk models are analyzed and compared to deepen the understanding of risk modelling and risk influencing factors for the HMVRP as well as their influence on the solution outcomes. The third aspects focus on the development of suitable solution procedures for the HMVRP. Heuristic solution methods are proposed to cope with the NP-hard nature of the HMVRP. Figure 1 displays the overall structure of this thesis and shows the connection between the four studies as well as their main research scope.

The studies 2, 3 and 4 of this thesis focus on the hazardous materials vehicle routing problem. A scenario for the distribution of heating oil in an urban area is used as case for the experimental settings. Given the current situation, and bearing in mind that climate protection has become an important topic in the public opinion, the growing wish for more sustainability could lead to a decrease in the demand of conventional fuels or heating oils in a nearer future. However, this will not lessen the importance of hazmat transportation. Liquefied petroleum gas (LPG) or hydrogen will become of growing importance for the personal mobility and the demand of chemicals, especially petrochemical, for satisfying the production industries will remain. A scenario for the distribution of heating oil can easily be adapted to the distribution of LPG or hydrogen for fuel stations, especially when considering that explosive gases (a hazmat of UN-class 2) are even more dangerous than flammable liquids (a hazmat of UN-class 3) (UN, 2009).

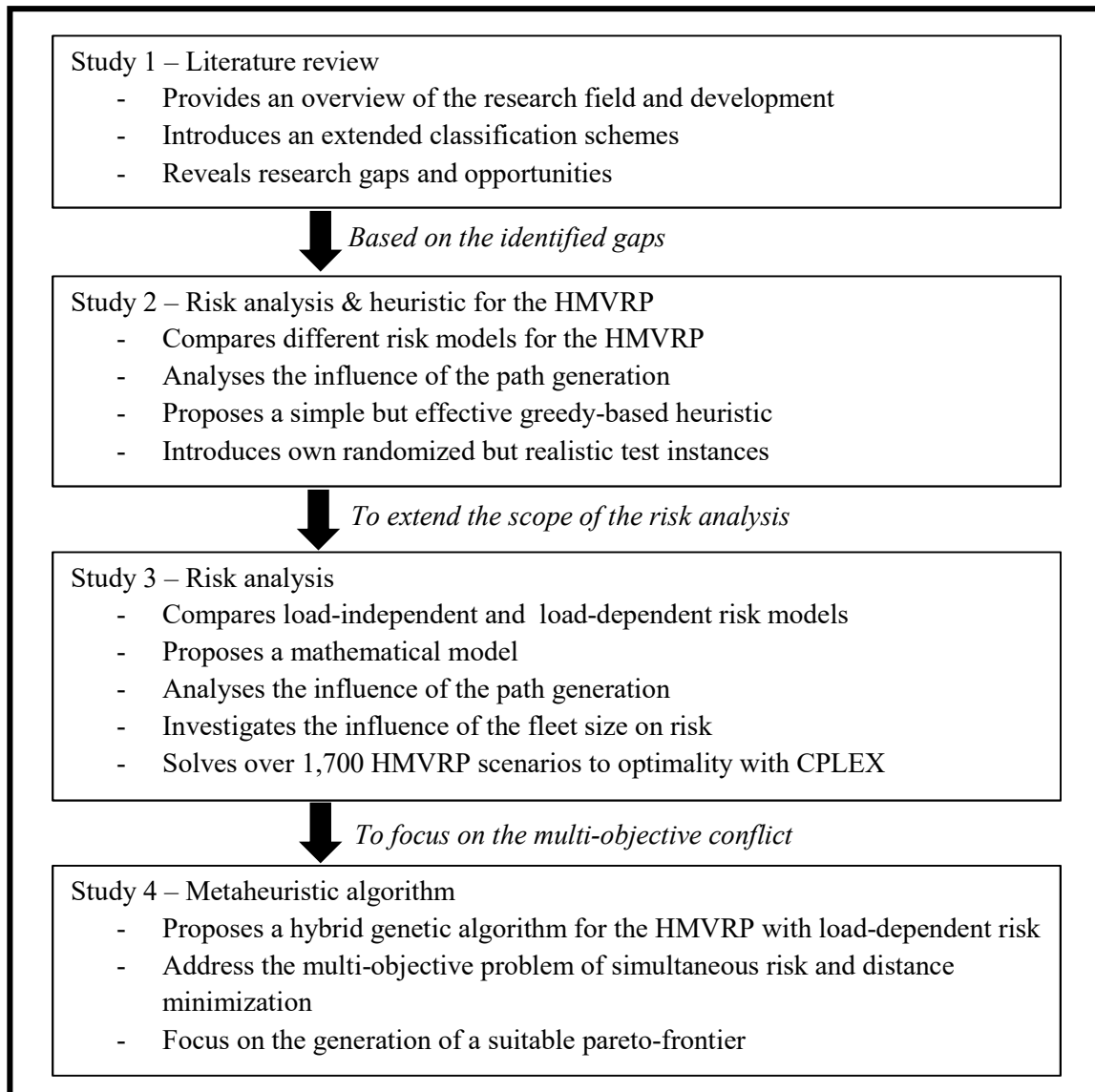


Figure 1- Illustration of the scope of this thesis, the different studies and their connection

Study 1

The study 1 (Holeczek, 2019) is a literature review and recapitulates over 300 contributions to the hazardous materials transportation problem from 1973 to 2017. The main motivation for this study was that since the last extensive literature review by Erkut et al. (2007), including over 170 articles, more than a decade has passed. A more recent literature survey by Erol and Yilmaz (2016) reviews only 179 articles from 1973 to 2014 and with a clearly less extensive classification than Erkut et al. (2007). The classification for this thesis is more extensive than the one by Erkut et al. (2007) and has identified over 300 publications, thereof 46 publications since 2014 and 179 publications since 2007. The growing number of publications in the last years underlines the need for a detailed and recent literature survey, particularly with focus on

the development in the field and the identification of trends as well as research gaps. For this purpose, study 1 addresses the following three points.

First, the study gives an overview of the entire field of hazmat transportation problems over the last forty-five years. The development of the entire field of hazmat logistics and the number of publications per year are analyzed and the most important journals are identified. The study finds a recent increase in NP-hard problems in the context of hazmat transportation. Furthermore, an overview of the publication of non-road transportation and intermodal transportation problems is provided.

Second, the study provides a detailed classification for hazardous materials truck routing problems. For this purpose, different problem categories are identified: (1) shortest path problems (SPP), (2) dissimilar path problems (DPP), (3) vehicle routing problems (VRP), (4) routing and location problems (RLP), (5) network design problems (NDP) and (6) toll setting problems (ToSP). Moreover, the SPP category is further divided in three sub-categories: (1.1) approaches without scheduling, (1.2) approaches with a-priori scheduling and (1.3) approaches with real-time adaptive route selection. The classification scheme consists of four different primary groups: the solution approach, special problem characteristics, the risk modelling and the test instances. Furthermore, the classification is adapted to each of the different problem categories. The classification is applied to 152 hazardous materials truck transportation papers.

Third, the study reveals research gaps. New research opportunities for all problem categories and sub-categories of hazmat transportation problems are proposed. Especially regarding further extensions of the HMVRP, the study reveals multiple possibilities. These findings later became a main motivation for the successive studies. One of the major findings was the lack of risk models that incorporate the varying load amount during the vehicle trip. Risk models adapted for shortest path problems normally do not need to deal with varying load amount during a trip because the cargo is unloaded entirely once the destination is reached. Therefore, the load amount does not need to be included in the risk model. The HMVRP is among the younger problems in the field of hazmat logistics and in contrary to the shortest path problems, one vehicle, in most cases, is serving multiple customers during a delivery trip. This leads to a decrease of the load amount during the vehicle trip. Incorporating the load amount in the risk model has only been addressed in a few articles. Comparative studies of

different risk models for the HMVRP were not identified at all. Furthermore, the study reveals a lack of benchmark instances for all problem categories of hazmat routing problems.

Study 2

The study 2 (Holeczek et al., 2018) is the preliminary work for the studies 3 and 4. It proposes a simple but effective heuristic algorithm for the capacitated HMVRP, analyzes the influence of path generation on the HMVRP and compares different risk models. The main motivation was the lack of comparative studies for risk models in the context of the vehicle routing problems. A study by Erkut and Verter (1998) reveals that different risk models lead to different solution outcomes but focuses solely on shortest path problems. The first VRP in the context of hazmat was proposed only three years later by Tarantilis and Kiranoudis (2001). Since then the HMVRP has known growing attention, especially in the last ten years (Holeczek, 2019). However, an analysis and comparison of different risk models, like Erkut and Verter (1998) did for the SPP, was not identified for the HMVRP. In contrast to the SPP, the VRP, even in its most simple form, is an NP-hard problem. This makes the solution process even more difficult. To analyze the influence of risk modelling on the HMVRP study 2 addresses the following four points.

First, the influence of different risk modelling approaches on the solution outcomes of the HMVRP is analyzed. For this study the three most common risk models based on the accident probability, the consequences and a compromise model of accident probability and consequences are used. The study reveals that each risk model leads to a different optimal solution. In addition, the trade-off between risk minimization and the minimization of the total travelled distance is analyzed for all risk models.

Second, to address the problem of lacking benchmarks for the HMVRP, a network generator is developed. Based on the layout and data of real German cities, the generator is able to generate randomized but realistic road transportation networks of urban areas. The generator can differentiate between three categories of roads: motorways, country roads and city roads. Realistic values for the accident probability and the population density are assigned to each arc.

Third, the study addresses the problem of the path generation for finding suitable paths between the customer and the depot nodes, before the VRP is addressed. Many HMVRP approaches use modified versions of classical VRP benchmarks, where the connection is

determined by the Euclidian distance between two nodes and a risk value is added. However, in many approaches it is not clear whether this connection should represent the shortest path, the safest path or a compromise path. Particularly in an urban environment, the population density can vary strongly over a short distance making the Euclidian distance approach not very reliable. So far, the path generation for the HMVRP was only addressed in the approaches of Androutsopoulos and Zografos (2012) as well as Pradhananga et al. (2014). However, an explorative analysis to what degree the path construction can influence the solution outcomes of the HMVRP is missing. Study 2 investigates the influence of the path generation on the solution outcomes of the HMVRP by using realistic networks of urban areas. In the test instances the customers and the depot are located in the road transportation network of an urban region. The network contains a given number of weighted, undirected arcs representing road segments of the region and a given number of nodes representing intersections and junctions. A subset of the set of all nodes represents the locations of the customers and the depot. Four different instances for the HMVRP are generated for each set of customer nodes. Each instance is generated by using a different objective function for finding suitable paths between the customers and the depot. The objective functions consider the minimization of the distance and three different risk models. Thereafter, the HMVRP instances are solved by using different objective functions. The results show that the path generation has an important impact on the solution outcomes.

Fourth, a simple but effective heuristic algorithm is proposed and tested. The algorithm is based on a greedy approach where the vehicles are choosing the best fitting customers. Additionally, an extensive local search is applied for a better solution quality. Before the heuristic algorithm is applied on the hazmat networks, it is tested on known benchmark instances for the VRP for distance minimization where it shows a reliable performance and a fast computation time.

Study 3

The study 3 extends the scope of the second study and introduces load-dependent (LD) risk models. The main motivation for this study was the lack of LD risk models for the HMVRP in the literature. So far, only few solution approaches consider LD risk, although Androutsopoulos and Zografos (2012) point out the importance of including load capacity in the risk model and propose a first mathematical model. Nevertheless, load-independent (LI) risk models are used more frequently due to mainly two reasons. The first reason is that many

risk models for the HMVRP are extensions of established risk models developed for shortest path problems. However, for SPP the vehicle load is not altered during its trip, hence the load does not need to be included in the risk model. The second reason is the increase in the problems complexity when load is included in the risk model. Even Androutsopoulos and Zografos (2012) use a LI risk model in their proposed heuristic solution approach, to speed up their algorithm. A few years later Bula et al. (2016; 2017) propose a heuristic approach with a LD risk model for the HMVRP and underline its importance. However, a comparison of different load-dependent risk models as well as a comparison between LD and LI risk models is missing. To improve the understanding of LD risk models and to provide further insights on the HMVRP study 3 investigates the following three aspects.

First, different risk modelling approaches for the HMVRP are discussed and compared. The study focusses on LD risk models and reviews different approaches using a LD risk model. Additionally, LD risk models used for location-routing problems are included in the review. The development from load-independent to load-dependent risk models is analyzed. A new risk model is proposed and tested. The proposed model extends the classic LI accident probability model to a LD accident probability model.

Second, a mathematical model of the HMVRP is proposed. The model tracks the amount of hazmat transported by the vehicles and allows tracking the LD risk value as well as the LI risk value. Seven different objective functions for the model are proposed, one for distance minimization, three for different LI risk models and three for different LD risk models.

Third, risk influencing factors are investigated. Similar as in study 2 the influence of the path generation on the solution outcomes of the HMVRP is analyzed. Furthermore, the importance of the fleet size is addressed. The study shows that fleet size has no significant impact with LI risk models, but becomes of importance for LD risk models. In many scenarios, many small trips with a smaller amount of cargo are preferred to long trips of fully loaded vehicles. However, this becomes a problem when considering economic aspects. The tradeoffs between the different risk models and distance minimization are analyzed to generate helpful insights for multi-objective scenarios where an economical goal, as well as a safety goal are addressed simultaneously. For this study, over 1,700 HMVRP instances are solved to optimality using the CPLEX solver.

Study 4

The study 4 addresses the problem of constructing a suitable pareto-frontier when risk and travel distance are addressed simultaneously and a LD risk model is used. The main motivation for study 4 was to develop a fast solution procedure for the HMVRP with a LD risk model. While the heuristic algorithm from study 2 performed well in combination with LI risk models, it encountered some problems when adapted to LD risk models. The exact solution procedure from study 3 required too much computation time when searching for multiple non-dominated solutions. To address both issues, a meta-heuristic framework of a hybrid genetic algorithm (HGA) was adapted to the HMVRP. Study 4 provides the following aspects.

First, the HGA is developed and the main elements of the algorithm are described. The HGA is based on the idea of the giant route chromosome by Prins (2004) and uses element of unified solution framework for VRP by Vidal et al. (2014). The solution is represented in the form of a single, giant tour chromosome including only the customers and without any trip delimiters. The encoding without delimiters allows an easy crossover phase due to all chromosomes having the same length. The giant tour chromosome is then decoded by a shortest path approach for finding the delimiters of the solution. The mutation phase is replaced by local search phase. Instead of randomly mutating a child, the neighborhood of each child chromosome is investigated by a local search procedure including different local search strategies. The fitness function is represented by the weighted sum of the risk value and the distance value.

Second, the HGA is applied to the HMVRP instances with the aim to minimize risk and distance simultaneously. All non-dominated solutions are then represented in a pareto-frontier so that a decision maker can pick the best fitting solution. Overall, the HGA performed quite well and was able to determine multiple non-dominated solutions for each problem instance.

3. Outlook and conclusions

This thesis contributes to the basic research in the field of hazmat logistics, with a special focus on truck transportation and the hazardous materials vehicle routing problem. In conclusion, three potential extensions of the here presented studies are highlighted for future research.

First, for this thesis the path generation and the HMVRP are solved in two separated steps. In a first step, the best suitable paths are selected. In a second step, the VRP is solved. Study 2 and 3 made it clear that the path generation plays an important role for the urban hazmat transportation and therefore it should always be mentioned how the paths are generated. Androutsopoulos and Zografos (2010) and Pradhananga et al. (2014) proposed some first approaches to a combined path finding the VRP solving. However, their heuristic approaches did not include load-dependent risk models. A further investigation of this problem aspect is promising.

Second, time varying network attributes were not included in this thesis. In general, heating oil is distributed during the normal working hours and therefore the daily traffic and population spikes in urban areas cannot be avoided. However, for other hazardous materials delivery problems, e.g. the supply of gas stations or industrial plants, time varying network can be of interest. By considering the varying level of traffic during the night and day time, the process safety can be improved. HMVRP so far only use scheduling for dealing with customer time windows but not with time varying network attributes. While the procurement of accurate data is challenging, the results will be rewarding.

Third, while the risk models used for the HMVRP aim to minimize the total risk, they do not address the problem of risk equity. Risk equity considers the spatial distribution of risk over the whole network. Its main motivation is to prevent that certain parts of a network are overused and thereby to expose certain citizens heavily to multiple hazmat shipments. Especially in the eye of the public, it may appear as a good strategy to distribute risk fair and evenly. However, this can lead to an increase in the total risk value. So far, no approaches considering risk equity for the HMVRP have been identified. Further investigation with regard to the influence of risk equity on the total risk value is necessary. In the context of load-depending risk models, a comparison of different risk equity approaches is of high interest. For example, when using a zonal approach for risk equity the exposure can be measured in the total mileage travelled through the zone or in the total amount of cargo transported through the zone.

Finally, it can be concluded that the hazardous materials transportation problem remains challenging even after over 45 years of research. The worldwide growing urbanization underlines the importance of hazmat transportation in highly populated areas. This thesis contributes toward a better understanding of risk modelling for the hazardous materials

vehicle routing problem in urban areas as it provides an extensive analysis and detailed comparison of risk models and factors. Heuristic methods are proposed to accelerate the solution process and to offer a larger variety of non-dominated solutions for the test instances when more than one objective function is considered. Additionally, the provided literature review provides a detailed overview of the development and contributions of the entire research field. Research gaps are analyzed and new opportunities are proposed.

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II

Hazardous Materials Truck Transportation Problems: A Classification and State of the Art Literature Review

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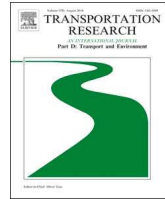
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Hazardous materials truck transportation problems: A classification and state of the art literature review



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ABSTRACT

The paper presents a structured overview of the literature on the hazardous material (hazmat) transportation problem of the last 45 years. Additionally, a detailed classification for the hazardous materials truck routing problem is provided. It extends existing classification schemes, reviews the historical development of research in the area of hazmat logistics and reveals recent progress. The main contribution of the paper is the discussion of the historical development and the identification of recent trends. It aims to reveal research opportunities and identifies research gaps. The paper's focus lies on the transportation of hazmat on public roads. An extended classification scheme for different problem categories of hazmat truck transportation is developed and applied.

1. Introduction

The transportation of hazardous materials (hazmat or dangerous goods) is strictly associated with safety, security and environmental concerns. For this reason, hazmat transportation needs to be treated separately from classical transportation problems. Due to its dangerous nature, the definition and classification of hazardous materials is regulated in most countries by law. According to the German legislator dangerous goods are any materials or objects that by their very nature, characteristics or state, when transported, pose risk to public safety or order, in particular, to the general public, the patrimony, the life and health of persons, animals and objects (GGBeFg, 2015). A similar definition is provided by the US Department of Transportation (US DOT, 2016). There are many different categories of hazmat and not all are emitting the same risk. Hazardous materials are divided into nine classes and several subclasses on the basis of their specific risk producing chemical characteristics (UN, 2009). Hazmat can be transported via road, rail, water, air and pipeline. The transportation mode is referred as intermodal if multiple modes are considered simultaneously and if the transportation mode is switched during the shipment. The differences in using these modes are significant and each transportation mode needs a specific approach for risk assessment and modelling. The most important mode for hazmat transportation is road transportation. In Germany over 46% of the transported hazmat, a total of 141.48 million tons in 2015, was shipped by trucks (Destatis, 2018). The transport of hazmat on public roads poses a direct threat to the resident population and environment. Truck routing offers a lot of optimization possibilities in the field of operations research. Therefore, the following review will focus on road transportation problems. Additionally to the challenges of classical routing problems, hazmat routing problems have to deal with the hazardous nature of the cargo. The main difference between the shipment of hazardous materials and the shipment of other materials is the associated heavy risk in case of an accidental spill of these materials during the transportation process (Erkut and Verter, 1998). While the term hazardous material is uniquely defined, the definition of risk varies widely and a lot of different approaches have been

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proposed and discussed in the last decades. The most frequent definition approach in hazmat routing is the traditional risk model (Erkut and Verter, 1998). The traditional risk model defines risk as the product of the consequence and the probability of an unwanted incident (Covello and Merkhofer, 1993). Even if the number of hazmat accidents with release is very small in comparison to the number of shipments of such materials, the consequences can be catastrophic. Furthermore, already small accidents without hazmat spill receive a lot of media attention. The potential dangers to population, environment and patrimony draw people's attention to these transportation types (Bianco et al., 2013). The huge impact of hazmat accidents justifies the deployment of serious measures to further limit the consequences and strengthen the importance of hazmat logistics as a research topic in operations research. Risk evaluation and assessment for hazmat transportation originates in the 1970s (Shappert et al., 1973). The first approaches to optimize the shipment process followed a few years later. One of the first were Kalelkar and Brooks (1978) who proposed a multidimensional framework for decision analysis to provide support for the shipment of hazardous materials. Their approach was applied to support a comparison of different transport modes (barge, rail and pipeline). Since then, the hazmat problem has received growing attention and a rising flow of contributions.

This article reviews the contributions to the hazmat transportation problem over the last 45 years with a particular focus on road transportation. The review shows the historical development and points out recent trends. Research gaps and new potential challenges are identified. In addition, the review should facilitate the access to the field of hazmat logistics for new researcher.

In a first step, an extensive overview of the all identified publications concerning hazmat logistics is provided and the historical development is analyzed. In a second step, the review focuses on hazmat truck transportation problems and a classification scheme is developed. Then, the classification is applied and the main findings for the different routing problem categories are discussed. In a last step, potential research gaps are identified.

2. An overview of the different problem categories in the literature on hazmat logistics

A structured search approach based on Webster and Watson (2002) is used to identify the source material for this review. In a first step, leading journals in the field of Operations Research and Logistics are examined for fitting contributions. In a second step, a backward search is done by reviewing the citations for the identified relevant articles. In a third and last step, a forward search is performed identifying contributions which cited the most important articles identified in the previous steps. Fig. 1 shows some of the most notable journals and their number of contributions accounted in this classification. From 1973 to 2017 a total of 300 papers are identified, published in a total of 93 different journals and conferences.

The hazmat problem has already been addressed by reviews due to its popularity in the last decades. The most important so far is the review of Erkut et al. (2007) including over 170 articles. A more recent literature survey by Erol and Yilmaz (2016) reviews 179 articles from 1973 to 2014 but with a less extensive classification than Erkut et al. (2007). An older comprehensive literature survey can be found in Erkut and Verter (1995b). Our proposed classification is more extensive than the one by Erol and Yilmaz (2016) and has identified over 300 publications, thereof 46 publications since 2014 and 179 publications since 2007. Furthermore, we think that a more specific classification scheme is needed to provide a more detailed overview of the existing literature, as well as addressing new problem categories and problem characteristics. Additionally, hazmat incidents receive a lot of media attention and have a severe impact on the affected parties. Recent overviews can facilitate the access to the field of hazmat logistics and help the further improvement for the safety and security of hazmat transportation.

Fig. 2 shows the number of publications from 1984 (first year with at least 2 publications) to 2017. Hazmat transportation problems have known an all-time high in the last decade even surpassing their first prime from the mid-nineties. The increase in the last years can be explained by two main factors. On the one hand, the main research fields in hazmat logistics, such as shortest path and risk assessment problems maintained a steady flow of contributions. On the other hand, new trends dealing with NP-hard problems, such as the vehicle routing, the network design and the toll setting problem, emerged in the field of hazmat logistics and received growing attention.

The large number of papers in the field of hazmat logistics underlines the need to apply a classification according to the main research contributions of each paper. Erkut et al. (2007) propose a simple classification for the different aspects of hazmat routing problems: (1) "Risk assessment", (2) "Routing", (3) "Combined facility location and routing", (4) "Network design". Further, (5) "Toll setting policies" are proposed by Bianco et al. (2013) as a merging trend in hazmat routing that can be considered in addition to the existing four problem aspects. Erkut et al. (2007) furthermore differentiate between the different modes of transportation. While the

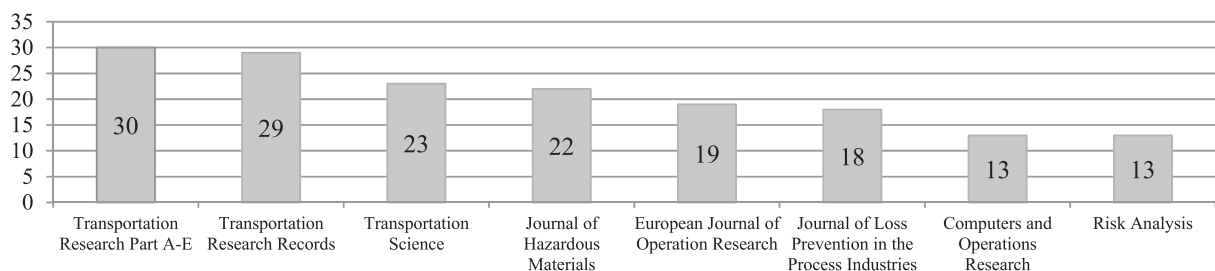


Fig. 1. Notable journals and their number of contributions to this review.

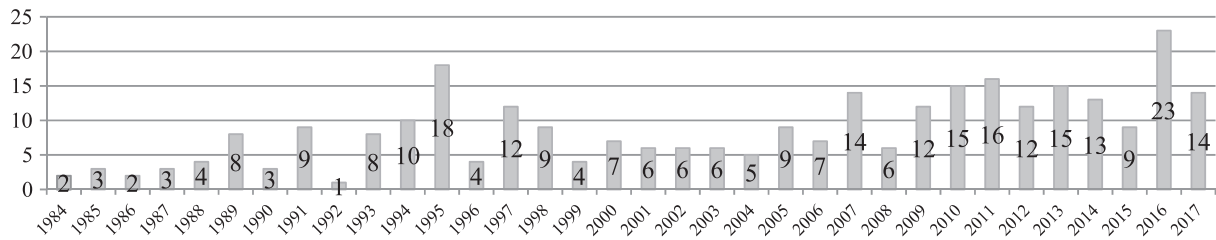


Fig. 2. Number of published papers between 1984 and 2017.

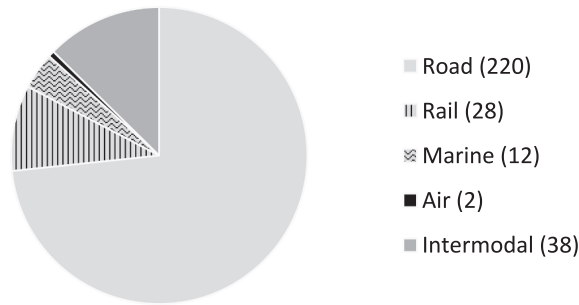


Fig. 3. Number of contributions by transportation mode.

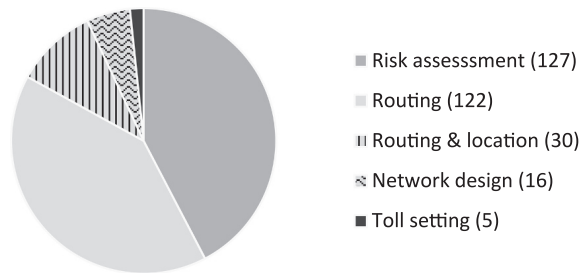


Fig. 4. Number of contributions by problem category.

latter classification offers a good overview of the different key problems in hazmat transportation, it has to be mentioned that numerous papers deal with more than one problem aspect or are positioned between the areas mentioned above.

Our review focuses on road transportation problems. Therefore, it requires a more detailed sub-classification to properly address new problem categories, to provide a more specific classification and a deeper insight into the different categories of road transportation. For this purpose, all selected papers are first sorted according to their addressed transportation mode. As Fig. 3 shows, over 72% of the reviewed articles focus on road transportation. Out of 38 intermodal papers, 37 include road transportation aspects. This underlines the importance of the transport mode road for hazardous materials.

After a first screening, the papers are assigned to the 5 problem categories mentioned above and the results are shown in Fig. 4.

As the risk aspect is the main difference between normal transportation problems and hazmat transportation problems (Erkut and Verter, 1998), it is no surprise that risk assessment problems make up the largest group of hazmat problems. Erkut et al. (2007) focus in their review on quantitative risk assessment involving the following steps: (1) hazard and exposed receptor identification; (2) frequency analysis; and (3) consequence modeling and risk calculation. Our review furthermore includes papers with a focus on risk reduction as well as risk and accident analysis. To provide a detailed overall view of the field of hazmat logistics Table 1 presents a current review of the non-road and intermodal contributions, sorted by mode of transport and problem category. Table 2 shows the identified contributions to the risk assessment problems for road transportation.

3. Development of an advanced classification scheme

3.1. Categories of hazmat routing problems

The differences in the problem foci of risk assessment problems make them hard to compare with problems focused on routing optimization. Therefore, the classification scheme developed in the following chapters is not applied to the risk assessment problem. Selected papers for the classification have to consider a routing optimization problem (ROP). The ROP aims to find one or multiple paths, routes or schedules for the transportation of hazardous materials, with the main idea of optimizing cost or risk. Papers dealing

Table 1
Classification of non-road and intermodal hazmat transportation problems.

Classification of non-road and intermodal hazmat transportation problems	
Rail	
<i>Risk assessment</i>	Glickman and Rosenfield (1984), Swoveland (1987), Saccomanno and El-Hage (1989), Glickman and Golding (1991), McNeil and Oh (1991), Saccomanno and El-Hage (1991), Dennis (1996), Raj and Pritchard (2000), Barkan et al. (2003), Anderson and Barkan (2004), Gheorghie et al. (2005), Cozzani et al. (2007), Verma and Verter (2007), Verma (2011), Liu et al. (2013), Batarlienè and Jarašūnienė (2014), Saat et al. (2014), Liu (2016), Cheng et al. (2016), Hosseini and Verma (2017), Liu et al. (2017a)
<i>Routing</i>	Glickman (1983), Coleman (1984), Glickman et al. (2007), Verma (2009)
<i>Routing & scheduling</i>	Fang et al. (2017)
<i>Network design</i>	Reilly et al. (2012)
<i>Routing & location</i>	Romero et al. (2016)
Marine	
<i>Risk assessment</i>	Luckritz and Schneider (1980), Roeleven et al. (1995), Rømer et al. (1995), Douligieris et al. (1997), Ellis (2011), van Dorp and Merrick (2011), Goerlandt and Montewka (2015)
<i>Routing</i>	Haas and Kichner (1987), Li et al. (1996), Iakovou et al. (1999), Iakovou (2001);
<i>Routing & scheduling</i>	Siddiqui and Verma (2015)
Air	
<i>Risk Assessment</i>	LaFrance-Linden et al. (2001), Hsu et al. (2016)
Intermodal	
Road + rail	
<i>Risk assessment</i>	Philipson and Napadensky (1982), Glickman (1988), van Aerde et al. (1988), Saccomanno et al. (1989), van Aerde et al. (1989), Purdy (1993), Saccomanno and Shortreed (1993), Leeming and Saccomanno (1994), Bubbico et al. (2000), Milazzo et al. (2002), Bubbico et al. (2004), Bubbico et al. (2006), Oggero et al. (2006), Schweitzer (2006), Brown and Dunn (2007), Kheirkhah et al. (2009), Paltrinieri et al. (2009), Milazzo et al. (2010), Bagheri et al. (2014)
<i>Routing</i>	Verma and Verter (2010), Verma et al. (2012), Xie et al. (2012), Assadipour et al. (2015)
<i>Routing & location</i>	Jiang et al. (2014), Mohammadi et al. (2017)
<i>Toll setting</i>	Assadipour et al. (2016)
Road + marine	
<i>Risk assessment</i>	Ronza et al. (2007)
Road + pipeline	
<i>Risk assessment</i>	Bonvicini et al. (1998)
Road + rail + marine	
<i>Risk assessment</i>	Shappert et al. (1973), Andersson (1994), Reniers et al. (2010)
<i>Routing</i>	Weigkrich and Fedra (1995)
Road + rail + marine + pipeline	
<i>Risk assessment</i>	Vílchez et al. (1995), van Raemdonck et al. (2013), Reniers and Dullaert (2013)
Road + rail + marine + air	
<i>Risk assessment</i>	Cutter and Ji (1997), Leonelli et al. (1999);
Rail + marine + pipeline	
<i>Routing</i>	Kalelkar and Brooks (1978)

with more than one of the above mentioned problem categories were selected for the review if their included ROP is well-elaborated. It has to be pointed out that many routing problems also include their own risk assessment frameworks, but incorporate them in a ROP. Due to the specific requirements of each mode of transportation, the classification is restricted to road transportation. Intermodal approaches are not taken into the account due to similar reasons.

After applying the selection criteria, 152 papers are selected for a more detailed classification. While routing and location-, network design- and toll setting problems all form small groups of very similar problems, the 107 problems in the “routing” category need further refinement.

The routing group is split into the following sub-problems:

- Shortest path problems (SP)
- Dissimilar path problems (DPP)
- Vehicle routing problems (VRP).

The SP group is then further divided into three additional groups:

- Shortest path problems without scheduling (SP-WOS)
- Shortest path problems with a priori scheduling (SP-APS)
- Shortest path problems with adaptive route selection (SP-ADS).

Table 2
Overview of risk assessment and analysis problems for road transportation.

Overview of risk assessment and analysis problems for hazmat road transportation
Pijawka et al. (1985), Scanlon and Cantilli (1985), Hillsman (1986), van Steen (1987), Abkowitz and Cheng (1989), Harwood et al. (1989), Glickman (1991), List et al. (1991), Abkowitz et al. (1992), Harwood et al. (1993), Gregory and Lichtenstein (1994), MacGregor et al. (1994), Alp (1995), Erkut (1995), Erkut and Verter (1995a), Moore et al. (1995), Spadoni et al. (1995), Chakraborty and Armstrong (1995), Lovett et al. (1997), Pine and Marx (1997), Verter and Erkut (1997), Cassini (1998), Mills and Neuhauser (1998), Pet-Armacost et al. (1999), Zhang et al. (2000), Abkowitz et al. (2001), Hwang et al. (2001), Verter and Kara (2001), Fabiano et al. (2002), Saccomanno and Haastrup (2002), Shorten et al. (2002), Kara et al. (2003), Martínez-Alegria et al. (2003), Nardini et al. (2003), Fabiano et al. (2005), Boulmakoul (2006), Godoy et al. (2007), Zhang and Zhao (2007), Sattayaprasert et al. (2008), Clark and Besterfield-Sacre (2009), Qiao et al. (2009), Samuel et al. (2009), Trépanier et al. (2009), Dzemydiene and Dzindzalieta (2010), Guo and Verma (2010), Fabiano and Palazzi (2010), Lozano et al. (2010), Yang et al. (2010), Chakrabarti and Parikh (2011a), Chakrabarti and Parikh (2011b), Chakrabarti and Parikh (2011c), Kazanti et al. (2011), López-Atamoros et al. (2011), Lozano et al. (2011), Pesic et al. (2011), Chakrabarti and Parikh (2012), Zhao et al. (2012), Chakrabarti and Parikh (2013a), Chakrabarti and Parikh (2013b), Tena-Chollet et al. (2013), Shen et al. (2014), Ambituuni et al. (2015), Brzozowska (2016), Conca et al. (2016), Cordeiro et al. (2016), Inanloo and Tansel (2016), Caliendo and de Guglielmo (2017), Leung et al. (2017)

Separating routing and scheduling problems into scheduling problems with a priori optimization and adaptive route selection is proposed by Erkut et al. (2007). DPP and VRP have received a growing popularity only after the review of Erkut et al. (2007), thereby, for our review they are considered as independent problem categories. For each of these problems, a description and a more detailed review is given in the following sections. The classification scheme developed for this review is adapted to each of the problems, but consists generally of four classification clusters: the solution approach, the problem characteristics, the risk modelling and the test instances. The scheme is based on the review presented by Erkut et al. (2007), but presents a more specific classification of the solution approach, the problem variants and network attributes. This classification aims to review the main contributions of each paper to the hazmat transportation problem. If a paper contains more than one approach both approaches are reviewed.

3.2. Problem characteristics

The problem characteristics are referring to specific peculiarities of hazmat problems. Table 3 offers an overview of the different problem characteristics identified in the context of hazmat routing which are relevant for this review.

Erkut et al. (2007) distinguish between global and local route planning. If more than one shipment is considered in a model, interdependencies between different shipments may be taken into account. If interdependencies are ignored, certain links in a network can be overloaded with hazmat vehicles and lead to an increased accident probability. In addition, the spatial distribution of risk over an entire network becomes very uneven, thus exposing certain parts of the resident population to a much higher risk. Problems with such interdependencies are often referred to as “global route planning models” (Bianco et al., 2013). Global routing problems often involve one or more governmental or regulatory agencies, which aim to minimize the total risk of all shipments or the spatial distribution of risk in their jurisdiction. In the following classification it is indicated if a problem addresses the optimization of more than one pair of origin-destination (MOD), and if regulatory actions are included as capacity constraints or the minimization of risk equity (RE).

Capacity constraints: By imposing constraints on the arcs of a road network, the number of shipments or the amount of hazmat transported over these arcs can be limited. This avoids an over usage of certain arcs. Zografos and Davis (1989) were among the first to impose capacity constraints on hazmat transportations. While capacity constraints can reduce risk on certain arcs, they do not address the spatial distribution of risk.

Multiple Origin-Destinations: For a large majority of hazmat routing problems, paths are determined between one origin and one destination (O-D) only. If an alternative path with a deviant origin-destination-pair is required, it can be computed independently from the first pair as long as the shipments are not influencing each other. If such interdependencies have to be considered in a model, a simultaneous pathfinding process with multiple origins and destinations is required. Such interdependencies could be capacity constraints on network links or risk equity.

Risk equity: Risk equity is considered when risk has to be spatially distributed over a network. A fair distribution of risk may appear as a good risk management strategy, especially in the eyes of the public, but it may lead to an increase of the total risk. Risk

Table 3
Problem characteristics acronyms.

Acronym	Problem characteristic
CC	Capacity constraints are used to regulate the hazmat flow on an arc
MOD	Shipments from multiple pairs of single origin-destination are considered simultaneously
RE	Risk equity is taken into consideration
ST	The problem contains at least one stochastic network attribute
FZ	The problem contains at least one fuzzy network attribute
WS	The model contains a weather system
TVN	The model considers a time variant network

equity is rarely considered by hazmat carriers and must be imposed by a governmental agency in most cases (Erkut et al., 2007). When dealing with multiple pairs of origins and destinations, the optimization process often involves multiple decision makers, because one or multiple carriers try to route their vehicles and government authorities try to minimize the total risk and to promote risk equity. Furthermore, risk equity may be taken into consideration when dealing with multiple shipments from one given origin and one given destination. This became one of the main motivations for the dissimilar path problem.

Stochastic values: When dealing with hazmat transportation, relevant measures tend to be uncertain, e.g., the accident probability. If stochastic values are included in a model, the decision process becomes more difficult. Instead of a deterministic value, the decision maker has to choose between solutions following different probability distributions (Wijeratne et al., 1993).

Fuzzy Logic: In addition to a conventional mathematical model, a fuzzy logic model allows the inclusion of linguistic information and smooth set boundaries. Fuzzy logic can, for example, be used for the estimation of accident frequencies (Qiao et al., 2009).

Weather Systems: Different weather conditions can affect network attributes such as travel time, risk probability and population at risk. Weather can have a direct impact on the surface friction of the road or the visibility range, and influences thereby the travel time and the accident probability. Wind speed and wind direction can affect the spreading of an aerosol hazmat, and thereby influence the population at risk. Rain can accelerate the dispersion of hazmat and increases so environmental damage. For a more detailed consideration of weather systems and effects, see Golalikhani and Karwan (2013). Kim et al. (2011) show that the solution quality can be improved by implementing weather or traffic forecasts in the a priori path finding approach.

Time variant network: In a time variant network, network attributes for arcs or nodes can vary with time. For hazmat transportation this can influence travel time or risk factors (e.g., traffic volume or accident probability) and may result in different optimal roads depending on the time of the day and the departure time of a vehicle (Erkut et al., 2007).

3.3. Risk modelling

An evaluation of the risk modelling approach becomes necessary for classifying different hazmat routing models. Erkut and Ingolfsson (2005) propose a classification for models of path risk, because not all approaches were using the traditional risk model. Due to a huge variety and adaption of the different risk models, this review does not focus on the risk models itself but on the basic dimensions used for the risk assessment and modelling approach. Table 4 shows the different acronyms for risk assessment values used in this review.

Risk measurements can either be implemented as an arc or a node attribute. In a large scale network, nodes can represent high density population areas like cities or villages, which need to be avoided. In smaller scaled networks, nodes can represent intersections or junctions, which tend to have a higher risk for an accident. Furthermore, nodes can be used to represent high population or special population areas such as schools or hospitals. Arcs represent the road segments of a network. To account risk one or multiple risk values are assigned to each arc. These values can represent, for example, the resident population along that arc or the accident probability on this segment.

Accident Probability: The accident probability expresses the likelihood of a hazmat vehicle to be involved in an accident. If enough information is available, each single arc or node can have a specified value. Roads can moreover be classified in different categories with each category having the same accident rates (Jia et al., 2011). While an accident does not automatically lead to a hazmat spill, the accident probability is most often set as the probability of an accident with a severe spill of hazardous material. In most cases, thereby, the accident probability is the probability of a worst case accident. For countries in North America or Europe, the accident probability with a severe hazmat release is often assessed by values between 10^{-6} and 10^{-9} per kilometer traveled (Harwood et al., 1993).

Population: The most common way to measure the consequences of a hazmat incident is by considering the population at risk. Due to the lack of information about the exact population distribution in some networks, the values are often approximated by using the population density in certain areas. The population at risk can then be considered as the average resident population. If more detailed information about the population is available, the population at risk can be modelled more precisely. A distinction between

Table 4
Risk value acronyms.

Acronym	Assessment value	Description
AP	Accident probability	The model uses accident probability for its risk calculation
RP	Resident population	The model assesses damage done to the resident population
TP	Traffic population	The model assesses damage done to the traffic population
SP	Special population	The model respects especially vulnerable centers, e.g., schools or hospitals
EN	Environment	Damages to the natural environment are taken into account
ER	Emergency response	The response time or damage reduction through emergency response operations
SC	Security considerations	The risk of being targeted by a third, hostile party
IN	Infrastructure	Damages to the infrastructure are taken into account
CQ	Consequences	When more than one risk group is affected by a hazmat spill, the overall damage can be expressed as a total value of consequences
CT	Cost	The model considers the cost of an accident, or the total consequence value is expressed as a cost value
OS	Ordinal scale	The model is using an ordinal scale for expressing risk values
UR	Unspecified risk	A unspecified risk value is used

different population measures can then be used. The traffic population consists of the number of people involved in the traffic surrounding a hazmat transport. Traffic conditions can be very fluctuating over time and are, therefore, suitable for time variant or stochastic networks. On large highways with a small or none adjacent resident population, the traffic population can become more important than the resident one. Furthermore, it can be of interest to avoid the proximity to especially vulnerable parts of the population like the population in hospitals or schools. Due to the high population density in these buildings, it can be of interest to treat them separately from the average resident population. Li and Leung (2011) show that different population values lead to different optimal paths. For the following classification, if a paper contains a population exposure model without further precision of the population measurement, it is assumed that the basic resident population is considered.

Environment: A hazmat release can cause severe damage to components of the natural environment such as water, soil and ecology (Ashtakala and Eno, 1996). Cordeiro et al. (2016) present an approach supported by a Geographical Information System (GIS) for assessing environmental risk in case of hazmat transportation. They point out that the damage potential is also strongly dependent on the nature of the hazmat transported.

Infrastructure: When a hazmat accident leads to a fire or an explosion, it can cause severe damage to the adjacent buildings, roads or infrastructure. An evacuation due to hazmat can have a negative impact on industrial buildings in the impact area. The expected damage on the economy can also be considered in a hazmat model.

Emergency response: Emergency response is not directly triggered by a hazmat accident itself, but when facing the consequences. The faster counter measures are taken, the greater are the chances that people at risk can be evacuated. A quick emergency response deployment can prevent further loss of life or damage to the surroundings of an accident and thereby minimizing the consequences. Emergency response can be modeled by using the proximity of an arc to the nearest emergency response building such as a hospital, a police station or a fire station. This proximity can either be calculated by distance (Monprapussorn et al., 2009) or the response time (Huang, 2006).

Security considerations: In addition to the risk of a naturally occurring accident, hazmat trucks, if abused by a hostile entity, can easily become a dangerous weapon. Taking into account the possible risk of a hijack or a terrorist attack on a hazmat transporter requires the road planning with security considerations (Huang et al., 2004).

Cost and consequences: If more than one of the above risk measures is used, a multi-criteria conflict can appear. A uniform measure of risk can be used to simplify these models. The most economical approach may be the calculation of the total cost of an accident. If a cost approach is not suitable or possible, an alternative measure for total consequences can be introduced which can either be based on a cardinal or an ordinal utility value.

Ordinal Scale: In almost all of the contributions risk is represented as a numeric value. But in certain conditions, e.g., when a human dispatcher has to reevaluate a routing decision under time pressure, a rating with an ordinal scale can be of advantage (Beroggi 1994).

Unspecified risk values: If a risk value is used in an approach, but the basics of the value are not further elaborated, the risk is addressed as unspecified risk value.

3.4. Solution approaches

Overall, many different solution approaches were identified. To keep the classification concise and providing a clear overview, the solution approach is reviewed by three important criteria. For each contribution, it is checked if a detailed mathematical model of the problem is provided, if the problem is solved by an exact method (E) or if a conventional heuristic (H) or a metaheuristic (MH) is proposed, and whether a single- or a multiobjective solution approach was chosen. Table 5 describes the acronyms used for the solution approach classification.

3.5. Test instances

When comparing different approaches, as well as for future research, it may be important to know on which test instances an approach has been tested. In the case of hazmat transportation, the test instances are transportation networks. Therefore, this review analyzes the size and the type of the different networks. Case studies have additionally been classified by their geographical location due to varying traffic conditions and regulations in different countries. If an approach is using multiple instances, the size for the largest one is addressed. The acronyms for the test instance characteristics are shown in Table 6.

Table 5
Solution approach acronyms.

Acronym	Description
MM	Indicates whether a mathematical model for the problem is provided or not
SM	Indicates whether the solution method is based on an exact (E) approach, an conventional heuristic (H) or a metaheuristic (MH)
MO	Indicates whether a single- or a multiobjective solution approach is used

Table 6
Test instance acronyms.

Acronym	Description	Acronym	Description
CS	Case study	MBM	Modified benchmark instance(s)
AS	Asia as location of the CS	OTN	Own test network(s)
EU	Europe as location of the CS	A	Number of arcs in the largest problem instance
NA	North America as location of the CS	N	Number of nodes in the largest problem instance
SA	South America as location of the CS	C	Number of customers in the largest problem instance
GIS	Geographical information system	~	The exact network size is not given, but can be approximated

4. Application of the classification on the selected literature

4.1. Shortest path problems

4.1.1. Shortest path problems without scheduling (SP-WOS)

This class of problems involves the routing of one or multiple vehicles. One or multiple single pair shortest path problems (SPSP) have to be solved for each shipment. SPSP are a special variant of shortest path problems where a shortest path from one given origin to one given destination has to be found in a network satisfying the objective function (Domschke, 2007). These problems are referred to as shortest path problems, but in the context of hazmat transportation the “shortest” path can be the “safest” path or a compromise in case of multiple objective functions. SP-WOS assume that the route is chosen before the transportation process starts. Scheduling approaches and time varying networks do not fall into this category. Table 7 gives a detailed overview and a classification for the identified shortest path problems without scheduling.

The modelling of risk and the development of new risk models for routing frameworks are the main foci of most SP-WOS. Batta and Chiu (1988) as well as Erkut and Verter (1998) demonstrate that different risk models lead to different optimal paths. The majority of the approaches use a traditional risk model which incorporates both accident probability as well as consequences and finds a compromise solution. The consequences of a hazmat spill are measured by the exposure of the resident population in the majority of the approaches. The modelling becomes even more challenging when different aspects for consequences are used simultaneously. Ashtakala and Eno (1996) show that the safest route for the resident population is not the safest route for the environment. Jin et al. (1996) measure the consequences by numbers between 0.1 and 1 which include the total damage to the resident population, the traffic population and property. Huang et al. (2004) propose a genetic algorithm, while Huang (2006) and Huang et al. (2003) suggest an analytic hierarchy process for weight determination when dealing with multiple measurements for risk and cost. Abkowitz and Cheng (1988) and Sivakumar and Batta (1994) use the total cost of a hazmat accident for a uniform measure of consequences. Leonelli et al. (2000) apply the human life value to model the consequences for the resident population.

The majority of the risk models only consider the accidents that can occur along arcs. Only few approaches use nodes for risk modelling. Batta and Chiu (1988) use nodes for high population centers in a highway network. Marianov and ReVelle (1998) and Patel and Horowitz (1994) utilize both, nodes and arcs, for risk modelling where nodes can represent cities or intersections which tend to have a higher accident probability. Desai and Lim (2013a) use nodes for cities classified into categories based on the population size. The population of the connected cities is included in the calculation of the link risk. Bronfman et al. (2015) use vulnerable centers (e.g., schools or hospitals) in a city network and aim to maximize the distance between these centers and the selected route.

SP-WOS do not consider scheduling. Thereby, they all use none-time-variant arc attributes. Some contributions, however, try to incorporate the dynamic nature of hazmat transportation into a non-variant network. Patel and Horowitz (1994) propose a model for the transportation of aerosol gases. Before deciding on the path, the risk is calculated using a specific wind direction and the risk values are considered as fixed for the path finding process. Different wind directions are tested in separated runs. Wijeratne et al. (1993) argue that the amount of traffic on roads is not a deterministic value. They use stochastic values for travel time and accident probability to integrate some fluctuation in daily traffic. Sivakumar and Batta (1994) use a stochastic value for the travel time while trying to minimize the total transportation cost, including the cost of the risk.

The majority of the approaches are solved by different adaptations of shortest path algorithms. SPSP can easily be solved with an exact process. The problem becomes more challenging when a multi-criteria approach is used. In many contributions a weighting method is applied to solve the conflict. Heuristic methods can be of use when the weight determination for multiple goals is addressed as in Huang et al. (2003) or Huang (2006). Additionally, a decision support system (DSS) can assist the decision maker in the route selection process when multiple goals are considered. In some approaches the DSS from ALK'S PC*HAZROUTE is used as, e.g., in Glickman and Sontag (1995) and Erkut and Glickman (1997).

Additionally, heuristics are advantageous when dealing with large problem instances. The network size has been continuously growing over the years, resulting in new heuristic solution approaches for very large networks as in Li et al. (2013), Bronfman et al. (2015, 2016) or Kuhn et al. (2016). The networks are mostly based on real life networks, most of them located in North America or South Asia. Also, the scale of the network seems to be important. On the one hand, transportation planning for a whole country can be done with a smaller network when only the national highway network is considered. On the other hand, the routing optimization for a single city or a small region can be done on a larger and very detailed network considering all possible road connections in this area. No benchmark networks were found for the SP-WOS.

Table 7
Shortest path problems without scheduling.

References	Solution approach			Problem char.	Risk	Network	
	MM	SM	MO			Type	Size
Saccomanno and Chan (1985)	Yes	E	No	–	AP	CS:NA	–
Abkowitz and Cheng (1988)	Yes	E	Yes	–	AP, CT:(RP, TP, IN)	CS:NA	~ 45N
Batta and Chiu (1988)	Yes	E	No	–	AP; RP	–	–
Chin and Cheng (1989)	Yes	E	Yes	–	RP	CS:NA	–
Zografos and Davis (1989)	Yes	E	Yes	MOD, CC	AP, RP, SP, IN	OTN	8N, 14A
Abkowitz et al. (1990)	No	E	No	–	RP	CS:NA, GIS	–
Gopalan et al. (1990a)	Yes	H	No	RE	AP, RP, TP, IN	CS:NA	50N
Lassarre et al. (1993)	No	E	Yes	–	AP, RP	CS:EU, GIS	–
Lepofsky et al. (1993)	No	E	Yes	–	AP, RP, ER	CS:NA, GIS	–
Sivakumar et al. (1993)	Yes	H	No	–	AP, RP	CS:NA	50N
Wijeratne et al. (1993)	Yes	E	Yes	ST	AP	CS:NA	45N
Patel and Horowitz (1994)	Yes	E	No	WS	AP, RP	CS:NA	423N, 517A
Sivakumar and Batta (1994)	Yes	E	No	ST	AP, CT:(RP, TP, IN)	CS:NA	50N
Boffey and Karkazis (1995)	Yes	E	No	–	AP, CT	OTN	3N, 3A
Glickman and Sontag (1995)	No	H	Yes	–	AP, RP	CS:NA	–
Karkazis and Boffey (1995)	Yes	E	No	–	AP, RP	OTN	~ 49N, 86A
Mccord and Leu (1995)	Yes	E	Yes	–	AP, RP	CS:NA	~ 83N
Ashtakala and Eno (1996)	Yes	E	No	–	AP, RP, EN	CS:NA	–
Jin et al. (1996)	Yes	E	No	–	AP, CQ:(RP, TP, IN)	CS:NA	50N
Erkut and Glickman (1997)	Yes	H	Yes	–	AP, RP	CS:NA	–
Jin and Batta (1997)	Yes	E	No	–	AP, CQ	CS:NA	50N
Nembhard and White (1997)	Yes	H	Yes	–	AP, RP	CS:NA	131N, 202A
Sherali et al. (1997)	Yes	E	Yes	–	AP, RP	CS:NA	12N, 15A
Erkut and Verter (1998)	Yes	H	No	–	AP, RP	CS:NA	–
Marianov and ReVelle (1998)	Yes	E	Yes	MOD, RE	AP	CS:NA	28N, 45A
Erkut and Ingolfsson (2000)	Yes	E	No	–	AP, RP	CS:NA	–
Frank et al. (2000)	No	H	Yes	–	AP, RP	CS:NA, GIS	–
Leonelli et al. (2000)	Yes	E	No	MOD, CC	AP, CT:(RP)	OTN	~ 86N
Marianov et al. (2002)	Yes	E	No	–	CT:(IN)	OTN	30N
Huang et al. (2003)	No	H	Yes	–	AP, RP, TP, SP, IN, ER	CS:AS GIS	–
Huang et al. (2004)	No	MH	Yes	–	AP, RP, TP, SP, IN, ER	CS:AS, GIS	–
Erkut and Ingolfsson (2005)	Yes	E	No	–	AP, RP	CS:NA	103N, 278A
Huang et al. (2005)	Yes	H	Yes	–	AP, RP, SP, EN, IN, ER, SC	CS:AS, GIS	–
Bell (2006)	Yes	H	No	RE	AP; RP	OTN	9N, 12A
Huang (2006)	No	H	Yes	–	AP, RP, TP, IN, ER	CS:AS, GIS	–
Bell (2007)	Yes	E	No	RE	RP	OTN	9N, 12A
Bonvicini and Spadoni (2008)	No	E	No	MOD	AP, CT:(RP, TP, SP)	CS:EU, GIS	111N, 143A
Monprapussorn et al. (2009)	Yes	H	Yes	–	RP, SP, TP, EN, IN	CS:AS, GIS	–
Li and Leung (2011)	Yes	H	Yes	–	AP, RP, SP, TP, IN	CS:AS, GIS	–
Das et al. (2012)	Yes	H	Yes	MOD, CC	AP, RP	CS:AS	26N, 41A
Kokkinos et al. (2012)	Yes	H	No	RE, MOD	AP, RP	OTN	50N, 420A
Li et al. (2013)	Yes	MH	Yes	–	AP, RP, SP, TP, IN, ER	CS:AS, GIS	12.704N, 28.974A
Kang et al. (2014a)	Yes	E	No	–	AP, RP	CS:NA	90N, 158A
Mahmoudabadi and Seyedhosseini (2014)	Yes	E	Yes	MOD, FZ	AP, RP, EN, IN	CS:AS	57N, 88A
Rahman et al. (2014)	Yes	E	Yes	–	AP, RP	CS:NA	24N, 76A
Bronfman et al. (2015)	Yes	E	No	–	SP	CS:SA	2.212N, 6.681A
		H	Yes			CS:SA	504N, 1.521A
Parsafard et al. (2015)	Yes	E	Yes	–	AP, RP, EN, IN, ER	CS:AS	8.000N, 20.000A
Toumazis and Kwon (2016)	Yes	E	No	–	AP, RP	CS:NA	90N, 149A
Bronfman et al. (2016)	Yes	H	Yes	MOD	AP, RP, SP	CS:SA	2.212N 6.681A
Du et al. (2016)	Yes	MH	Yes	FZ	AP, RP	OTN	32N, 56A
Kuhn et al. (2016)	Yes	H	Yes	–	RP	CS:NA	11.191N, 35.338A
Garrido and Bronfman (2017)	Yes	E	No	RE	AP, RP	CS:SA	2.030N, 5.790A

Most of the approaches use only one origin-destination pair for a single trip. Solely [Marianov and ReVelle \(1998\)](#) directly address the risk equity problem. [Zografos and Davis \(1989\)](#) introduce capacity constraints on arcs to prevent an over usage. Similar constraints are used by [Leonelli et al. \(2000\)](#) and [Das et al. \(2012\)](#) but without referring to the risk equity problem in general.

4.1.2. Shortest path problems with a priori scheduling (SP-APS)

Similar to the SP-WOS, the SP-APS involve the finding of the shortest path through a network, but they additionally address a scheduling problem. Travel time or risk factors associated with a road can vary with time leading to different optimal roads depending on the time of the day ([Erkut et al., 2007](#)). The departure time of a vehicle can, thereby, influence the transport risk. In some cases, the shipment of hazmat even involves the scheduling of multiple vehicles. SP-APS assume that the route and schedule are chosen before the transportation process starts, with no possibilities of intervention once the routing starts. For a better classification,

Table 8

Acronyms for time variant network attributes and problem characteristics for routing and scheduling problems.

Acronym	Time variants network attributes (TVA)	Acronym	Additional problem characteristics for time dependent problems
TT	Travel time	CTW	Customer time windows
AP	Accident probability	SA	Stops allowed
RP	Resident population		
TP	Traffic population		
CU	Curfews		
RC	Road closure		

two additional problem characteristics for scheduling problems are identified. Out of 18 contributions 17 are dealing with time variant networks, therefore time varying network attributes become a relevant classification criterion for the SP-APS. The acronyms for new problem characteristics as well as for the time variant network attributes are shown in Table 8. A detailed overview and a classification over all shortest path problems with a priori scheduling are given in Table 9.

In addition to the SP-WOS, two more problem characteristics have been identified. The first one consists of customer time windows, a restricted period of time in which a customer can only be visited and served. The time window is known in advance. This problem is addressed only by [Androutsopoulos and Zografos \(2010\)](#), who aim to determine a single non-dominated, time-dependent path to serve a fixed and given sequence of customers (intermediate stops) within given time windows. In later work, they extend their single path approach to a vehicle routing framework. The second characteristic is the allowance of stops during the transportation process. A vehicle can stop at all or a set of given nodes, e.g., parking spots or resting places. During this stop the vehicle is not moving in the network. Stops can be of importance, e.g., when curfews are imposed on a network. In some scenarios, waiting a short amount of time until a curfew has passed can save more travel time than taking a detour. For problems dealing with weather systems, stopping the vehicle and waiting for a bad weather condition to pass can be an alternative to a way around. [Cox and Turnquist \(1986\)](#) were among the first to address a scheduling problem with hazardous materials. They analyze the influence of imposed curfews for hazmat transportation in cities and aim to minimize the waiting of hazmat trucks in cities during their trip. [Fan et al. \(2015\)](#) differentiate road closure from mere curfews due to the fact that road closure can be caused by curfews, traffic controls, weather conditions or construction sites. It has to be noted that curfews and road closure have a different impact on the solution process. If a curfew is on an arc from a node *i* to a node *j*, the arc as well as the nodes (*i* and *j*) are restricted. In the case of a road closure, only the arc (*i*, *j*) is restricted, the nodes *i* and *j* still can be visited using other arcs.

Out of 18 contributions only 8 address the possibility of hazmat trucks to stop and wait during the transportation trip. [Erkut and Alp \(2007a\)](#) demonstrate that permitting stops during the transportation process allows taking full advantage of time-varying attributes such as population exposure, accident probability and traveling time. They demonstrate that routes with stops yield a better solution quality than routes with no stops.

Compared to the other problem categories, SPS-APS have relatively more contributions with stochastic values which allow a more realistic handling when dealing with time changing attributes and uncertainty. Additionally, it has become more popular to include

Table 9

Shortest path problems with a priori scheduling.

References	Solution approach			Problem char.	Risk	Network		
	MM	SM	MO			Type	TVA	Size
Cox and Turnquist (1986)	Yes	E	No	TVN, SA, ST	–	OTN	CU	13N
Nozick et al. (1997)	Yes	H	Yes	TVN	AP, TP	CS:NA	AP, TT, TP	–
Miller-Hooks and Mahmassani (1998)	Yes	H	Yes	TVN, ST	RP	CS:NA	RP, TT	183N, 548A
Suljoadikusumo and Nozick (1998)	Yes	H	Yes	TVN	AP, TP	CS:NA	AP, TP	255N, 548A
Chang et al. (2005)	Yes	H	Yes	TVN, ST	AP, TP	CS:NA	AP, TT, TP	247N, 1158A
Meng et al. (2005)	Yes	E	Yes	TVN, ST, SA	AP, RP	CS:AS	RP, TT	22N, 29A
Akgün et al. (2007)	Yes	H	No	TVN, WS, SA	AP, RP	CS:NA	TT, AP	5.521N, 6.756A
Carotenuto et al. (2007b)	Yes	MH	No	RE, MOD	–	CS:EU	–	311N, 441A
Erkut and Alp (2007a)	Yes	E	No	TVN, SA	AP, TP	CS:NA	AP, TT, TP	138N, 143A
Androutsopoulos and Zografos (2010)	Yes	H	Yes	TVN, SA, CTW	AP, CQ	OTN	AP, CQ, TT	600N
Jia et al. (2011)	Yes	MH	No	TVN, FZ	AP, RP, SC	CS	RP	21N, 46A
Desai and Lim (2013a)	Yes	E	No	TVN, ST	AP, RP	CS:NA	RP, TT	47N, 100A
Shen et al. (2013)	Yes	E	No	TVN, SA	UR	CS	TT, UR	18N, 23A
Szeto (2013)	Yes	E	No	TVN, SA	RP, SC	OTN	RP	4N, 6A
Toumazis and Kwon (2013)	Yes	E	No	TVN	AP, RP	CS:NA	TT, AP	90N, 149A
Fan et al. (2015)	Yes	H	Yes	TVN	RP	CS:AS	RC	8.914N, 27.625A
Faghih-Roohi et al. (2016)	Yes	E	No	TVN, MOD	AP, RP	OTN	AP	22N
Szeto et al. (2017)	Yes	E	No	TVN, SA, MOD	RP, SC	CS:AS	(TT) RP	22N, 28 A
						OTN		180N, 500A

Table 10
Shortest path problems with adaptive route selection.

Reference	Solution approach			Problem char.	Rerouting entity	Risk	Network	
	MM	SM	MO				Type	Size
Beroggi (1994)	Yes	H	Yes	–	HDM	AP, CT OS	CS:EU	–
Beroggi and Wallace (1994a)	Yes	H	Yes	SA	HDM	OS	CS:NA	69A
Beroggi and Wallace (1994b)	No	H	Yes	–	HDM	OS	CS:EU	–
Beroggi and Wallace (1995)	No	H	Yes	SA	HDM	AP, CT OS	CS:EU	–
Kim et al. (2011)	No	H	Yes	–	FCP	AP, RP	CS:NA, GIS	382N, 587A
Desai and Lim (2013b)	Yes	E	No	ST	FCP	–	CS:NA	17N, 100A

the traffic population in the risk model. Traffic population can directly be derived from the traffic volume. Changing traffic volume can be used to directly affect accident probability and the population at risk as in [Nozick et al. \(1997\)](#), [Chang et al. \(2005\)](#) and [Erkut and Alp \(2007a\)](#) or just the accident probability as in [Toumazis and Kwon \(2013\)](#). The majority of the risk model used for SP-APS is relatively simple. Most of them are only including accident probabilities or population exposure. So far, risk equity is only addressed in the work of [Carotenuto et al. \(2007b\)](#).

4.1.3. Shortest path problems with adaptive route selection (SP-ADS)

Modern information and communication technologies allow a permanent exchange of information between a vehicle and the route planner in the dispatch center during the transportation process ([Erkut et al., 2007](#)). Furthermore, GPS tracking allows the dispatcher to know the exact position of a vehicle at any time. In the case of unpredictable events such as a sudden weather change or heavy traffic, the dispatcher can redirect the vehicles or even order the vehicle to pause the transportation process. For hazmat transportation this additional information can be used to assure a safer transport. [Beroggi and Wallace \(1991\)](#) were the first to express the necessity of a real-time control system for the flow of hazardous materials. They defined the transit control for hazmat “...as the set of activities, designed to control the transit of discrete hazardous material units on a predefined network from all origins to all the destinations...” ([Beroggi and Wallace, 1991](#)). A comparison by [Kim et al. \(2011\)](#) of a priori computed routes and routes computed with adaptive routing and real time information, attests that the adaptive scheduling leads to a further improvement of the solution quality. The adaptive scheduling furthermore requires a decision maker in charge of the rerouting process in case of an undesirable event. In an a priori routing and scheduling scenario, a decision maker has time to solve the problem. In case of an adaptive framework, the decision situation for the dispatcher is time-constrained and most likely very stressful ([Beroggi and Wallace, 1994b](#)). The rerouting can, therefore, be done by a human decision maker (HDM) assisted by a computer or completely automated by a fully computerized process (FCP). The rerouting entity is therefore an additional classification criterion for the SP-ADS. A detailed overview and a classification for the 6 identified shortest path problems with adaptive route selection is presented in [Table 10](#).

[Beroggi \(1994\)](#) proposes a first framework of a decision support system allowing a HDM to monitor a hazmat transporter and to interfere in the case of an unpredicted event. An ordinal preference model for risk assessment was introduced and found to be superior to a utility based approach. The preference model only allows three different risk values: high, low and none. [Beroggi and Wallace \(1994b\)](#) notice the advantage of emergency response management when real time information exchange exists and the dispatcher knows the exact position and condition of the vehicle. [Beroggi and Wallace \(1995\)](#) compare four different models for rerouting hazmat transporters and confirm that an assessment with an ordinal preference structure is more efficient. [Desai and Lim \(2013b\)](#) propose an information-based real-time routing approach in a dynamic stochastic network. The paper directly addresses a hazmat routing problematic, but no risk assessment is used in the model. It is argued that the minimization of travel time will reduce driver fatigue which will result in improved safety. [Kim et al. \(2011\)](#) propose a GIS-based DSS framework allowing real-time decision support for hazmat transportation.

4.2. Dissimilar path problems (DPP)

DPP involve the routing from one origin to one destination, but with the focus on finding a suited set of good but different paths. The concept of generating multiple similar solutions originates from the k-shortest paths problem ([Yen, 1971](#)). However, most of the best k-paths have a high similarity and a large number of common arcs. In the context of hazmat transportation, the purpose of dissimilarity is to equally split the risk of multiple shipments on different road segments ([Bianco et al., 2013](#)). [Suurballe \(1974\)](#) introduced the disjoint-path problem, in which no common links among all the generated paths are allowed. Nevertheless, strictly disjoint paths can pose problems for a lot of real-life applications. The introduction of a dissimilarity measure allows the construction of solution paths, so that a required spatial dissimilarity between each pair of paths is achieved. Four different indexes to measure the dissimilarity among a pair of paths are proposed by [Erkut and Verter \(1998\)](#). The DPP has received attention in the literature of shortest path problems in the last years. Only recently, several approaches for the VRP have been introduced ([Talarico et al., 2015](#)), but none of them is purposely designed for hazmat transportation so far. [Table 11](#) presents a detailed overview and a classification for the dissimilar path problem for the transportation of hazardous materials.

Table 11
Dissimilar path problems for hazmat transportation.

References	Solution Approach			Problem char.	Risk	Network	
	MM	SM	MO			Type	Size
Gopalan et al. (1990b)	Yes	H	No	RE	AP, RP, TP, IN	CS:NA	50N
Lindner-Dutton et al. (1991)	Yes	E	No	RE	AP, RP	CS:NA,OTN	–
Miaou and Chin (1991)	Yes	E	No	–	–	CS:NA	994N, 2.714A
Sivakumar et al. (1995)	Yes	H	No	RE	AP, RP	CS:NA	50N
Akgün et al. (2000)	Yes	H	No	RE	–	CS:NA	305N, 854A
Carotenuto et al. (2005)	Yes	MH	Yes	RE	AP, RP	CS:EU	331N, 441A
Dell’Olmo et al. (2005)	No	H	Yes	RE	AP	CS:EU, GIS	699N, 1.754A
Carotenuto et al. (2007a)	Yes	MH	No	RE	AP, RP	CS:EU	331N, 441A
Dadkar et al. (2008)	Yes	MH	Yes	RE, S	AP, RP	CS:NA	1.173N, 1.403A
Caramia and Giordani (2009)	Yes	H	Yes	RE	–	OTN	300A
Martí et al. (2009)	Yes	MH	Yes	RE	–	CS:EU	–
Caramia et al. (2010)	Yes	H	Yes	RE	RP	OTN	300N
						CS:EU	311N, 441A
Kang et al. (2014b)	Yes	H	No	RE, MOD	AP, RP	CS:NA	90N, 108A
Liu et al. (2017b)	Yes	MH	Yes	RE	–	OTN	783N

The search for alternative paths for hazmat transportation originates in the early nineties. One of the main motivations was to improve risk equity by spreading risk spatially over the transportation network. While the first approaches by Gopalan et al. (1990b) and Lindner-Dutton et al. (1991) do not refer to the problem as a dissimilar path problem, they use zones to create different routes with spatial dissimilarity. Miaou and Chin (1991) present different adaptations of a label-setting k-shortest paths algorithm for solving the routing of a truck of nuclear spent fuel on the American highway network. This contribution is one of the early works dealing with the research of large sets of alternative routes in case of hazmat transportation, although their k-path method does not use a spatial dissimilarity measure. Sivakumar et al. (1993, 1995) propose a conditional risk model. This model assumes that a transportation process does not end in case of an accident of a vehicle and that a new vehicle has to be rerouted afterwards to satisfy the customer demand. For this purpose, they aim to determine a set of best routes that can be used alternatively in case of an accident. Finally, with the work of Akgün et al. (2000) the name “dissimilar path problem” was officially brought to the field of hazmat transportation. Since then, the interest in this research field has slowly increased.

Dell’Olmo et al. (2005) introduce the concept of a buffer zone around each link. The dissimilarity between different paths is evaluated by the common space inside the buffer zones around the arcs of two distinct paths. Kang et al. (2014b) include the simultaneous route planning for multiple pairs of origin-destination.

A few approaches are not including a risk model. The main purpose of the DPP is the search for an alternative set of paths so that risk can be split equally. A risk measure is not implicitly necessary for the search of dissimilar paths. Risk equity can be optimized by searching a set of dissimilar paths minimizing path length as in Akgün et al. (2000), or a set of dissimilar paths minimizing the risk as in Carotenuto et al. (2007a). Caramia et al. (2010) even provide a multiobjective approach for dissimilar paths to minimize risk, travel time and length.

4.3. Vehicle routing problems (VRP)

The VRP is an extension of the classical travelling salesman problem. Its objective is to find an optimal set of routes for a fleet of vehicles to deliver a certain good to a given set of customers. The problem was introduced by Dantzig and Ramser (1959) and has found a lot of extensions and variations, especially in the last thirty years (Domschke and Scholl, 2010). While the first VRP by Dantzig and Ramser (1959) optimizes the routing of a fleet of gasoline trucks, the objective is to minimize the total mileage of the fleet without paying attention to the hazardous nature of the cargo. Four decades later, Tarantilis and Kiranoudis (2001) were among the first to adapt a VRP to deal with the special requirements of hazmat transportation. Since originating in the early years of the current century, hazmat VRP have received a lot of attention. With most of the contributions in the last ten years, they can be considered as one important emerging trend in hazmat transportation. Additional problem characteristics for hazmat VRP have been identified for a better classification and are presented in Table 12.

Table 12
Acronyms for the VRP problem characteristics.

Acronym	Problem characteristic	Description
CTW	Customer Time Windows	VRP extension where the customers have to be served in a given time window
HV	Heterogeneous Vehicle	VRP extension where the vehicles are not homogenous
MP	Multi Period	VRP extension where customer demand has to be satisfied over multiple periods
MD	Multi Depot	The VRP is using multiple depots

Table 13
Vehicle routing problems.

References	Solution approach			Problem char.	Risk	Network	
	MM	SM	MO			Type	Size
Tarantilis and Kiranoudis (2001)	No	H	No	–	RP	CS:EU	300C
Zografos and Androutsopoulos (2002)	Yes	H	No	CTW, ER	AP, RP	MBM	100C
			Yes			OTN	8c
Zografos and Androutsopoulos (2004)	Yes	H	No	CTW	AP, RP	MBM	100C
			Yes			OTN	8C
Zhang et al. (2005)	No	MH	No	CTW, CC	–	MBM	100C
Zografos and Androutsopoulos (2008)	Yes	H	Yes	CTW, ER	AP, RP	CS:EU, GIS	12C
Pradhananga et al. (2010a)	Yes	MH	Yes	CTW	AP, RP	SB	100C
Pradhananga et al. (2010b)	Yes	MH	Yes	CTW	AP, RP	SB	100C
Zheng (2010)	Yes	MH	Yes	HV	AP, RP, SP	MBM	20C
Pradhananga et al. (2011)	Yes	MH	Yes	CTW	AP, CT:(RP, SP)	CS:AS	9C
Androutsopoulos and Zografos (2012)	Yes	E	Yes	CTW, TVN	AP, RP, TP	OTN	49N, 168A, 5C 100N, 360A, 20C
Dabiri and Tarokh (2012)	Yes	MH	Yes	MP	UR	OTN	30C
Ma et al. (2012)	Yes	MH	No	CTW, CC	–	MBM	–
Pradhananga et al. (2014)	Yes	MH	Yes	CTW	AP, RP	CS:AS	225N, 781A, 25C
Bula et al. (2016)	Yes	MH	No	HV	AP, RP	MBM	20C
Zhao and Zhu (2016)	Yes	E	Yes	MD	RP	CS:AS	50C
Bula et al. (2017)	Yes	MH	No	HV	AP, RP	MBM	100C
Du et al. (2017)	Yes	MH	No	MD, FZ	AP, RP	OTN	20C

A detailed overview and a classification for the hazmat vehicle routing problems are given in Table 13.

For solving a classical VRP an origin-destination value matrix containing the shortest path between the depot and all pairs of customers (C) is required to determine the best sequence of customers to be served. These values can be obtained for many VRP by calculating the Euclidian or the Manhattan distance between two customers or a customer and the depot. These metrics can have problems when risk has to be minimized, e.g., in urban areas with a strongly divergent population density. In case of hazmat routing, especially when considering multiple objective functions, the question occurs, whether the matrix should be based on the shortest or the safest paths or even a compromise solution. If the paths are selected a priori, before the sequencing, good solutions can be missed. If the “shortest path” determination and VRP are solved simultaneously, the problem becomes more complex to solve. So far only Androutsopoulos and Zografos (2012) and Pradhananga et al. (2014) address the problem of solving the path finding problem and the VRP simultaneously.

Known extensions of the normal VRP have also found some adaptation in the hazmat routing context. Problem extensions considering customer time windows are used in some of the approaches, e.g., Zografos and Androutsopoulos (2002, 2004, 2008), Pradhananga et al. (2010a, 2010b) or Ma et al. (2012). Dabiri and Tarokh (2012) deal with a problem where customer demand has to be satisfied over multiple periods. Problems with heterogeneous vehicle fleet are considered by Zheng (2010) and Bula et al. (2016, 2017). An extension considering multiple depot nodes is proposed by Zhao and Zhu (2016) and Du et al. (2017).

Bula et al. (2016, 2017) address the problem that different vehicle load capacities affect the risk originating from the vehicle. For shortest path problems, where the transported amount of cargo is known in advance and does not alter during the trip, no further modelling is required. But for a VRP, where the amount of customers and thereby the initial amount of cargo associated to one vehicle is not known in advance and can decrease during the trip, it makes the solving more complicated.

Due to a lack of benchmark instances containing reliable risk associated values, some of the approaches have been tested on modified versions of existing traditional VRP benchmarks. Zografos and Androutsopoulos (2002, 2004), Zheng (2010) and Ma et al. (2012) used modified version of Solomon (2005) benchmarks. Bula et al. (2016, 2017) test their approach on modified versions of the problem instances presented by Golden et al. (1984) and by Taillard (1999).

4.4. Routing and location problems (RLP)

The risk emitted during the hazmat transportation process is not only limited to the shipment process, it likewise affects the place where hazmat is produced, processed or stored. For hazmat distributions problems, the origin node of a shipment is most probably a production or storage site for large amounts of hazmat. This node thereby represents a potential danger to its surroundings (Erkut et al., 2007). For hazmat collection problems (e.g., hazardous waste collection), the destination node where large amounts of hazardous waste are stored or treated can become such a danger point (Zhao and Verter, 2015). The considered location problem thereby becomes an important classification aspect. Table 14 shows the different location (Lo) problems identified in the context of hazmat routing.

For the processing of hazardous waste different technologies such as chemical treatments, recycling or incineration can be used. The decision process is even more complicated when different treatment technologies for the same or different types of hazmat are included. For this purpose, the multiple technology (MT) aspect is added as an additional problem aspect. The classification of 25 different routing and location problems is presented in Table 15.

Table 14
Location acronyms.

Acronym	Considered location
OL	Origin location with only outgoing shipments
DL	Destination location with only incoming shipments
PL	Processing location with incoming as well as outgoing shipments
GL	Gateway location that has to be visited with the sole purpose of global risk optimization
ERL	Location for an emergency response unit

Table 15
Routing and location problems.

References	Solution approach			Problem char.	Location	Risk	Network	
	MM	SM	MO				Type	Size
Zografos and Samara (1989)	Yes	E	Yes	CC	DL	AP	OTN	16N, 37A
List and Mirchandani (1991)	Yes	E	Yes	RE, MT	DL	AP, RP	CS:NA	86N, 124A
ReVelle et al. (1991)	Yes	E	Yes	–	DL	RP	CS:NA	24N
Stowers and Palekar (1993)	Yes	E	No	–	DL	RP	OTN	14N, 21A
Jacobs and Warmerdam (1994)	Yes	E	Yes	–	DL	AP	OTN	14N, 29A
Current and Ratick (1995)	Yes	E	Yes	RE	DL	RP	OTN	31N, 146A
Wyman and Kuby (1995)	Yes	E	Yes	MT	DL	RP	CS:NA	23N
Coutinho-Rodrigues et al. (1997)	No	E	Yes	RE	DL	RP	OTN	19N, 32A
Helander and Melachrinoudis (1997)	Yes	E	No	–	DL	AP	CS:NA	36N, 53A
Giannikos (1998)	Yes	E	Yes	RE	DL	RP	OTN	18N, 33A
List and Turnquist (1998)	Yes	H	Yes	–	ERL	AP, RP	CS:NA	50N
Nema and Gupta (1999)	Yes	E	Yes	MT	PL, DL	AP, RP	OTN	16N, 20A
Nema and Gupta (2003)	Yes	E	Yes	MT, RE	PL, DL	AP, RP	OTN	9N, 12A
Ahluwalia and Nema (2006)	Yes	E	Yes	–	PL, DL	AP, RP	CS:AS	16N
Alumur and Kara (2007)	Yes	E	Yes	MT	PL, DL	RP	CS:AS	92N
Zhao and Zhao (2010)	Yes	E	Yes	MT	PL, DL	RP	–	–
Bruglieri et al. (2011)	Yes	E	No	MOD	GL	Risk	CS:EU	105N, 134A
Aboutahoun (2012)	Yes	E	Yes	–	DL	AP	OTN	33N, 45A
Samanlioglu (2013)	Yes	E	Yes	MT	DL	RP	CS:AS	41N
Bruglieri et al. (2014)	Yes	E	No	MOD	GL	RP, SP, TP	CS:EU	105N, 134A
Cappanera and Nonato (2014)	Yes	E	Yes	MOD	GL	RP, SP, TP	CS:EU	105N, 134A
Zhao and Verter (2015)	Yes	E	Yes	MT	PL, DL	EN	CS:AS	40N
Meiyi et al. (2015)	Yes	MH	No	FZ, TVN	OL	AP, RP	OTN	150N
Ardjmand et al. (2016)	Yes	MH	Yes	ST	PL, DL	EN	OTN	280N
Yilmaz et al. (2017)	Yes	E	Yes	MT	PL, DL	RP	CS:AS	82N

The majority of the here considered problems deal with the challenge of finding one or multiple suited destination locations for the shipments of hazardous materials. In most of the problems, this final destination consists of a storage or treatment facility for hazardous wastes. A further addition to the destination location problem was the introduction of processing locations such as treatment centers that process hazardous waste before the waste can be transferred to a storage site or an incineration facility. However, the problem complexity increases strongly when multiple treatment technologies are considered as in [Nema and Gupta \(1999\)](#), [Zhao and Verter \(2015\)](#) or [Yilmaz et al. \(2017\)](#).

Emergency response location in direct combination with the routing of hazardous materials is only considered by [List and Turnquist \(1998\)](#). [Meiyi et al. \(2015\)](#) are the only authors who deal with a location-scheduling problem where the depot nodes have to be located and assorted to a number of customers. Additionally, they are the sole authors who use a time-variant network and incorporate the transportation risk as time-dependent fuzzy random variables in their approach.

Only three approaches address the gateway location problem (GLP). This problem was first introduced by [Bruglieri et al. \(2011\)](#). It aims to optimize the total risk from a global perspective and transportation costs in transportation networks by locating a given number of gateways and assigning each gateway to a vehicle crossing the transportation network. The gateway thereby does not represent a real physical location, but is considered as a check point which has to be visited by the assigned vehicles. By optimizing the total risk for multiple pairs of single origin-destination (O-D) simultaneously from a global perspective, the GLP is closely related to the network design problem. Contrary to the other location problems, the selected gateways do not require any financial investment as it is necessary for a facility or waste storage site. The GLP is the only problem that is working with given pairs of single O-D, while the other RLP mostly use multiple origin or destination nodes, and where the association of the O-D pattern is not known in advance and the optimal assignment is part of the problem.

Overall, most of the approaches use an exact solution method based on linear programming for small networks. Only recently, some heuristic approaches such as the particle swarm optimization from [Meiyi et al. \(2015\)](#) and the genetic algorithm from [Ardjmand et al. \(2016\)](#) have been applied to large problem instances.

Table 16
Acronyms for the involved parties of interest.

Acronym	Party of interest
CHS	Carriers of hazmat shipments
CNS	Carriers of non-hazmat shipments
LAU	Local authorities aiming to regulate the transportation network
TRA	Trans-regional authorities aiming to regulate the transportation network
TER	A hostile terroristic group aiming to attack the hazmat transportation
ERD	Emergency response department

4.5. Network design problems (NDP)

Only recently, the NDP has received increased attention in the field of hazmat logistics. The problem was first introduced by [Kara and Verter \(2004\)](#). In general, the NDP consists of a multi-level decision problem where governmental authorities try to minimize risk while multiple carriers try to optimize their transportation cost. [Amaldi et al. \(2011\)](#) prove that the NDP is NP-hard even for problems where just a single commodity has to be transported. Normal NDP exist far longer and aim to optimize the expansion of a given infrastructure. Network design in the context of hazmat routing aims to find road segments in an existing network which should be closed or restricted to the transportation of hazmat ([Bianco et al., 2013](#)). The majority of SPSP and VRP aim to minimize only the risk for one single carrier and do not take into account the interdependencies of multiple carriers acting in the same network. In contrary, the network design approach lays his optimization focus on a global point of view where these interdependencies are considered for a whole region and for multiple simultaneous transportation processes. The involved parties of interests (PoI) thereby become an important classification aspect for the NDP. The identified PoIs are presented in [Table 16](#).

A detailed classification over all NDP is presented in [Table 17](#).

While addressing risk minimization from a global perspective, all network design approaches deal with multiple pairs of O-D from different carriers. In most of the approaches, the bi-level optimization problem, including a local authority who wants to minimize the total risk and hazmat carriers aiming to minimize their cost, is addressed. [Dadkar et al. \(2010\)](#) extend the approach to a tri-level optimization problem by including a hostile third party. A similar tri-level model with terroristic threat is proposed by [Reilly et al. \(2012\)](#), but applied to a rail network case study.

[Bianco et al. \(2009\)](#) propose a bi-level model which considers two different instances of authorities, a regional authority who wants to minimize the total risk over an entire region and a local authority who wants to assure risk equity. Risk equity is so far only addressed by [Bianco et al. \(2009\)](#) and [Taslimi et al. \(2017\)](#). [Sun et al. \(2016b\)](#) consider cost equity among the carriers in their model. [Xu et al. \(2013\)](#) are the first to introduce emergency response decision in their approach. On the upper level of their approach, the authorities try to design a suited transportation network. On the lower level, the carriers select their routes and the emergency response department selects the best location for the response units. [Taslimi et al. \(2017\)](#) change the policy of road segment closure of [Kara and Verter \(2004\)](#) to a policy that enables the opening of additional road segments to hazmat carriers. In addition, they allow the local government to locate hazmat response teams, so that the response time in case of an accident is optimized. They furthermore include the emergency response time as measurement in their risk model. Time variant networks have received only little attention so far and are only addressed by [Esfandeh et al. \(2018\)](#). It occurs while observing the test data that out of 15 papers, 6 have been

Table 17
Network design problems.

References	Solution approach			Problem char.	Parties of interest	Risk	Network	
	MM	SM	MO				Type	Size
Kara and Verter (2004)	Yes	E	No	MOD	LAU, CHS	RP	CS:NA	48N, 57A
Erkut and Alp (2007b)	Yes	H	No	MOD	LAU, CHS	RP, TP, SP	CS:EU	105N, 134A
Erkut and Gzara (2008)	Yes	H	Yes	MOD	LAU, CHS	RP, TP, SP	CS:EU	105N, 134A
Verter and Kara (2008)	Yes	E	No	MOD	LAU, CHS	RP, TP, SP	CS:NA	176N, 205A
Bianco et al. (2009)	Yes	H	No	MOD, RE, CC	LAU, TRA	RP	CS:EU	311N, 441A
Dadkar et al. (2010)	Yes	MH	No	MOD, ST	LAU, CHS, TER	RP	CS:NA	604A
Amaldi et al. (2011)	Yes	E	No	MOD	LAU, CHS	RP, SP	CS:EU	105N, 134A
Gzara (2013)	Yes	E	Yes	MOD	LAU, CHS	RP	CS:EU	105N, 134A
Xu et al. (2013)	Yes	MH	No	MOD, FZ	LAU, CHS, ERD	AP, CQ(RP, IN)	CS:AS	37N, 53A
Xin et al. (2015)	Yes	H	Yes	MOD	LAU, CHS	RP, SP	CS:AS	21N, 30A
Sun et al. (2016a)	Yes	E	No	MOD	LAU, CHS	AP, CQ	CS:EU	105N, 134A
		H				UR		1020N, 2522A
Sun et al. (2016b)	Yes	E	Yes	MOD	LAU, CHS	AP, CT	CS:EU	105N, 134A
Chiou (2016)	Yes	E	Yes	MOD	LAU, CHS	AP, RP	CS:NA	24N, 76A
Taslimi et al. (2017)	Yes	H	No	MOD, RE	LAU, CHS, ERD	AP, RP, ER	CS:NA	90N, 149A
Esfandeh et al. (2018)	Yes	H	No	MOD, TVN	LAU, CHS	AP, RP, TP	CS:NA	90N, 149A

Table 18
Toll setting problems.

References	Solution approach			Problem char.	Parties of interest	Risk	Network	
	MM	SM	MO				Type	Size
Marcotte et al. (2009)	Yes	E	No	MOD	LAU, CHS	RP	CS:NA	48N, 114A
Wang et al. (2012)	Yes	H	Yes	MOD	LAU, CHS, CNS	RP	CS:NA	46N, 70A
Assadipour et al. (2016)	Yes	MH	No	MOD	LAU, CHS	RP	CS:NA	–
Bianco et al. (2016)	Yes	H	No	MOD, RE	LAU, CHS	RP	CS:EU	105N, 268A
Esfandeh et al. (2016)	Yes	H	No	MOD	LAU, CHS, CNS	RP	CS:NA	24N, 76A

working with the 105 node network from the region of the city of Ravenna in Italy. The test network size remains under 200 nodes in most of the approaches. Only Sun et al. (2016a) are applying their heuristic on network with over a thousand nodes.

4.6. Toll setting problems (ToSP)

Similar to the NDP the ToSP is a multi-level optimization approach. In contrast to the NDP where the regulating authority forbids entirely the usage links in the transportation network, the authorities in the ToSP try to regulate the traffic flow by imposing tolls on certain network links. When tolls are imposed, carriers can still use these links but the usage becomes more costly for them. Therefore, carriers are encouraged to swap to alternate routes. The ToSP in the context of hazmat routing was first introduced by Marcotte et al. (2009) as an extended approach of the model of Labbé et al. (1998) and counts as an NP-hard, bi-level problem (Bianco et al., 2013). Table 18 presents a classification of the existing ToSP in the field of hazmat logistic.

ToSP are the youngest category of hazmat routing problems. Since the first contribution in 2009, only few publications have been made. So far, all approaches are formulated as bi-level problems including a regulating authority on the one side and the carriers on the other. Wang et al. (2012) and Esfandeh et al. (2016) additionally distinguish between carriers transporting hazmat and normal carriers. The risk equity optimization is addressed by Bianco et al. (2016). In their model, the tolls on each arc additionally become dependent on the total risk on that arc.

5. Research gaps

In the following, some identified research gaps for each problem category are proposed and discussed. Additionally, the general problem of lacking benchmarks is addressed.

SP-WOS: The shortest path problem without scheduling belongs to the category of routing problems with the most contributions. While reaching its prime in the mid-nineties, the contributions are still ongoing until today. The development of new and the extension of existing risk models are two of the main foci, especially when dealing with the multiobjective nature of risk modelling itself. Heuristics become important when very large networks or multi-criteria optimization are addressed, especially if unweighted multiobjective problems or more than two risk dimensions are involved. The development of new risk models, as well as further advances in multiobjective solution approaches, offers plenty of possibilities for new contributions. In addition, models developed for a shortest-path problem without scheduling can be adapted to all other problem categories, as they are frequently used as a first approach for developing new models and, if useful, can later be applied to more complex scheduling or routing problems. Shortest path problems offer a simplified entry-level approach for newcomers in the complex field of hazardous transportation problems. Most of the risk models are using risk as a link attribute. Nodes are only considered in few approaches. Particularly in urban areas many accidents happen at road junctions (Greibe, 2003). Junctions with different accident probabilities could likewise be implemented in existing risk models or could lead to the creation of new ones. Further investigation, if a left or a right turn at a junction can influence the accident probability can be of interest.

SP-APS: In contrary to SP-WOS, SP-APS have only received little attention. Scheduling is either included to serve customers in restricted time windows or to take into account time-varying network attributes. In the case of hazmat transportation, the focus mostly lies on time-varying network attributes. A main challenge lies in the acquisition of the necessary data, especially when time varying risk attributes such as population movement or traffic volume are considered. Two of the main gaps revealed are the development of risk models, adapted to the needs of time varying networks, and the further improvement of heuristic solution approaches for dealing with large problems instances. Most of the risk models are only addressing one or two different measurements. Environmental damages have not been included until now. So far, only Carotenuto et al. (2007b) consider risk equity in their model. A further investigation combining spatial and temporal risk equity appears interesting. Risk values can vary widely if different weather conditions are considered. Routing and scheduling with weather changes have only been addressed by Akgün et al. (2007) although Kim et al. (2011) showed that weather consideration in an a priori framework can improve the solution quality. Weather forecast could also be implemented with stochastic variables into a scheduling approach influencing road conditions and thereby accident probability or traffic volume.

SP-ADS: Only few approaches deal with adaptive scheduling possibilities. Over 22 years of development in communication and information technology have passed since the work of Beroggi and Wallace (1995), and only two further contributions have been published. The development of new adaptive scheduling frameworks for shortest path problems as well for VRPs or DPP, offers new

possibilities. The spread of smartphones and mobile internet allows a faster and more precise communication between a vehicle and its dispatch center. Internet services offer the most recent and accurate information about weather and traffic conditions which can easily, and without media disruption, be retrieved and implemented in an adaptive routing system. Better information retrieval and even a connection with social-media platforms could further be incorporated to identify social events affecting the transportation network. Important sport events, concerts, festivals or demonstrations lead to unusual high population density in certain areas. The event itself as well as the related arrival or departure traffic peaks can easily be predicted and avoided by a hazmat truck to further enhance the safety. Especially when security considerations are addressed, hazmat vehicles would avoid public events to further minimize the risk of a hijack or terrorist attack. The development of specialized machine-learning algorithms and artificial intelligence for the hazmat transportation guidance can be promising considering the importance of the rerouting decisions under a limited amount of time.

DPP: Only few contributions have been considering the dissimilar path problem for the last years. For this review, only dissimilar path approaches adapted to the needs of hazmat transportation are selected. The research field for path dissimilarity, however, is larger and needs further investigation comparing hazmat approaches and non-hazmat specified approaches. The main challenge lies in the implementation of a spatial dissimilarity index. Up to now, most of the approaches only deal with spatial dissimilarity. A further extension to a multi-period problem could enable the consideration of temporal dissimilarity. As mentioned before, a merge of DPP and scheduling problems can offer interesting new possibilities. Customer time windows and time varying network attributes can present further challenges. [Talarico et al. \(2015\)](#) show that a VRP with dissimilar paths is possible. A specific adaption for a hazmat transportation scenario with risk consideration promises to be rewarding.

VRP: The adaptation of classical VRP variants to a hazmat scenario offers a lot of potential. Problem variants with CTW have successfully been transferred into a hazmat context. Still, plenty of other problem variants from the classical VRP can be considered. Some possibilities are: a split delivery approach (e.g., when different kinds of gasoline have to be distributed), a pickup-and-delivery approach (e.g., when dealing with different kinds of hazmat and the pickup of hazardous waste), or an extended a multi period approach. Heterogeneous fleets, as shown by [Bula et al. \(2016, 2017\)](#), offer further optimization possibilities. The investigation of additional risk models that incorporate the varying load of hazmat during a vehicle trip can be promising. Dealing with risk equity in VRP can also be of interest. While arc capacity constraints are one possibility, they do not seem to be very reliable to guarantee a good spatial distribution of risk. The concentration of hazmat vehicles around the depot will always be the highest in the network, as long as only one depot is used. Therefore, a multi-depot approach could offer a possibility for further improvement. Only few approaches consider the VRP with time variant networks. The SP-APS have shown that time variant attributes can further improve the transportation safety. VRP usually incorporate a scheduling framework when time windows are accounted. These problems can be expanded by time variant network attributes.

RLP: The majority of the RLP focus on finding a suitable destiny location when dealing with the disposal of hazardous waste. Therefore, allocation and location problems (of origin locations) that deal with the construction of new hazmat distribution centers or assignment of existing ones to customers offer thereby new possibilities for researchers. The gateway location problem has only received little attention so far. Further research approaches are possible, e.g., extensions with scheduling or time varying networks can be of interest. Combining location and VRP can be a challenging new extension for complex hazardous waste collection problems.

NDP: NDP are addressing a global perspective on the hazmat transportation problem. While the total risk is minimized on a global level, only few approaches try to minimize risk equity. [Bianco et al. \(2009\)](#) aim to minimize the maximum link risk while [Taslimi et al. \(2017\)](#) focused on a minimization of the maximum risk among territory zones to balance equity. Incorporating a dissimilar path finding approach and a path dissimilarity measurement into a NDP framework could be a challenge for further research. Time variant networks, scheduling and the possibility of only temporary road closure as addressed by [Fan et al. \(2015\)](#) also offer new opportunities. The NDP with incorporated emergency response considerations may be extended to a time varying context, where mobile ER-units can be deployed and relocated while the carrier's shipments are routed and scheduled. Moreover, it can be of interest to extend risk models to incorporate population exposure as well as the potential environmental and infrastructure damages. Particularly, in scenarios where different kinds of hazmat are shipped and the level of threat of each hazmat is different to each of the risk dimensions, e.g., an oil transport that causes a higher risk to the environment, while the transportation of toxic gases presents a higher risk to the resident population.

ToSP: ToSP are very similar to NDP. That counts as well for the research gaps identified for the NDP. As an NP-hard problem and the youngest as well as smallest category in the field of hazmat transportation, ToSP offer plenty of possibilities for the development and implementation of new heuristic or metaheuristic approaches. The multiobjective conflict and the extension to a tri-level problem can be of interest for further research as well. The adjustment of the risk models, including more than population exposure (e.g., environmental damages or security considerations) is required.

Benchmark instances: The lack of benchmarks adapted to the special requirements of hazmat transportation makes it complicated to evaluate and compare different heuristic approaches, especially for the NP-Hard problems as VRP, NDP and ToSP, but as well for the other problems. Purely randomly generated networks are often not able to reproduce a realistic distribution of risk or risk related factors such as the population density. Due to the different data requirements of the different risk models, an objective comparison is further aggravated. This review indicates that most models use accident probability and resident population values for the measurement of risk which can therefore be used as a first approach. It is important to distinguish whether a model should be applied to smaller urban region or nationwide using an entire highway network. The routing in a city region requires more precise network information, because each node stands for a single junction or crossroad while in a highway wide network a node can represent an entire city or village. When time variant networks are considered the information acquirement becomes more challenging, especially in urban regions.

So far, the majority of approaches were tested on case studies in real life networks. Most of the networks are located in North-America, but there are also some located in Europe or Asia. South-America has received growing attention in the last years. No case studies for the African continent were found. While the location at a first view seems trivial for the purpose of the optimization of operative goals, it becomes more important when risk is included. Population distribution, especially in urban areas, traffic regulations and safety regulations for hazmat transportation or the network layout can vary widely depending on the selected country. This may directly influence risk parameters such as the accident probability, the population density or the environment. Even aspects like emergency response capacities or hijack probability can be affected. When applied on foreign case studies, these parameters can influence the performance of solution approaches. When dealing with a weighting approach, different weights can be required for different countries. Country specific rules and regulations concerning hazmat transportation have to be incorporated. This offers the possibility for further research in order to compare the performance of solution approaches on different networks and to identify essential parameters and weights. Furthermore, regional differences should be taken into account for the creation of test and benchmark instances.

6. Summary and conclusion

This paper provides a structured literature review and a classification for the hazardous material transportation problem of the last 45 years. Papers with focus on the road transportation of hazardous materials are analyzed and classified. The “routing” problem is further divided into different classes of problems. A specific review is given for each category and research gaps in the different fields are evaluated and analyzed.

Overall, the research field of hazmat logistics has been continuously active with an all-time high of contributions within the last decade. SP-WOS have received the most contributions while other problem categories such as the DPP and the SP-ADS have been investigated noticeably less. A recent trend for NP-hard problems such as the VRP, NDP and ToSP can be observed. Research gaps are revealed for all problem categories, but especially the “trendy” categories are of high interest. The predestinated multi-criteria optimization nature of hazardous materials still has a lot of potential, in particular with additional focus on environmental damages. The need of hazmat specific benchmarks for a better investigation and comparison of heuristic solution approaches for the VRP, NDP and ToSP, but as well as for large shortest path problems, is shown.

It can be concluded that the field of hazmat logistic remains challenging, even after 45 years. The further development of existing problems, as well as dealing with the challenges of new problems and trends, offer plenty of possibilities for new research.

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III

A Heuristic Solution Method for the Hazardous Materials Vehicle Routing Problem in Urban Areas

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A Heuristic Solution Method for the Hazardous Materials Vehicle Routing Problem in Urban Areas

Abstract: *The transportation of hazardous materials (hazmat) has attracted much attention in the last 20 years. Due to the dangerous nature of the cargo and the threat for population, environment and infrastructure, risk needs to be included in the decision problem. A large number of papers deals with shortest path problems between a given single origin-destination combination. However, hazardous materials like heating oil, fuel gas or gasoline often need to be distributed in highly populated urban areas and to multiple customers. In this work, we address the capacitated hazardous materials vehicle routing problem (CHMVRP) with multiple customers in urban areas and propose a simple and fast heuristic solution method. The proposed algorithm is applied on a random generated but realistic road network of an urban area. In order to generate appropriate origin-destination matrices based on different objective functions for the CHMVRP, different shortest path approaches are employed in a first step. To deal with the multi-criteria conflict between travel distance and risk minimization, in a second step, different combinations of the origin-destination matrices and the heuristic algorithm are investigated.*

Keywords: *hazardous materials, hazmat, transportation, vehicle routing, heuristic, multi-criteria optimization*

1. Introduction

Transportation of dangerous or hazardous materials (hazmat) needs to be treated separately from classical transportation problems due to its threatening nature. The German legislator describes hazmat as materials or objects that, by their very nature, characteristics or state, when transported, pose risk to public safety or order, in particular to the general public, the patrimony, the life and health of persons, animals and objects (GGBefG 2015). A similar definition is also given by the US Department of Transportation (US DOT 2016). Hazmat can be transported via air, pipeline, rail, road or water (Erkut et al. 2007). In Germany over 303 million tons of hazmat were transported in 2014, from which over 46% were transported by

trucks on public roads (Destatis 2016). A large part of the literature is focusing on finding minimal risk roads for hazmat and avoiding highly populated areas or cities. However, hazmat like heating oil, gas or different types of fuel need to be distributed inside urban areas and can thereby not avoid the crossing of highly populated areas.

This paper addresses the problem of distribution of hazardous materials in urban areas. The problem is referred to as a capacitated hazardous materials vehicle routing problem (CHMVRP) with multiple customers. A simple and fast heuristic solution method is proposed to deal with the vehicle routing problem (VRP). Our contribution also aims to show that the challenge already starts one step before the classical VRP can be addressed. For a lot of VRPs the Euclidian distance between two customers is used as basis for further calculation. However, this approach does not consider the complex structure of urban networks or risk-related factors like the population density and accident probabilities. In a first step, we employ different shortest path approaches on a realistic road network in order to generate appropriate and more accurate origin-destination (O-D) matrices based on different objective functions for the CHMVRP. In a second step, the CHMVRP is solved by using different objective functions. We then investigate how the combination of different objective functions in the two steps influence the final solution and how they are suited for the multi criteria optimization conflict between distance and risk minimization. Erkut and Verter (1998) show that different risk models are leading to different optimal paths which do not exhibit strong similarities. This analysis was done for different pairs of origin-destination on the US highway network. Our approach additionally checks how different risk models affect the routing outcome in the case of VRPs with multiple customers in an urban area.

The rest of the paper is structured as follows: first, a short literature review is given for a better classification of the considered problem. Then, the heuristic algorithm is described and its performance is tested on known benchmark instances. The algorithm is then applied on different hazmat VRP instances. Finally, the conclusion of the research is presented.

2. Literature overview

The problems that occur when dealing with hazardous materials truck transportation can be distinguished in different categories. The largest class consists of a variety of shortest path model approaches, originating from the mid-1980s. These problems involve the routing of one or multiple vehicles. For each shipment a shortest paths problem (SPSP) has to be solved. SPSP are a special variant of shortest path problems where a shortest path between one given

origin and one given destination has to be found in a network optimizing the objective function (Domschke 2007). In the context of hazmat transportation the “shortest” path can be the “safest” path or in case of multiple objective functions, a compromise. For a more detailed overview over the field of hazmat logistics, see Erkut et al. (2007). Another, and for this paper relevant, problem aspect in the field of hazmat transportation consists of VRP problems with hazardous materials. The classic VRP was introduced by Dantzig and Ramser (1959) and has known a lot of attention in the last four decades. Its objective is to find an optimal set of routes for a fleet of vehicles to deliver a certain good to a given set of customers (Domschke and Scholl 2010). Tarantilis and Kiranoudis (2001) were among the first to adapt the VRP to the special requirements of hazmat transportation. The field of hazardous materials vehicle routing problems (HMVRP) is much smaller and younger than the field of hazmat SPSPs. Since its introduction, the HMVRP has received growing attention. Extensions with time windows (Zografos and Androutsopoulos 2002; 2004; 2008), (Pradhananga et al. 2010a; 2010b; Pradhananga et al. 2014), heterogeneous vehicles (Zheng 2010), (Bula et al. 2016; 2017) or inventory routing (Dabiri and Tarokh 2012) were introduced in a hazmat context.

Many of the approaches are tested on known VRP benchmarks. Only few approaches consider the special requirements in urban areas. Also the construction of paths between the depot and the customers is addressed in a few papers only. The most important contributions are shortly addressed in the following. Tarantilis and Kiranoudis (2001) propose a list-based threshold accepting algorithm to determine the best sequence to serve a given number of customers in order to minimize population exposure. The origin-destination matrix for the VRP is constructed by executing a Dijkstra shortest path algorithm to find the shortest paths between all pairs of customer nodes and the depot located in the road network of Athens. Zografos and Androutsopoulos (2008) propose a decision support system for the hazmat VRP and locating first-response units close to the hazardous materials routes. The proposed system has been implemented and evaluated for the region of Attica in Greece. Lozano et al. (2011) analyze the transport of chlorine and gasoline in an urban area and show how different categories of hazmat, different evacuation radii and the consideration of traffic time and varying traffic population can influence the routing decisions. Androutsopoulos and Zografos (2012) propose a bi-objective VRP with customer time windows and time varying values for risk and travel time. The problem is decomposed into a set of single-objective instances and the multi-criteria conflict solved by a weighted sum approach. A sequential insertion based route construction heuristic is then applied on the single-objective problems. For solving the

time-dependent shortest path problem a label setting algorithm is integrated in the heuristic. The heuristic is applied on test networks designed to comply with the structure of real-life problems. Pradhananga et al. (2014) introduce a decision support system capable of dealing with the path finding problem and the vehicle routing problem simultaneously. The system is applied to a case study in the city of Osaka, Japan. An ant-colony algorithm is proposed which generates a set of solutions approximating the frontier of the pareto-optimal solutions based on travel time and total risk.

3. Problem characterization

The problem considered in this paper consists of supplying a given number of customers with hazardous materials by trucks in an urban area. A fleet of identical vehicles with limited load capacity is available for the distribution. Each customer has to be assigned to one single vehicle for serving and hence for each vehicle the set of customers to be served has to be determined. In addition, for each vehicle the optimal customer serving order has to be determined such that one or multiple objective function values are optimized. Each vehicle has to start and end its tour at the depot. Each customer can only be visited once and has to be served by one single vehicle. The customers and the depot are located in the road transportation network of an urban region. The network contains a given number of weighted, undirected arcs representing road segments of the region and a given number of nodes representing intersections and driveways of the transportation network. A subset of the set of all nodes represents the locations of the customers and the depot. This leads to the additional challenge of finding suitable routes between all pairs of customers and the depot. Contrary to solving the shortest path problem, determining the optimal solution to the vehicle routing problem is NP-hard. To solve the VRP in a reasonable amount of time a heuristic solution approach is needed. For this purpose a suitable heuristic for the CHMVRP is developed and presented in the following sections.

4. The heuristic algorithm

The heuristic algorithm developed consists of an initialization phase, a customer list based improvement phase and a customer-vehicle list based improvement phase. In the initialization phase, a first solution is generated by using sorted customers and a greedy method for assigning customers to vehicles.

Phase 1: Initialization

Select an ordering rule (e.g. in descending order of the distance from a customer to the depot) and the number of iterations for the customer list based improvement phase. Sort the customers according to the chosen ordering rule and add them to a customer list (Co). Construct an initial feasible solution using the customer greedy method. If no feasible solution is possible with the initial customer list, sort the customers in descending order of their demand and apply the customer greedy method. If this does not yield a feasible solution, stop and analyze the problem data. Initialize the best solution with the solution found and the best customer order with the corresponding customer order.

Customer Greedy Method:

Step 1: Select the first customer from the customer list Co .

Step 2: Sort all vehicles to a temporary vehicle list (Vl) in ascending order of the distance from the last customer served by the vehicle (or depot if the vehicle is still unused) to the selected customer.

Step 3: Select the first vehicle in the vehicle order list.

Step 4: If the vehicle has enough load capacity for serving the selected customer, assign the customer to the selected vehicle and update the vehicle load. Select the next customer in Co and return to *Step 2*.

Step 5: If the customer demand exceeds the vehicle capacity, select the next vehicle in Vl and return to *Step 4*.

The initialization phase of the algorithm is based on a greedy approach in which the customers are selecting the vehicles. Different metrics have been considered as selection criteria during the development of the heuristic. In the end, the shortest distance metric outperformed all others. In this metric the customer is assigned to the vehicle with the “shortest distance” (or the lowest risk) from the last customer served by a vehicle (or the depot if the vehicle is still unused) and the selected customer. The next closest vehicle is

selected if the selected vehicle does not have enough load capacity. For all problems solved in the experiments a feasible solution was generated in the initialization phase.

In the customer list based improvement phase for finding better solutions first the initial customer order is permuted by a shift phase in which each customer is inserted in all other possible positions. After the shift phase, a swap phase is performed in which each customer is swapped with all other customers. Each time a better feasible solution is found, the customer order is updated immediately.

Phase 2: Customer List Based Improvement

Step 1: Shift each customer to each other possible position in Co . After each shift construct a new solution using the customer greedy method. If a new best solution is found, immediately update the best solution and the Co .

Step 2: Swap each customer with each other customer in Co . After each swap construct a new solution using the customer greedy method. If a new best solution is found, immediately update the best solution and the Co .

Step 3: Return to *Step 1* and repeat until the selected number of iterations is reached.

In the final customer-vehicle list based improvement phase a dynamic customer-vehicle list is used. The list consists of as many segments as vehicles are used. Each segment contains an equal number of customers to be served by the corresponding vehicle. The customers can be distinguished in real customers and dummy customers that are introduced if the number of real customers in a segment is less than the length of the segment. The length of each segment is equal to the maximum number of customers served by a single vehicle at the end of the customer list based improvement phase plus two. The list structure and the number of dummy customers required are adjusted each time a new best solution is found, though the number of dummies can be augmented or reduced if the maximum of customers served by a vehicle changes. Keeping the customer-vehicle list short has a severe impact on the runtime.

Customer-Vehicle List Construction:

- Step 1:* Initialize the total number of vehicles nv and the total number of customers nc . Identify the vehicle serving the most customers in the current best solution. The number of customers served by this vehicle corresponds to the value m .
- Step 2:* Construct a list of dummy customers with distance and demand values of 0. The required number of dummy customers corresponds to $(m+2)*nv - nc$.
- Step 3:* Build a customer-vehicle list Cv consisting of nv segments, each one of them corresponding to a vehicle as follows:
 Each segment with length $m+2$ starts with a dummy customer. Then the real customers served by the corresponding vehicle follow in the order determined by the current best solution. The remaining positions of the segment are filled with dummy customers.

An illustrative example for a customer-vehicle list is given in Figure 1.

$$\begin{array}{c}
 nv = 3; nc = 9; m = 4 \text{ (for vehicle 1); } d = \text{dummy customer} \\
 Cv = [\underbrace{d, 1, 3, 4, 9, d}_{\text{Vehicle 1}}, \underbrace{d, 2, 5, 8, d, d}_{\text{Vehicle 2}}, \underbrace{d, 7, 6, d, d, d}_{\text{Vehicle 3}}]
 \end{array}$$

Figure 1 - Example of a customer vehicle list

Phase 3: Customer-Vehicle List Based Improvement

- Step 1:* Construct a customer-vehicle list (Cv) based on the best solution found in the customer list based improvement phase.
- Step 2:* Shift each real customer to each other possible position in Cv . After each shift calculate the objective function value. If a new best solution is found, immediately update the best solution and the Cv .
- Step 3:* Swap each real customer with each other real customer. After each swap calculate the objective function value. If a new best solution is found, immediately update the best solution and the Cv .
- Step 4:* (Optional) Perform a sequential double swap for all adjacent pairs of customers in the Cv . After each swap calculate the objective function value. If a new best solution is found, immediately update the best solution and the Cv .
- Step 5:* (Optional) Perform a sequential triple swap for all adjacent triplets of customers in the Cv . After each swap calculate the objective function value. If a new best solution is found, immediately update the best solution and the Cv .

Step 6: (Optional) Perform a sequential quadruple swap for all adjacent quadruplets of customers in the C_v . After each swap calculate the objective function value. If a new best solution is found, immediately update the best solution and the C_v .

Step 7: If a new best solution was found during the iteration return to *Step 2*. Else end the algorithm.

Starting and ending the corresponding list segment of all vehicles with dummy customers, allows the insertion of each real customer in each position of all existing tours without perturbation of the other tours during the shift phase. During the single swap phase only real customers are swapped. Swapping real customers and dummy customers does not lead to new permutations in combination with the shift phase. Swapping only dummy customers has no impact at all. The sequential multi swaps are introduced to allow larger permutations during the second phase. The main purpose of these swaps is to exchange good customer sequences between two vehicles. Multi swaps are only skipped if all concerned customers are dummies. Even swapping one real customer and two dummies with three real customers leads to interesting new permutations.

Swapping customers in the customer-vehicle list:

Step 1: Select the customer in the first position $p1=1$ of the customer-vehicle list (C_v).

Step 2: Select as second adjacent customer the customer in position $p2 = p1+1$ and as the two customers for the first swap the customers in positions $t1 = p2 + 1$ and $t2 = p2 + 2$. In case of a triple swap select the third adjacent customer in $p3 = p1 + 2$, and then $t1 = p3 + 1$, $t2 = p3 + 2$, $t3 = p3 + 3$. For a quadruple swap select the fourth customer in $p4 = p1+3$ and then $t1 = p4 + 1$, $t2 = p4 + 2$, $t3 = p4 + 3$; $t4 = p4 + 4$).

Step 3: If the destination of the last swap customer exceeds the length of C_v then end the multi swap; else continue with *Step 4*.

Step 4: Swap the customers in positions $p1$ & $t1$ and $p2$ & $t2$. For triple swap also $p3$ & $t3$ and for quadruple swap $p4$ & $t4$.

Step 5: Set $t1 := t1 + 1$ and $t2 := t2 + 1$. For triple swap $t3 := t3 + 1$ and for quadruple swap $t4 := t4 + 1$.

Step 6: If the position of the last swap customer exceeds the length of C_v set $p1 := p1 + 1$, return to *Step 1*.

Step 7: Else return to *Step 2*.

An illustrative example of a triple swap is shown in Figure 2.

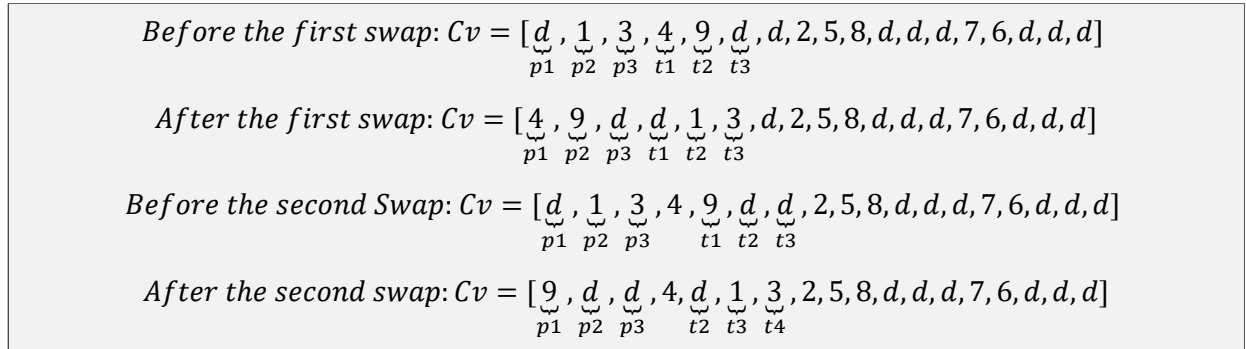


Figure 2 - Example of a triple swap

5. Experimental analysis of the algorithm

5.1. Performance analysis with non-hazmat problems

Before the heuristic algorithm was applied on the hazmat instances, its performance was tested on known benchmarks for the capacitated VRP to analyze the solution quality and runtime performance. For this purpose 14 benchmark instances from Augerat et al. (1995) ranging from 35 to 55 customers were selected. Additionally the four 75 customer instances from Rochat and Taillard (1995) were added to test the performance in larger networks. The algorithm was implemented in Python 3.6 and executed on a Core i5-6600K with 8 GB ram. The minimization of the total distance was the single objective function for the benchmarks. Also the optimal solution is known for all benchmarks. Table 1 shows the percentage by which the proposed heuristic and the selected sorting rule missed the optimal objective value. In the last row, the average deviation over all instances is given. Eight different sorting rules have been tested for phase 1. Order by: Ascending (ACN) and descending (DCN) customer number; ascending (ADD) and descending (DDD) distance from the customer to the depot, ascending (ACL) and descending (DCL) customer demand (load) value; ascending (ADL) and descending (DDL) customer distance to the depot divided by customer demand value.

Sorting customers by ascending or descending order of their number is not really useful in consideration of the objective function but allows the comparison of sorting rules with a more random customer order.

Table 1 - Benchmark results

	Selected ordering rule								Avg. runtime
	ACN	DCN	ADD	DDD	ACL	DCL	ADL	DDL	
AG_36-5	5.50	7.25	6.38	4.25	3.13	3.63	2.00*	4.88	3.3 sec
AG_37-5	3.73	7.77	6.12	1.34*	3.44	5.38	3.74	3.59	3.5 sec
AG_37-6	4.00	9.70	5.90	8.11	2.21*	7.58	3.26	4.21	3.4 sec
AG_38-5	1.91	5.20	4.66	5.61	0.14*	2.87	6.03	3.70	3.7 sec
AG_39-5	2.79	4.99	10.70	2.55	3.89	2.79	5.23	1.09*	3.6 sec
AG_39-6	3.13	3.00	2.40	9.50	3.13	0.24*	5.77	2.04	4.5 sec
AG_45-6	19.17	11.22	20.23	1.59*	1.69	11.86	16.31	5.72	4.7 sec
AG_45-7	9.07	11.69	6.19	7.15	6.37	5.41*	5.84	6.54	6.9 sec
AG_46-7	13.68	3.94	10.83	7.43	3.93	7.43	3.17*	8.31	7.0 sec
AG_48-7	6.71	6.52	7.92	12.95	3.72*	8.20	8.76	7.73	7.7 sec
AG_53-7	5.15	10.10	6.73	3.76*	5.94	5.64	7.52	4.55	8.5 sec
AG_54-7	5.31	8.56	5.40	2.91*	3.60	12.51	7.54	7.97	11.0 sec
AG_55-9	2.42	4.29	4.10	2.79	1.96	6.43	1.12*	10.62	10.5 sec
AG_60-9	6.20	3.32	7.75	1.47*	6.06	13.30	8.56	9.15	16.2 sec
T75_A	10.31	9.08	3.33	1.05*	12.66	9.69	13.34	6.30	34.5 sec
T75_B	15.98	15.69	11.37	4.16*	6.69	6.91	4.46	24.60	27.7 sec
T75_C	5.34*	10.29	18.73	5.80	7.35	14.08	11.69	9.59	32.5 sec
T75_D	6.15	5.49	6.95	4.46	2.34*	3.95	5.42	3.51	33.3 sec
Avg. deviation	7.03	7.67	8.09	4.83	4.35	7.11	6.65	6.89	

* Best solution found

The maximum number of iterations used in Step 3 of phase 2 was set to two, because this yielded better results than setting it to one. Setting the number to 3 gave only very slight improvements. It has to be noticed that the solution quality of phase 1 is very sensitive to the initial customer order. The sorting rule DDD and ACL performed the most reliable over all instances.

5.2. Application of the heuristic algorithm to hazmat transportation problems

A special network generator was developed for the generation of realistic urban networks. In a first step, the roads of the transportation network of the urban region of the Bavarian city Munich and some other smaller Bavarian cities were analyzed and evaluated. Following the pattern of this evaluation, the generator is able to create realistic transportation networks suitable for the transport of hazardous materials. Highways, motorways and city road segments are distributed following a realistic pattern. Accident probabilities are assigned to

the corresponding road types based on the evaluation of Harwood et al. (1993). For a realistic distribution of population values inner city regions are generated and placed in the network. They contain a higher population density and also a denser road network than the rest of the network. Figure 3 shows the structure of an example network created by the generator. The shown network is reduced to the transportation network suitable for truck routing. Two different networks were created, network N1 with 278 nodes and 392 arcs and network N2 with 244 nodes and 460 arcs. Two different problem instances were generated for each network by placing 1 depot node and 30 customer nodes as well as 1 depot node and 40 customer nodes in each network.

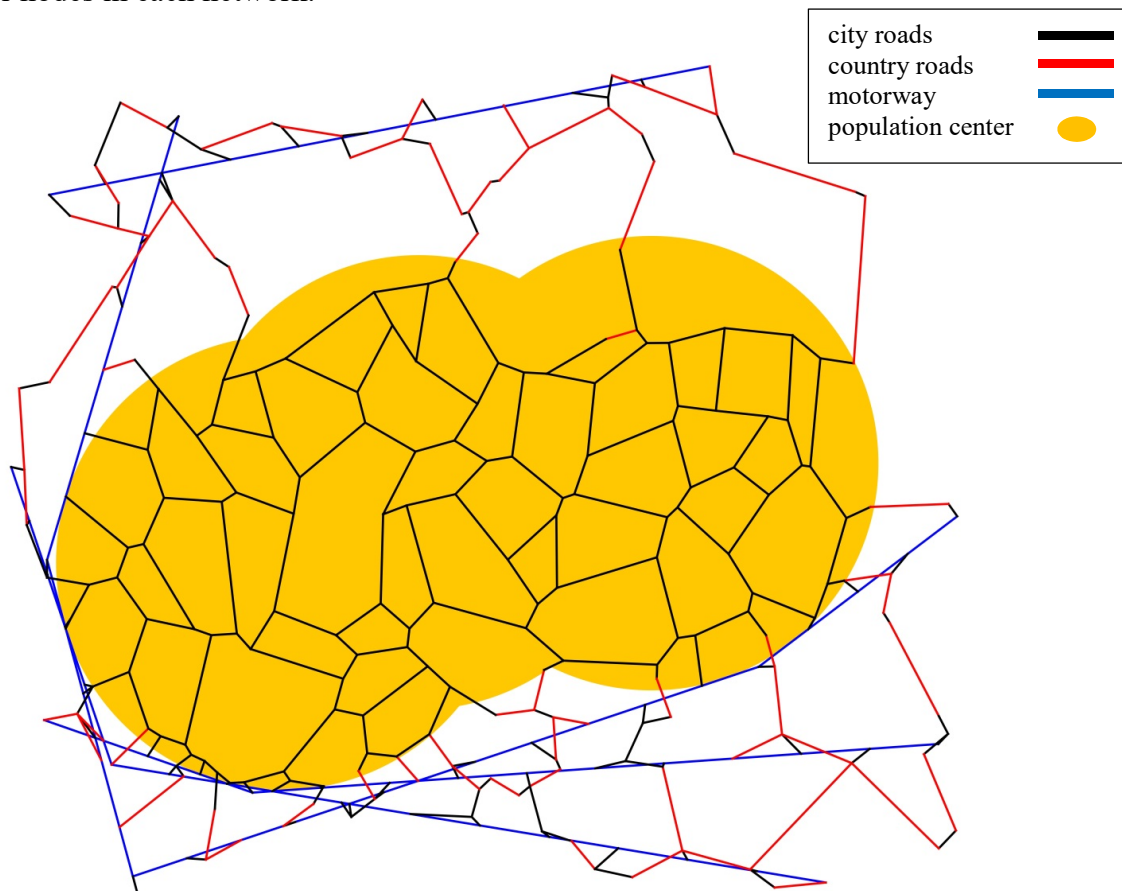


Figure 3 - Network of the test instance N1

The depot node was always selected in the outskirts region of the map. Due to the reasons that larger heating oil distribution centers mostly lie in the outskirts region of a city, or if the city has no own distribution centers, the dispatcher will enter the transportation network over a highway or motorway node outside of the city. Customer nodes are selected randomly over the whole network. Customer demands were generated randomly based on recent statistics to demand values, with a minimum order quantity of 600 liter and a maximum possible order quantity of 20,000 liters, the average demand value being 2,500 liters. The vehicles are all

homogenous with a total capacity of 20,000 liters. Based on the total demand values 4 vehicles were assigned to the 30 customer instances and 5 to the 40 customer instances. The evacuation band for the transport was set to 50 meters, the band is thereby much smaller than for other hazmat but realistic for a hazmat like oil or gasoline (Lozano et al. 2011).

In a first step, the “shortest” path between all pairs of customer nodes and the depot was determined by using a modified version of the Floyd-Warshall algorithm (Floyd, 1962). On each problem instance the SPSP algorithm was executed four times, each time satisfying another objective function. The different objective functions are the minimization of the total distance traveled (Dist), the minimization of the total population at risk (Pop), the minimization of the total accident probability (AP), and the minimization of the traditional risk value (risk). The risk value is based on the traditional risk model and consists of the product of accident probability and population exposure (Erkut and Verter 1998). Each problem instance led to the generation of four different O-D matrices, each one containing the optimal routes satisfying the appropriate objective function.

The matrices served as basis for the CHMVRP. The resulting CHMVRP was solved by using the developed heuristic algorithm.¹ The algorithm has been applied four times on each matrix, each time satisfying another one of the four objective functions mentioned above. This led to 16 different combinations of O-D matrices and objectives functions for each instance.

Table 2 gives a detailed overview over the results obtained for all 16 combinations of objective functions in the two phases for the 30 customer instance in network N1, as well as the percentage of deviation from the best object value found over all matrices. Table 2 also shows that the origin-destination matrix has a huge impact on the following optimization of the VRP.

¹ To assure the best possible solution quality, the heuristic algorithm was applied by using all sorting rules described in Chapter 3. The average computation time for 30 customer instances was 1.8 seconds and for 40 customer instances 3.5 seconds.

Table 2 - Results for network N1 with 30 customers

Matrix		Objective Function			
		Min. Dist	Min. Pop	Min. AP	Min. Risk
Dist Matrix	Total traveled Length (km)	279.46	287.23	296.06	318.20
	Percentage deviation	-	2.78%	5.94%	13.86 %
	Population	55,433	46,142	47,095	46,851
	Percentage deviation	30.10%	8.30%	10.53%	9.96%
	AP (x10E-5)	6.19	5.62	5.55	5.80
	Percentage deviation	19.04%	8.08%	6.73%	11.54%
	Risk (x10E-3)	16.65	11.97	11.74	11.10
	Percentage deviation	70.25%	22.39%	20.04%	13.50%
Pop Matrix	Total traveled Length (km)	297.92	315.17	300.36	315.17
	Percentage deviation	6.61%	12.78%	7.48%	12.78%
	Population	45,749	42,607	43,733	42,607
	Percentage deviation	7.37%	-	2.64%	-
	AP (x10E-5)	5.87	5.67	5.51	5.67
	Percentage deviation	12.88%	9.04%	5.96%	9.04%
	Risk (x10E-3)	11.96	9.84	10.47	9.84
	Percentage deviation	22.29%	0.61%	7.06%	0.61%
AP Matrix	Total traveled Length (km)	291.52	307.40	301.89	312.10
	Percentage deviation	4.32%	10.00%	8.03%	11.68%
	Population	50,807	47,487.05	48,712	47,560
	Percentage deviation	19.25%	11.45%	14.33%	11.62%
	AP (x10E-5)	5.32	5.35	5.20	5.33
	Percentage deviation	2.31%	2.88%	-	2.50%
	Risk (x10E-3)	12.70	10.88	11.37	10.58
	Percentage deviation	29.90%	11.25%	16.26%	8.18%
Risk Matrix	Total traveled Length (km)	312.37	316.75	308.33	323.64
	Percentage deviation	11.78%	13.34%	10.33%	15.81%
	Population	43,175	43,114	43,649	44,060
	Percentage deviation	1.33%	1.19%	2.45%	3.41%
	AP (x10E-5)	5.46	5.54	5.51	5.50
	Percentage deviation	5.00%	6.54%	5.96%	5.77%
	Risk (x10E-3)	9.94	9.90	10.30	9.78
	Percentage deviation	1.64%	1.23%	5.32%	-

Table 3 - Average deviation over all instances (in %)

Matrix		Objective Function			
		Min. Dist	Min. Pop	Min. AP	Min Risk
Dist Matrix	Length average deviation	0.00 ^B	11.80	6.31	17.29 ^W
	Population average deviation	43.44 ^W	7.89	14.47	8.71
	AP average deviation	22.05 ^W	9.94	7.23	11.95
	Risk average deviation	82.00 ^W	13.58	25.08	10.49
Pop Matrix	Length average deviation	7.40	13.18	10.53	14.28
	Population average deviation	14.58	0.24 ^B	1.60	0.68
	AP average deviation	13.68	8.47	5.34	8.43
	Risk average deviation	33.81	2.27	4.20	1.61
AP Matrix	Length average deviation	7.67	11.82	10.66	16.63
	Population average deviation	22.66	5.98	9.35	7.24
	AP average deviation	6.39	1.29	0.00 ^B	3.20
	Risk average deviation	34.15	5.92	9.84	4.73
Risk Matrix	Length average deviation	12.29	14.20	13.26	16.70
	Population average deviation	12.97	0.68	2.18	2.13
	AP average deviation	9.50	4.83	4.32	5.38
	Risk average deviation	20.49	0.87	3.17	0.00 ^B

^W worst value; ^B best value

Table 3 shows the average deviation over all four instances (N1 and N2 with 30 and 40 customers each). It is notable that when only length is minimized, all 3 risk measures reach their worst values. Moreover, the selection of the risk model has a direct impact on the solution quality. The results furthermore confirm that for HMVRPs population-based approaches lead to different outcomes compared to accident-probability-based approaches. The traditional risk model is confirmed as a good compromise between accident probability and population exposure. In term of compromise with an economical goal, the population based and the accident probability based risk models can lead to some good compromise solutions (under 10% deviation from the best length value), while the traditional risk model performed the worst for most of the instances. But even when length is not minimized in either of the two steps, the worst deviation is about 17% from the economical goal. In the end, it is up to the dispatcher to decide how much of his economical goal he is willing to sacrifice for the improvement of safety.

It has to be noticed, that the minimization of the total population value based on the population O-D matrix has an average deviation of 0.24%. This is due to the reason that for instance N2 with 40 customers, the solution with the minimal population exposure was found based on the risk matrix and was 0.9% percent better than the best solution found with the population matrix. For all other instances and objective functions, the best solution value corresponding to the objective function was found on the corresponding O-D matrix.

The traditional risk model offers the best compromise between population exposure and accident probability. In reality, accurate accident probability data for a specific region and for hazmat transportation is hard to generate. Population density is far easier to estimate, especially in countries like Germany where city administrations can provide quite accurate data over the population density in the different regions and quarters of a city and where censuses are carried out on a regular basis. Table 3 shows, that even when only population data is considered in the optimization process, the results lead to a drop in the accident probability and the traditional risk value.

6. Conclusions

In this paper, a more accurate form of approach for the dealing with the capacitated hazardous materials vehicle routing problem in urban areas is proposed. It is shown that when dealing with hazmat, already the creation of paths between customer nodes can have a direct influence on the solution quality of the later VRP. Due to the lack of benchmarks for the CHMVRP a network generator for random but realistic networks has been developed.

A fast solution heuristic is proposed and tested on existing benchmarks. The heuristic is then applied on the CHMVRP. The algorithm is able to find good solutions in a short amount of time. While still sensitive to the initial customer order, the approach appears to be promising.

The analysis highlights the necessity of including risk minimization in the routing models of hazardous materials, because the sole minimization of distance leads to the worst outcomes in terms of safety. The approach also offers possibilities for further research. Customer time windows are not considered and the proposed problem instances are all time-invariant. Thereby varying traffic conditions and variations in the population density are not accounted. These fluctuations can especially be important in urban regions.

The vehicles are considered to be homogenous. However, some dispatchers have to distribute different kind of heating oil with vehicles of different loading capacity. Also in the case of heating oil distribution, vehicles can differ in their length of the dispatching tube. Thereby some customers can only be served by vehicles with an extra-long tube while others can be served by all.

The solution of the CHMVRP in this approach is based on the minimization of one objective function. An extended multi-criteria analysis and a construction of a set of pareto-efficient solutions can lead to a bigger diversification in the solution quality and probably to more and better compromise solutions.

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IV

Analysis of Different Risk Models for the Hazardous Materials Vehicle Routing Problem in Urban Areas

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Analysis of Different Risk Models for the Hazardous Materials Vehicle Routing Problem in Urban Areas

Abstract: *The distribution of hazardous materials in highly populated urban areas is an important tactical and strategic decision problem. For the last four decades, a multitude of approaches for risk assessment and modelling have been proposed. However, the majority of these approaches are focusing on different adaptations of shortest path problems. Risk modelling for routing and distributions problems, like the vehicle routing problem (VRP) have received far less attention, especially when the vehicle load is varying during a trip. This paper investigates how different factors are influencing the risk values and the outcomes of the hazardous materials vehicle routing problem (HMVRP). As foundation for the HMVRP, the path generation between the customer and the depot nodes in realistic urban road networks is considered. The influence of the fleet size is investigated. Different risk models are compared, with a special focus on the comparison of classical load-independent risk models with load-dependent risk models. Six different risk models for the HMVRP are analyzed and compared, and the tradeoff between risk minimization and the minimization of traveled distance is investigated. The results show, that these factors can have strong impact on the outcomes and lead to different “optimal” solutions.*

Keywords: *transportation, hazardous materials, vehicle routing, risk modelling, safety*

1. Introduction

The transportation of hazardous materials (hazmat) is an essential component for satisfying the industrial as well as the customer demand in our modern society. Hazmat are defined as any materials or objects that by their very nature, characteristics or state, when transported, pose risk to public safety or order, in particular, to the general public, the life and health of persons, animals and objects (GGBefG, 2015)¹. In most countries, the awareness of hazmat transportation by the authorities and the general public is very high. Strict laws and

¹ Definition by the German legislator

regulations aim to assure the safety of the transportation process. However, a certain risk of a hazmat accident with a release of the cargo always remains. Depending on the nature of the hazmat, an unintended release can result in a catastrophic incident such as an explosion, a fire or a toxic gas cloud. Thereby, hazmat vehicles should avoid driving through regions with a high population density. However, hazardous materials such as heating oil, fuel gas or gasoline often need to be distributed in highly populated urban areas. To optimize the risk management during the transportation process, hazmat transportation has become a popular research topic in the field of operations research. Risk assessment and shortest path problems (SPP) for hazmat transportation have been a research topic for over 40 years. More frequently, new trends dealing with NP-hard problems have occurred in the field of hazmat logistics, such as toll setting problems (ToSP), network design problems (NDP) and vehicle routing problems (VRP) (Holeczek, 2019). In contrary to the other problems, the VRP deals with the serving of multiple customers by a fleet of vehicles. Before a VRP can be solved, suitable paths between all customers and the depot have to be calculated. In many scenarios, a Manhattan or Euclidian distance approach is used, but this may not be suitable for risk minimization. When considering shortest path problems, the hazardous cargo is transported from one origin node to one destination node. The amount of cargo is normally not altered during the transportation process and discharged fully once the vehicle reaches its destination. However, when a vehicle is serving multiple customers, the amount of cargo is altered during the transportation process. This paper investigates the influence of the path generation on the outcomes of the VRP, as well as the impact of load-dependent (LD) and load-independent (LI) risk models. Additionally, the influence on the multi-criteria conflict between an economical goal, here represented by a minimization of the travel distance, and risk minimization is investigated.

The paper is organized as follows. In section two, a short literature review is given. The problem is characterized in section three. In section four, a mathematical model of the problem is provided. In section five, the experimental outcomes are analyzed and discussed.

2. Literature review

2.1. Hazardous materials transportation

The first hazmat transportation problems have originated as a research topic in the seventies, see e.g., Shappert et al. (1973) or Kalelkar and Brooks (1978). The majority of the early

contributions dealt with risk assessment and SPP. Only more recently, NP-hard problems like VRP, NDP and ToSP have received growing attention (Holeczek, 2019). The transportation of hazardous materials is of international importance and contributions dealing with risk assessment and routing scenarios all around the world can be found; e.g. Asia (Chakrabarti and Parikh, 2011; 2013; Yang et al., 2018) Europe (Bonvicini and Spadoni, 2008; Landucci et al., 2017), North America (Kuhn et al., 2016) and South America (Garrido and Bronfman, 2017).

Hazmat can be transported via air, pipeline, rail, road or water. Shipments are considered as intermodal, if they are switched from one mode to another during the transportation process (Erkut et al., 2007). The most important transportation mode so far is road. In Germany, over 306.8 million tons of hazmat were transported in 2016, from which over 46% were transported by trucks on public roads (Destatis, 2018). Road is also the transportation mode getting the most attention in the literature (Holeczek, 2019). Risk modelling for road transportation has received a lot of attention in the context of SPP. An overview over the most common risk models is provided by Erkut et al. (2007). Risk can mainly be modelled by either considering the probability of an accident with hazmat spill or the consequences of such an incident. Three of the most popular risk models are the accident probability (AP) model, the population exposure (Pop) model and the traditional risk (TR) model. The accident probability model aims to minimize the likelihood of an accident with hazmat release during transportation. The population exposure model considers the societal risk and quantifies the population inside a certain danger zone around a road segment and represents thereby the possible number of injuries and fatalities in case of an unwanted hazmat incident (Erkut et al., 2007). The traditional risk model defines risk as the product of the consequence and the probability of an unwanted incident (Covello and Merkhofer, 1993). Most traditional risk models use population exposure as the consequence measure, but also other consequences such as damages to the natural environment or the infrastructure can be accounted. A comparison of different risk models for the SPP and an analysis of their influence on the solution quality can be found in Erkut and Verter (1998).

2.2. *The hazardous materials vehicle routing problem*

The VRP is an extension of the travelling salesman problem. The goal is to find an optimal set of routes for a fleet of vehicles in order to deliver goods to a given set of customers. Introduced by Dantzig and Ramser (1959), the problem has received a lot of attention and

several extensions have been proposed especially in the last thirty years (Domschke and Scholl, 2010). While the approach by Dantzig and Ramser (1959) aims to minimize the total mileage of a fleet of gasoline trucks, the dangerous nature of the cargo and a potential risk minimization are not addressed. Over forty years later, Tarantilis and Kiranoudis (2001) were among the first to introduce a hazardous materials vehicle routing problem (HMVRP). Since then, the HMVRP has received growing attention. Extensions with time windows are proposed by Zografos and Androutsopoulos (2002; 2004; 2008) as well as Pradhananga et al. (2010a; 2010b; 2014). Heterogeneous fleets are considered by Zheng (2010) as well as Bula et al. (2016; 2017). An extension considering multiple depot nodes is proposed by Du et al. (2017).

For solving a classical VRP an origin-destination value matrix (VM) containing the shortest path between all pairs of customers and the depot is necessary. By calculating the Euclidian or the Manhattan distance between two customer nodes these values can be obtained easily for many VRP. However, these metrics may encounter difficulties when risk has to be assessed, e.g., in urban areas with a strongly divergent population density. In the case of HMVRP, the question occurs whether the matrix should be based on the shortest path, the safest paths or on a compromise solution. If the paths are selected a priori, before the sequencing, good solutions can be missed. If the path determination and VRP are solved simultaneously, the problem becomes more complex. So far, only Androutsopoulos and Zografos (2012) and Pradhananga et al. (2014) address the problem of solving the path finding problem and the VRP simultaneously. The influence of different pathing approaches on the HMVRP has, to our knowledge, not been investigated further.

2.3. *Load-dependent risk models*

The majority of the risk models used for the HMVRP is load-independent. Guo and Verma (2010) are among the first to investigate the influence of different vehicle capacities for the SPP. Only a few risk models consider a varying load amount during the transportation process. Androutsopoulos and Zografos (2012) were the first to incorporate the variation of vehicle load in their mathematical risk model. Their proposed solution algorithm, however only considers load-invariant risk values. Bula et al. (2016) and Bula et al. (2017) consider a load-dependent risk model in combination with a heterogeneous fleet. Hu et al. (2018) incorporate a load-dependent risk model in an inventory routing problem (IRP). Their approach considers a supply chain model with a single supplier and multiple manufacturers as

well as retailers. They use a unit mass transportation risk and a unit mass inventory risk value for their model.

Load-dependent risk models are also considered in some extension of the facility location and routing problems (LRP) for hazardous materials. In addition to determine the optimal set of routes (and shipping schedules) to satisfy the customer demand, the LRP also consider the determination of the optimal location and capacity of facilities associated with the hazmat transportation process. These facilities can either be locations where hazmat is produced or proceeded (e.g., petroleum refineries or chemical factories) or locations where hazmat is stored, collected or recycled (e.g., gas stations or waste disposal sites) (Erkut et al., 2007). Table 1 presents an overview of the different problem approaches considering a load-dependent risk model. The majority of the approaches use an adaptation of the classical risk model including incident probability and population exposure. The population exposure model is also popular for the LRP. So far, a direct comparison of different risk models and their influence on the solution of the HMVRP, as Erkut and Verter (1998) did for the SPP, is missing.

Table 1 - Hazmat transportation problems considering load-dependent risk

References	Problem	Type of Risk	Transportation Risk Model
Nema and Gupta (1999)	LRP	Societal	Population exposure x incident probability x load amount
Nema and Gupta (2003)	LRP	Societal	Population exposure x incident probability x load amount
Alumur and Kara (2007)	LRP	Societal	Population exposure x load amount
Zhao and Zhao (2010)	LRP	Societal	Population exposure x load amount
Androutopoulos and Zografos (2012)	VRP	Societal	Population exposure x incident probability x load amount
Samanlioglu (2013)	LRP	Societal	Population exposure x load amount
Bula et al. (2016)	VRP	Societal	Population exposure x incident probability x load amount
Bula et al. (2017)	VRP	Societal	Population exposure x incident probability x load amount
Hu et al. (2018)	IRP	Societal	Unit mass transportation risk x vehicle load amount

3. Problem characterization

This paper considers the problem of supplying a given number of customers with hazardous materials by trucks in an urban area. A fleet of identical vehicles with limited load capacity is available for the distribution. Each customer has to be assigned to one single vehicle for serving, and hence, for each vehicle the set of customers to be served has to be determined. In addition, for each vehicle the optimal customer serving order has to be determined such that one or multiple objective function values are optimized. The tour of each vehicle has to start and end at the depot. Each customer has to be served by one single vehicle and can only be visited once. The customers and the depot are located in a transportation network of an urban region. The network contains a given number of weighted, undirected arcs representing road segments of the region and a given number of nodes representing intersections and driveways of the transportation network. A subset of the set of all nodes represents the locations of the customers and the depot. This leads to the additional challenge of finding suitable routes between all pairs of customers and the depot. This paper investigates how the path generation and the use of different risk models influence the outcomes of the VRP. Different load-dependent and load-independent risk models are compared. Additionally, their influence on the bi-objective conflict is investigated which occurs when risk minimization as well as an economical goal is pursued. Figure 1 shows an example of the problem and the two-step approach taken in the following sections.

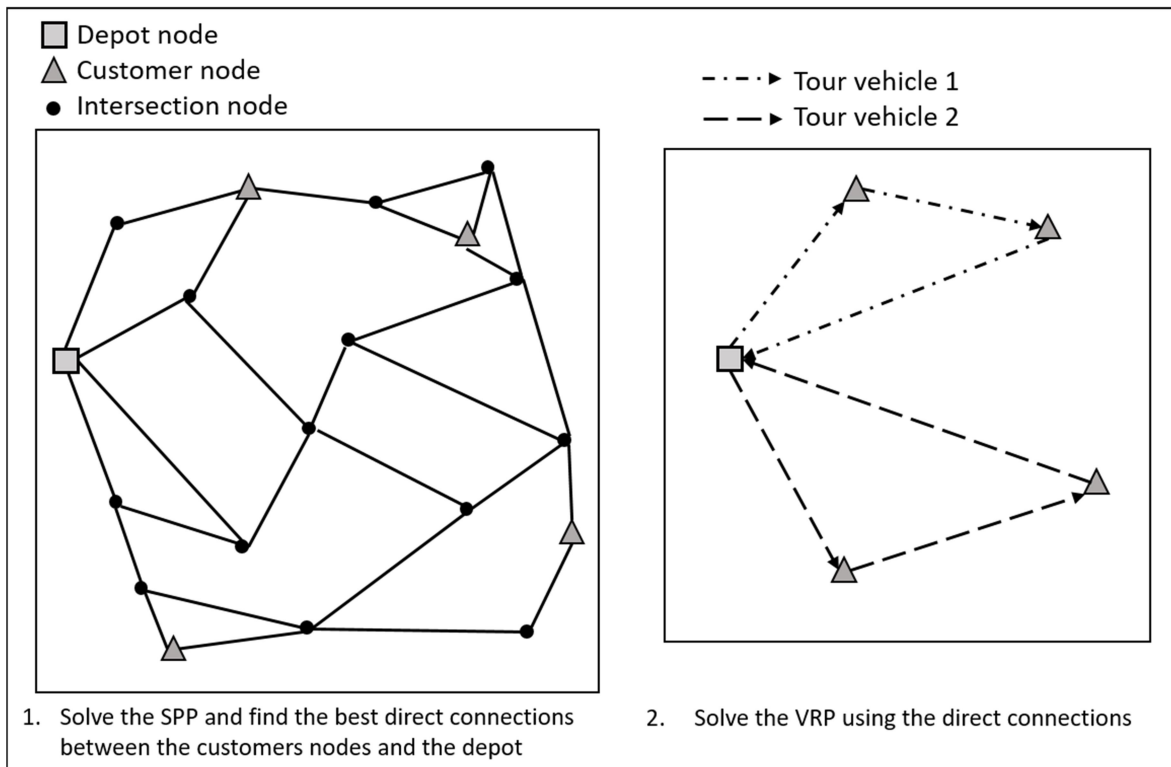


Figure 1 - Example for the problem approach

4. Mathematical model

4.1. Risk modelling

When a hazmat accident occurs, there are many possible undesirable consequences. Depending on the nature of the hazmat, the consequences can vary and are a function of the affected population, natural environment, infrastructure and the impact area. Thereby, it is important to not only select a suited risk measurement but also to choose an appropriate shape for the impact area. So far, different geometric shapes have been proposed in the literature (Erkut et al., 2007). Figure 2 shows the most important models and their shape.

This article compares different risk models. Risk is measured by the accident probability, the consequences and by the traditional risk model. Due to the high population density in urban areas, the consequences are measured by the population exposure. For each arc, the population exposure is calculated by using a fixed bandwidth approach, which is a common approach for risk assessment. The radius λ of the danger zone is dependent on the category and the amount of hazmat loaded (Erkut et al., 2007). Here, the radius represents the danger

zone of a fully loaded vehicle for one given category of hazmat. The length of an arc (i, j) is denoted by l_{ij} . The area of the bandwidth is calculated by: $l_{ij} \times \lambda \times 2 + \pi \times \lambda^2$.

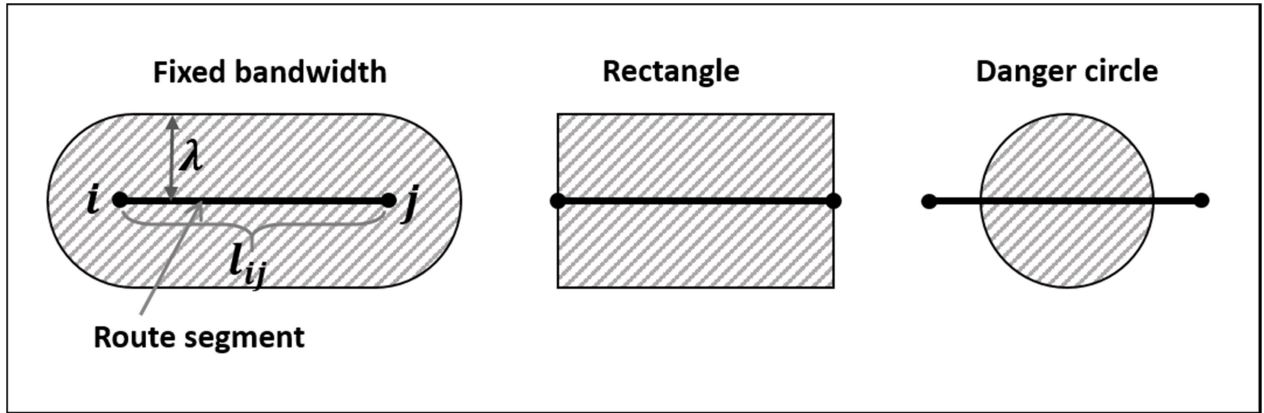


Figure 2 - Possible shapes of impact area around the route segment

The population value for an arc (i, j) is represented by pop_{ij} and represents the population at risk inside the danger zone. The later described SPP and HMVRP will both be using the same risk values. For a better clarification, the risk values are denoted slightly different when used for the SPP as when used for the HMVRP. For both problems the values represent the weights of an arc. For the HMVRP the arc represent the direct connection between two customers or a customer and the depot node. For the SPP an arc represent a road segment used when determining the direct connection between two customers in a road network (Figure 2).

For the SPP the population weight of an arc is denoted as pop_{ij}^{SP} and for the HMVRP the population weight of an arc is noted as pop_{ij}^{VP} . The probability of the unwanted incident is represented by the probability of a hazmat accident with a full release of the transported cargo. The accident probability value for an arc (i, j) is represented by ap_{ij} . For the SPP the accident probability of an arc is denoted as ap_{ij}^{SP} and for the HMVRP as ap_{ij}^{VP} . For the HMVRP the AP is calculated as the sum of the AP of all road segment between two customers nodes i and j . The traditional risk value for each road segment is denoted by tr_{ij}^{SP} for the SPP and by tr_{ij}^{VP} for the HMVRP. For the SPP the traditional risk value is calculated as the product of the probability and the consequences for an accident $tr_{ij}^{SP} = ap_{ij}^{SP} \times pop_{ij}^{SP}$ (Erkut and Verter, 1998).

Based on the three different risk values described above, three different load-independent risk models can be formulated. These risk models are approximation models and are shown in

Table 2. The three models are the most used in hazmat transportation and have been discussed and validated in the past multiple times (Erkut and Ingolfsson, 2005). The LI risk models can be used for the SPP as well as for the HMVRP.

Table 2 - LI risk models (adapted from Erkut and Ingolfsson, 2005)

Model	Approximation approach	References
Load-independent traditional risk	$\sum_{i \in N} \sum_{j \in N} tr_{ij}$	Batta and Chiu (1988); Zhang et al. (2000); Pradhananga et al. (2014)
Load-independent population exposure	$\sum_{i \in N} \sum_{j \in N} pop_{ij}$	Batta and Chiu (1988); ReVelle et al. (1991); Zhao and Zhu (2016)
Load-independent accident probability	$\sum_{i \in N} \sum_{j \in N} ap_{ij}$	Saccomanno and Chan (1985); Abkowitz et al. (1992); Marianov and ReVelle (1998)

Load-dependent risk models, however, are only of importance for the HMVRP. For the SPP the risk values are all calculated for a fully loaded vehicle and the load is not altered during the transportation. Only in the HMVRP, the amount of cargo will alter during the trip, for an example, see Figure 3.

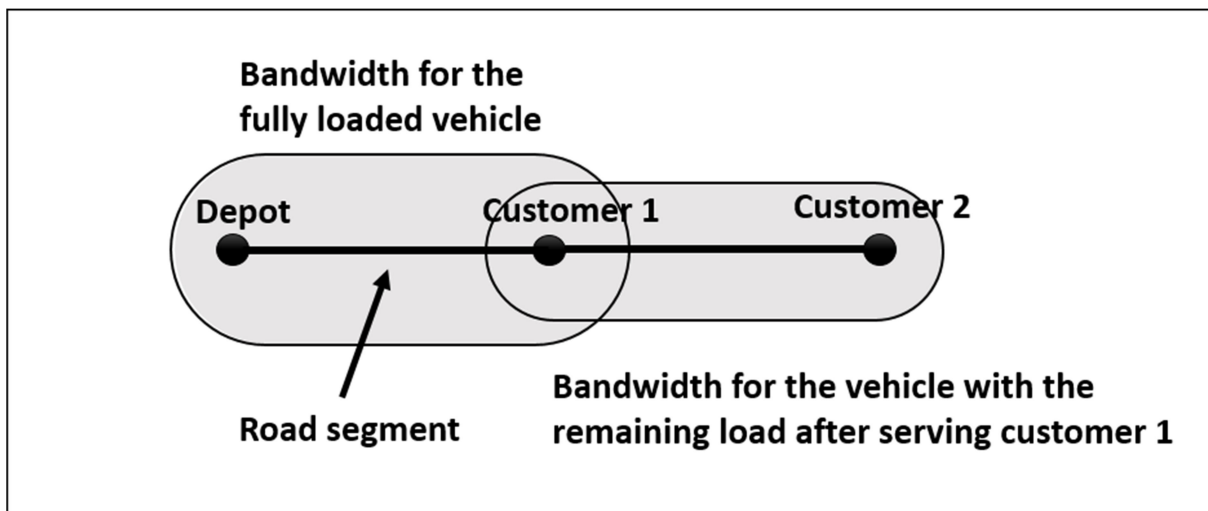


Figure 3 - The load-dependent danger zone

The LD risk models in this paper are obtained as the product of the load amount transported on an arc and the respective risk value of this arc. This is so far the most common approach as mentioned in section 2.3. Additionally, the LD risk models in this paper assume that the risk value is decreasing linear with the load capacity. It has to be noted, that a linear decrease of the risk value depending on the amount of cargo is not suitable for all categories of hazmat. For example, when transporting radioactive materials the radiation will not automatically

disappear once the cargo is unloaded. However, a distribution scenario of radioactive materials inside an urban area is quite unlikely.

An additional challenge that occurs when dealing with load-dependent risk model is how to model the risk originating from an empty vehicle. The question occurs, if an empty hazmat vehicle is still posing a bigger threat than a non-hazmat vehicle. On the one hand, it can be argued that due to the high awareness of the general public to hazmat transportation, even empty trucks should be routed with special caution. On the other hand, the safety standards and driver requirements for hazmat vehicles are higher than for normal non-hazmat vehicles, which lead to an overall safer transportation process. In addition, even the tank size of a non-hazmat truck can contain up to 1,500 liters of gasoline or diesel. An empty hazmat transporter, returning from its delivery trip, will thereby have in many scenarios a lesser risk than a fully refueled non-hazmat truck leaving the depot.

Following the above reasoning and based on the findings from the literature review, the LD risk model will be formulated as the product of the risk value of an arc and the total load amount transported on this arc. Thus, the HMVRP model needs to incorporate the variables w_{ij} representing the amount of hazmat transported on the arc from node i to node j . w_{ij} cannot exceed the maximum load capacity Q of the vehicle. In example, for the traditional risk model and for a single arc i,j the LD-TR value is denoted as tr_{ij}^{ld} and is calculated as the product of the LI-TR risk value (the value for a fully loaded vehicle) and the percentage load amount of hazmat shipped on this arc.

$$tr_{ij}^{ld} = tr_{ij}^{VP} \times \frac{w_{ij}}{Q} \quad (1)$$

For an arc traveled by fully loaded vehicle, where $w_{ij} = Q$, the load-dependent risk would be identical to the load-independent risk.

$$tr_{ij}^{ld} = tr_{ij}^{VP} \mid w_{ij} = Q \quad (2)$$

Following the reasoning of the approximation approach for LI risk models, the total load-dependent risk for the HMVRP can be expressed by:

$$\sum_{i \in N} \sum_{j \in N} \frac{w_{ij}}{Q} \times tr_{ij}^{VP} \quad (3)$$

Or also:

$$\frac{1}{Q} \times \sum_{i \in N} \sum_{j \in N} w_{ij} \times tr_{ij}^{VP} \quad (4)$$

The load capacity Q is not decision-relevant for the load-dependent risk model. Incorporating Q can be of interest for a better interpretation or comparison with other risk models, but is not necessary. A simpler version of the load-dependent risk model can be expressed by:

$$\sum_{i \in N} \sum_{j \in N} w_{ij} \times tr_{ij}^{VP} \quad (5)$$

Table 3 shows the risk approximation for the LD models and the most important references. However, no reference was found for the LD accident probability model. The approximation model presented here is designed by following the logic of the LD traditional risk model (which also contains the accident probability) and the LI accident probability model.

Table 3 - LD risk models

Model	Approximation approach	References
Load-dependent traditional risk	$\sum_{i \in N} \sum_{j \in N} w_{ij} \times tr_{ij}^{VP}$	Nema and Gupta (1999, 2003); Androutsopoulos and Zografos (2012)
Load-dependent population exposure	$\sum_{i \in N} \sum_{j \in N} w_{ij} \times pop_{ij}^{VP}$	Alumur and Kara (2007); Zhao and Zhao (2010); Samanlioglu (2013)
Load-dependent accident probability	$\sum_{i \in N} \sum_{j \in N} w_{ij} \times ap_{ij}^{VP}$	-

4.2. The path generation problem

Before the HMVRP can be solved, the underlying SPP and the generation of a suitable value matrix (VM) have to be addressed. The SPP is defined on a complete graph $G(N, A)$. The node set $N = \{1, 2, \dots, n\}$ represents intersections and driveways of the transportation network and contains a subset ($C \subset N$) of nodes representing customers and the depot. Each arc (i, j) from the set of all arcs A is associated with a length value denoted by l_{ij}^{SP} and different risk values. The starting node of a path is denoted s by and the target nodes by t .

The SPP has to be solved for each pair of customers and each pair of customer and the depot ($\forall s \in C, t \in C, s \neq t$).

For solving the problem the following decision variables are required:

$$y_{ij} : \begin{cases} 1, & \text{if the arc from node } i \text{ to node } j \text{ is part of the shortest path} \\ 0, & \text{otherwise} \end{cases}$$

$$\text{Min } (Z) \tag{6}$$

Subject to:

$$\sum_{j \in N} y_{sj} = 1 \tag{7}$$

$$\sum_{i \in N} y_{it} = 1 \tag{8}$$

$$\sum_{i \in N} y_{ij} - \sum_{i \in N} y_{ji} = 0 \quad \forall j \in N, j \neq s, j \neq t \tag{9}$$

$$y_{ij} = 0, \quad \forall i = j \tag{10}$$

(7) state that starting node must only be left once. (8) imply that the target node must only be entered once. (9) guarantee that each visited node must also be left. The objective for Z in (6) can be to minimize the distance between the nodes s and t represented by $Z1$ in (11), to minimize the population exposure between the nodes s and t represented by $Z2$ in (12), to minimize the traditional risk value represented by $Z3$ in (13) or to minimize the accident probability represented by $Z4$ in (14).

$$Z1 = \sum_{i \in N} \sum_{j \in N} y_{ij} \times l_{ij}^{SP} \tag{11}$$

$$Z2 = \sum_{i \in N} \sum_{j \in N} y_{ij} \times pop_{ij}^{SP} \tag{12}$$

$$Z3 = \sum_{i \in N} \sum_{j \in N} y_{ij} \times tr_{ij}^{SP} \tag{13}$$

$$Z4 = \sum_{i \in N} \sum_{j \in N} y_{ij} \times ap_{ij}^{SP} \tag{14}$$

All risk measures are load-independent and calculated for a fully loaded vehicle. Once the best path is computed, the values of the objective functions $Z1^*$, $Z2^*$, $Z3^*$ or $Z4^*$ for all pairs of s and t , are assigned as arc weights for the VM of the HMVRP.

4.3. The HMVRP

Once the direct connections between all customers and the depot are known the HMVRP can be addressed. The model in this article is an adaptation of the model proposed by Androutsopoulos and Zografos (2012). The HMVRP is defined on a complete graph $G(N, A)$. The node set $N = \{0, 1, 2, \dots, n\}$ includes the depot node 0 and a set of customer nodes $C =$

$\{1, 2, \dots, n\}$. Each customer $i \in C$ has a known demand value d_i and is connected with each other node $j \in C$ by an arc $(i, j) \in A$. Each arc (i, j) represents the direct connection between these nodes and is associated with a length value denoted by l_{ij}^{VP} as well as different risk values. The number of vehicles available to serve the customers is denoted by K . All vehicles have the same maximal loading capacity denoted by Q . For solving the problem two types of decision variables are defined:

w_{ij} : amount of hazmat transported on the arc from node i to node j

x_{ij} : $\begin{cases} 1, & \text{if a vehicle uses the arc from node } i \text{ to node } j \\ 0, & \text{otherwise} \end{cases}$

The HMVRP is formulated as:

$$\text{Min } (Z) \tag{15}$$

Subject to :

$$\sum_{i \in C} x_{ij} = 1, \forall j \in N \tag{16}$$

$$\sum_{j \in C} x_{ij} = 1, \forall i \in N \tag{17}$$

$$\sum_{i \in N} w_{ij} - \sum_{i \in N} w_{ji} = d_j, \quad \forall j \in C \tag{18}$$

$$w_{ih} - w_{hj} + (1 - x_{ih})M \geq d_h, \quad \forall i, j \in N, \forall h \in C, h \neq i, h \neq j \tag{19}$$

$$w_{i0} = 0, \quad \forall i \in N \tag{20}$$

$$w_{ij} \leq Q \times x_{ij}, \quad \forall i, j \in N \tag{21}$$

$$\sum_{i \in N} x_{0i} \leq K \tag{22}$$

$$w_{ij} \geq 0, \forall i, j \in N \tag{23}$$

$$x_{ij} \in \{0, 1\}, \forall i, j \in N \tag{24}$$

(16) and (17) state that each customer node is entered and left only once. (18) ensure the continuity of the hazmat load flow and guarantee together with (19) customer satisfaction. Additionally, (19) prevent the formation of sub tours. (20) imply that each truck returns to the depot empty. (19) together with (20) guarantee also that the initial load of each truck does not exceed the required minimum load quantity to satisfy all customers on the trip, and that only the minimum required amount is transported on arcs used by vehicles. (21) ensure that the

load does not exceed the loading capacity and that the load can only flow on arcs used by a vehicle. (22) restrict the number of vehicles.

The objective for Z in (15) can be to minimize the total distance traveled by all vehicles and is represented by $Z5$ in (25). Additionally, $Z5$ is considered as an economical goal. To minimize the population exposure for the whole HMVRP the objective $Z6$ in (26) and $Z7$ in (27) are selected, with $Z6$ representing the load-dependent value (LD-Pop) and $Z7$ the load-independent value (LI-Pop). $Z8$ in (28) and $Z9$ in (29) represent the objective of minimizing the traditional risk value, with $Z8$ being load-dependent (LD-TR) and $Z9$ being load-independent (LI-TR). The objectives $Z10$ (30) and $Z11$ in (31) represent the minimization of the accident probability, with $Z6$ being load-dependent (LD-AP) and $Z7$ being load-independent (LI-AP).

$$Z5 = \sum_{i \in N} \sum_{j \in N} x_{ij} \times l_{ij}^{VP} \quad (25)$$

$$Z6 = \sum_{i \in N} \sum_{j \in N} w_{ij} \times pop_{ij}^{vp} \quad (26)$$

$$Z7 = \sum_{i \in N} \sum_{j \in N} x_{ij} \times pop_{ij}^{VP} \quad (27)$$

$$Z8 = \sum_{i \in N} \sum_{j \in N} w_{ij} \times tr_{ij}^{vp} \quad (28)$$

$$Z9 = \sum_{i \in N} \sum_{j \in N} x_{ij} \times tr_{ij}^{vp} \quad (29)$$

$$Z10 = \sum_{i \in N} \sum_{j \in N} w_{ij} \times ap_{ij}^{vp} \quad (30)$$

$$Z11 = \sum_{i \in N} \sum_{j \in N} x_{ij} \times ap_{ij}^{vp} \quad (31)$$

4.4. An illustrative example for the HMVRP

A simple illustrative example for the HMVRP is provided to illustrate the possibility of further improvement through a load-dependent risk model. Figure 4 shows a network for the HMVRP.

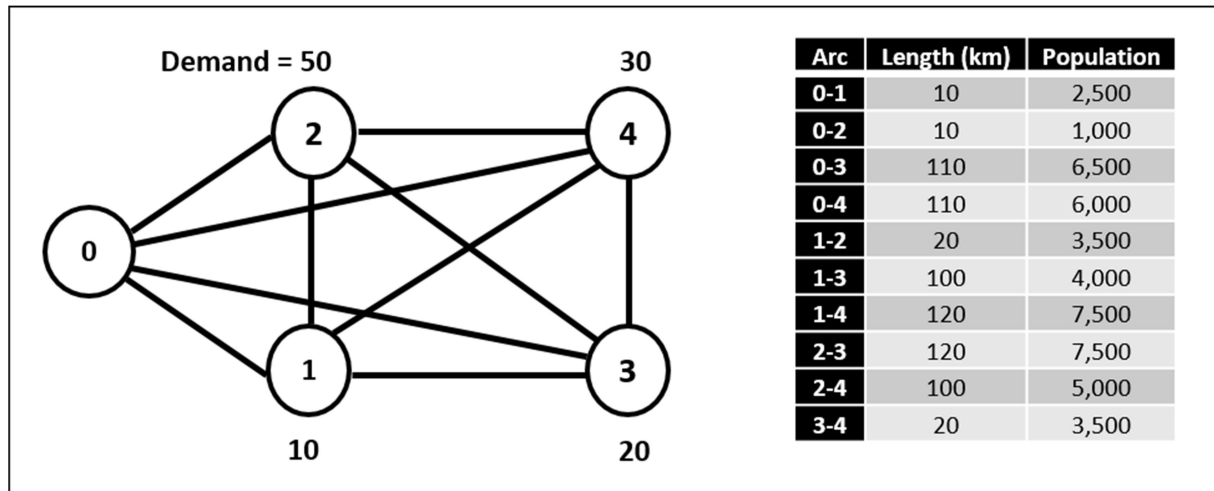


Figure 4 - Example network

To keep the example simple, it uses only the population values as risk measurement and consists of a small network with 4 customers and 1 depot. The arc weights for all direct connections between the depot and all customers, based on the shortest distances, are given in the table. The vehicle capacity is equal to the total customer demand. For the beginning, the number of vehicles is not fixed. Solving the HMVRP by minimizing population exposure while using a load-independent approach, leads to two possible optimal solutions:

[Solution 1: 0 – 1 – 3 – 4 – 2 – 0] or [Solution 2: 0 – 2 – 4 – 3 – 1 – 0]. Both solutions consist of a single tour with 240km travel distance and 16,000 people at risk (LI-Pop). However, the LD-Pop value is 12,050 people for solution 1 and 5,550 for solution 2.

If the HMVRP is solved by minimizing population exposure while using a load-dependent model, the optimal solution results in a scenario using three vehicles and resulting in three tours. [Solution 3: 0 – 1 – 3 – 0, 0 – 2 – 0 and 0 – 4 – 0] with the values: [460km; 27,500 LI-Pop; 2,330 LD-Pop]. Solution 3 represents a scenario with an unlimited fleet size. In the following, two additional scenarios with a restricted fleet size are investigated.

If the fleet size is restricted to two vehicles, the optimal solution results in a scenario with two tours. [Solution 4: 0 – 1 – 3 – 0 and 0 – 2 – 4 – 0] with the values: [440km; 25,500 LI-Pop; 3,230 LD-Pop].

If the fleet size is restricted to only one vehicle the optimal solution consists of a single tour. [Solution 5 (= Solution 2): 0 – 2 – 4 – 3 – 1 – 0] with the values: [240 km; 5,550 LD-Pop; 16,000 LI-Pop].

This example shows that a LD-based approach leads to outcomes different from those of a LI-based approach. It also clarifies how the results are influenced by the fleet size. In the unrestricted scenario, the LD-Pop value is the lowest, but the distance the highest. By reducing the fleet size one by one, the distance is reduced while the LD-Pop value is slightly increased. The example should help to clarify the basic problem and the interpretation of the experimental outcomes.

5. Experimental outcomes

5.1. The problem instances

For the generation of realistic urban networks, a special network generator was developed. The roads of the transportation network of the urban region of the Bavarian city Munich and some other smaller Bavarian cities were analyzed and evaluated. The evaluation focused on the parts of the road network suitable for the transport of hazardous materials by truck and the population distribution. Following the pattern of this evaluation, the generator is able to create realistic transportation networks with three different types of roads. Highways, motorways and city road segments are distributed following a realistic pattern. The accident probabilities are assigned to the corresponding road types based on the evaluation of Harwood et al. (1993) but with a small random deviation for each road segment. Inner city regions are generated and placed in the network. They contain a higher population density and also a denser road network than the rest of the network and provide a realistic distribution of population values. Five different road networks are created, varying from 211 nodes to 344 nodes. Figure 5 shows some of the networks used for the problem instance generation in this article. The HMVRP instances are generated by selecting a subset of customer nodes and a depot. The depot node is always located in the outskirts region of the network. Larger heating oil distribution centers are most likely to lie in the outskirts region of an urban area (if the region does not have an own distribution center, the vehicle will enter the network through one of the outside nodes). The customer nodes are distributed randomly over the network. Customer demands are generated randomly based on recent statistics of demand values, with a minimum order quantity of 600 liters and a maximum possible order quantity of 20,000 liters,

the average demand value being 2,500 liters. The vehicles are all homogenous with a total capacity of 20,000 liters. The evacuation band for the transport is selected with $\lambda = 50$ meters, the band is thereby much smaller than for other hazmat problems but realistic for a hazmat like oil or gasoline (Lozano et al., 2011). A total of 42 different problems instances was generated, thereof 20 smaller instances with 13 to 16 customers and 22 larger instances with 18 to 25 customers.

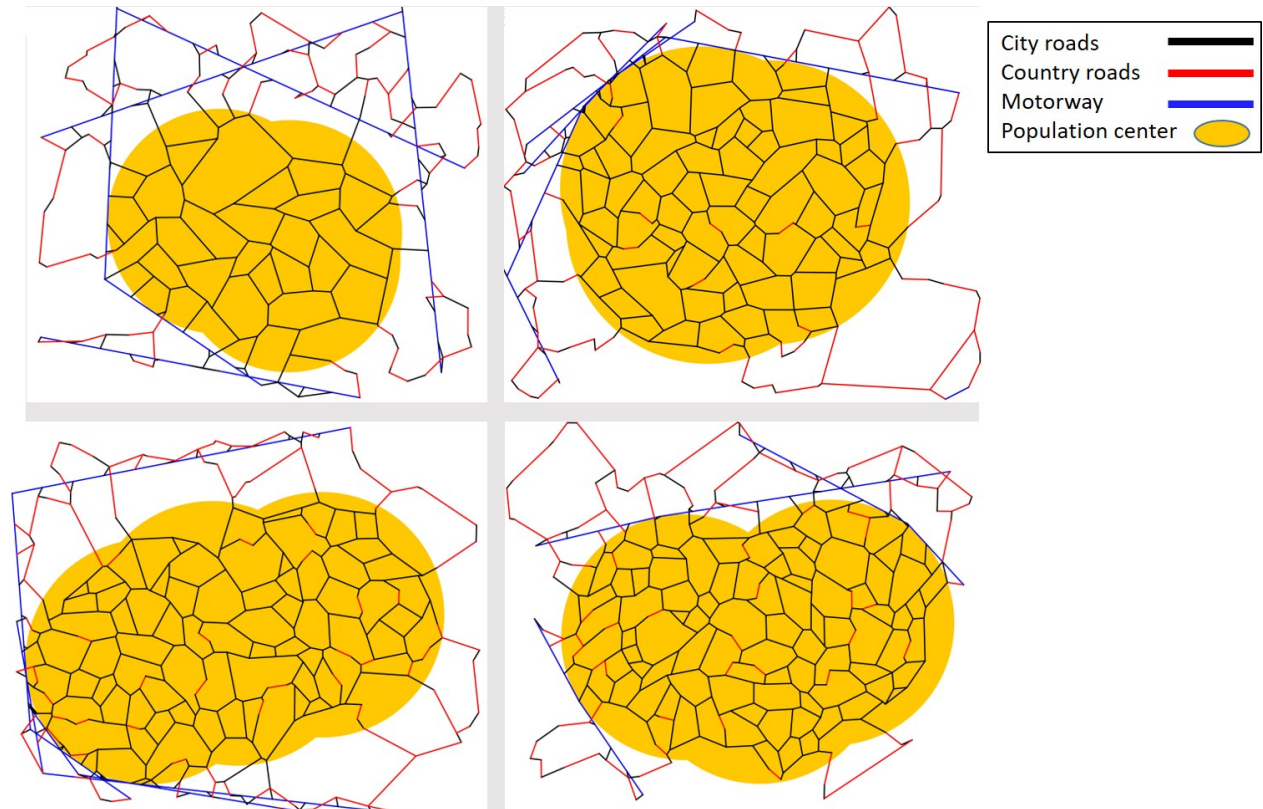


Figure 5 - Example of the networks used for the problem instances

The problem is addressed by a two-step approach. First, the shortest path problem is solved and the optimal paths connecting all pairs of customer nodes and the depot are determined. The algorithm of Floyd (1962) is used for this purpose. The algorithm is executed four times for every instance, each time satisfying one of the objectives functions ($Z1$ to $Z4$) described in section 4.3. This leads to the generations of four different value matrices for each problem instance. The HMVRP is solved seven times for each VM, each time satisfying one of the objectives functions ($Z5$ to $Z11$) described in section 4.3. A total of $42 \times 4 \times 7 = 1,176$ HMVRP are solved exactly, with a restricted fleet size. Furthermore, the 20 smaller problem instances are solved with an unrestricted fleet size leading to an additional $20 \times 4 \times 7 = 560$ solved HMVRP.

The restricted fleet size is varying between 2 and 5 vehicles and is calculated for each instance by:

$$K = \left\lceil \frac{\sum_{i \in C} d_i}{Q} \right\rceil \quad (32)$$

The SPP algorithm was implemented in Python 3.6 and executed on a Core i5-6600K with 8 GB RAM. The HMVRP instances were solved in GAMS 25.1 by the CPLEX 12.8 solver.

5.2. Restricted and unrestricted fleet size for the HMVRP

The results for restricted and unrestricted fleet size are compared for the smaller problem instances. Table 4 shows the average increase of the fleet size in the unrestricted scenario in comparison to the fleet size of the restricted scenario. The load-dependent risk models lead to an overall large increase in the fleet size, while for the load-independent models only a small increase for only very few problem instances can be observed. The large increase for the LD risk models can be explained by the fact, that an empty truck does not increase the LD risk value, so that many small trips can achieve better results than a few large trips with a large loading amount. This can also be observed in the example in section 4.4. For many VRP problems, the number of vehicles is given in advance. However, if the fleet size is unrestricted it can grow more than proportional in the optimal solution leading to a tremendous increase in travelled distance as well as vehicles and thereby to additional costs for the carrier. If this problem occurs, it can be controlled by assigning a small threshold risk value to the return trip to the depot.

Table 4 - Average increase in fleet size in the unrestricted vehicle scenario

	Min Z6 (LD-Pop)	Min Z7 (LI-Pop)	Min Z8 (LD-TR)	Min Z9 (LI-TR)	Min Z10 (LD-AP)	Min Z11 (LI-AP)
Dist-VM	214%	4%	160%	13%	244%	2%
Pop-VM	346%	3%	288%	3%	331%	0%
TR-VM	321%	2%	375%	2%	349%	2%
AP-VM	290%	5%	290%	3%	428%	3%
Mean	292.7%	3.5%	278.3%	5.3%	338%	1.7%

To visualize the impact of fleet size on the LD risk value, two similar 16-customers problem instances are selected. Both instances need a minimum of three and a maximum of 13 vehicles. The problem instances are run ten times, each time increasing the maximum fleet

size by one. Figure 6 shows how the different load-dependent risk values improve (here decrease) when the size of the fleet increases. It is important to note, that the biggest improvement is achieved by allowing two additional vehicles. For future work, it can be of interest, to consider smaller increases in fleet size, when LD risk models are used.

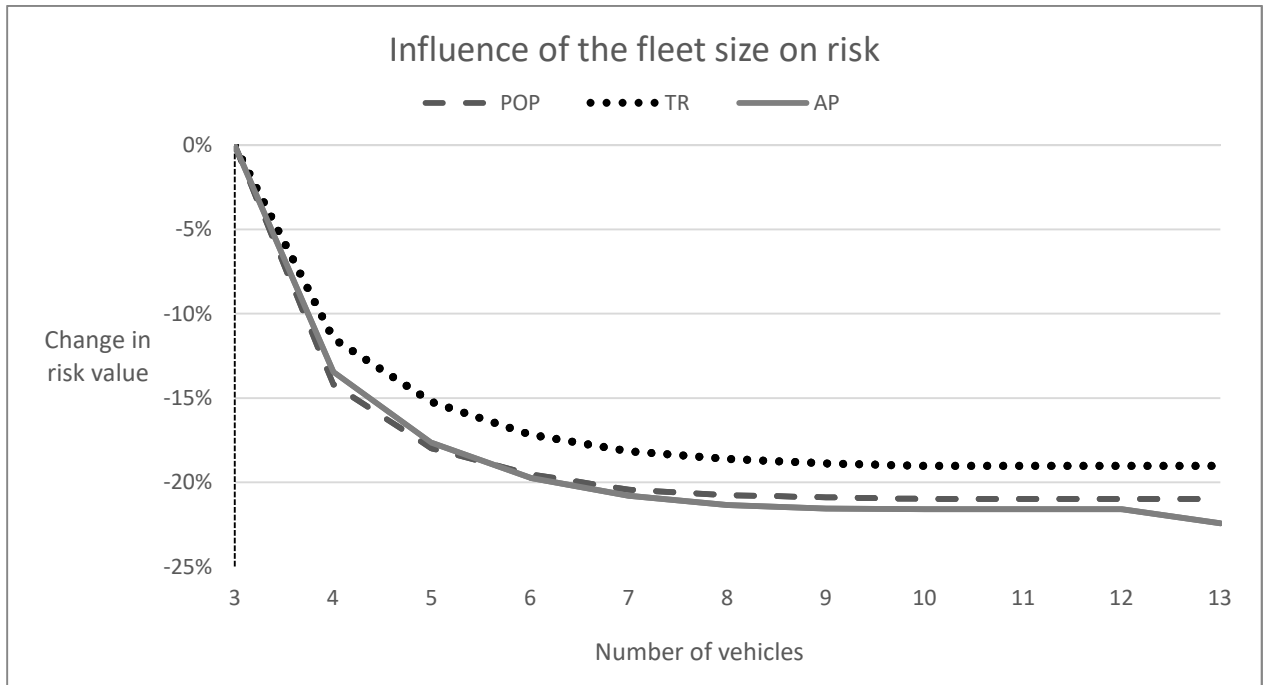


Figure 6 - Influence of the fleet size on the LD risk value

Additionally, it is investigated how the unlimited vehicle scenario affects the economic goals (here represented by the total travelled distance). An increase in fleet size means that the workload for each individual vehicle is reduced which additionally leads to an increase of the total travelled distance. Table 5 shows the average maximum improvement for load-dependent risk models as well as the average increase in travelled distance for the unrestricted fleet side instances, in comparison to the best values achieved for the restricted fleet size instances.

Table 5 - Difference in risk and distance values by comparing restricted and unrestricted vehicles

	Min LD-Pop	Min LD-TR	Min LD-AP
Average decrease in risk	-28%	-26%	-27%
Average increase in distance	123%	110%	145%

5.3. Outcomes for the HMVRP with restricted fleet size

No perfect solution minimizing all objective functions was found. The maximum number of complementary objectives was found as three out of seven for one single problem. For all 42 instances, the optimal value for minimizing the total distance (dist) of the vehicle fleet is always found on the distance-based VM. The optimal values for the LD- as well as the LI-population based risk models are always found on the population-based VM. The optimal values for the traditional-risk-based objectives are found on the traditional-risk-based VM and the optimal values for accident probability are found on the accident probability VM. The choice of the risk model has not only an influence on the path generation problem but also on the HMVRP. In addition, it can be deduced that the same risk model should be used for both problem aspects in order to obtain the optimal solution.

Table 6, 7, 8 and 9 show the minimum, the maximum and the average deviation (in %) from the optimal solution value over all problems instances [Min; Avg.; Max]. The overall worst average value is indicated by (^w) for each objective.

The results show that the path generation has an important impact on the HMVRP. Overall, the VM based on distance minimization (which is often very similar to the Euclidian distance) is least suited for risk minimization. For 5 out of 7 risk models, the worst values are obtained on the distance-VM (Table 6). Only for the load-independent accident probability model the worst value is found on the traditional risk-VM (Table 8). In the worst case, the choice of the wrong VM can lead to a deviation of over 68% from the optimal solution for a risk value (see Min Z9, Table 6). The conflict between the minimization of distance and risk is the greatest when dealing with the traditional risk model. The AP-based risk model performed quite satisfying and seems to work the best in perspective with distance minimization.

Table 6 - Results based on the distance-VM

	Min Z5 (distance)			Min Z6 (LD-Pop)			Min Z7 (LI-Pop)			Min Z8 (LD-TR)			Min Z9 (LI-TR)			Min Z10 (LD-AP)			Min Z11 (LI-AP)		
	min	Ø	max	min	Ø	max	min	Ø	max	min	Ø	max	min	Ø	max	min	Ø	max	min	Ø	max
dist	0	0	0	2	17	43	0	9	38	6	22	50	2	16	65	2	16	78	0	5	14
LD-Pop	18	88	355	1	7^W	20	25	74	228	1	14	51	7	70	179	1	14	59	14	74	220
LI-Pop	2	27	88	16	44	98	1	10^W	29	16	40	82	2	14	33	9	49	116	1	14	82
LD-TR	34	226	1291	7	29	74	53	165	578	4	20^W	52	18	122	379	13	56	204	27	178	783
LI-TR	8	75	284	21	90	235	1	30	84	17	73	194	1	24^W	68	24	99	254	3	43	267
LD-AP	15	59	158	3	9	28	18	60	138	4	17	70	18	63	144	1	6^W	17	3	54	157
LI-AP	2	13	32	10	21	61	1	9	22	10	32	62	2	14	39	8	32	66	1	7	27

Table 7 - Results based on the population-VM

	Min Z5 (distance)			Min Z6 (LD-Pop)			Min Z7 (LI-Pop)			Min Z8 (LD-TR)			Min Z9 (LI-TR)			Min Z10 (LD-AP)			Min Z11 (LI-AP)		
	min	Ø	max	min	Ø	max	min	Ø	max	min	Ø	max	min	Ø	max	min	Ø	max	min	Ø	max
dist	3	9	34	16	35	67	3	14	38	16	39	67	3	26	69	14	33	81	3	13	38
LD-Pop	18	61	132	0	0	0	11	47	135	0	6	18	14	66	198	0	3	34	14	56	199
LI-Pop	0	6	30	5	16	42	0	0	0	5	20	52	0	5	18	4	17	54	0	2	9
LD-TR	37	139	482	2	13	55	16	101	434	1	6	14	24	114	479	3	21	126	25	115	482
LI-TR	1	26	88	3	26	71	1	11	23	3	25	73	1	6	13	3	29	67	1	14	45
LD-AP	18	54	110	1	7	16	14	47	88	2	12	22	23	63	139	1	5	12	18	51	141
LI-AP	2	9	26	9	23	49	2	6	20	9	27	59	2	11	30	9	22	55	2	5	20

Table 8 - Results based on the traditional risk-VM

	Min Z5 (distance)			Min Z6 (LD-Pop)			Min Z7 (LI-Pop)			Min Z8 (LD-TR)			Min Z9 (LI-TR)			Min Z10 (LD-AP)			Min Z11 (LI-AP)		
	min	Ø	max	min	Ø	max	min	Ø	max	min	Ø	max	min	Ø	max	min	Ø	max	min	Ø	max
dist	8	20^W	50	17	48	91	9	24	50	22	49	78	11	31	64	17	44	80	11	24	50
LD-Pop	18	73	202	2	7	16	10	68	201	3	12	23	20	65	142	3	10	44	18	71	203
LI-Pop	4	13	28	9	26	55	3	8	19	9	27	49	3	10	28	8	23	44	3	9	20
LD-TR	16	115	463	0	5	20	4	109	458	0	0	0	18	90	334	0	11	113	24	104	368
LI-TR	0	10	42	1	15	45	0	2	10	0	15	46	0	0	0	1	14	31	0	3	12
LD-AP	17	61	167	1	8	18	18	56	169	1	12	27	14	54	159	1	6	12	16	57	166
LI-AP	4	12	26	10	26	42	3	9	19	9	27	52	4	10	24	7	23	37	3	8^W	19

Table 9 - Results based on the accident probability-VM

	Min Z5 (distance)			Min Z6 (LD-Pop)			Min Z7 (LI-Pop)			Min Z8 (LD-TR)			Min Z9 (LI-TR)			Min Z10 (LD-AP)			Min Z11 (LI-AP)		
	min	θ	max	min	θ	max	min	θ	max	min	θ	max	min	θ	max	min	θ	max	min	θ	max
dist	1	6	19	12	33	70	2	14	41	14	36	66	2	28	55	8	31	93	2	13	36
LD-Pop	18	82	184	1	5	15	16	61	144	4	12	27	27	70	202	2	9	36	21	59	111
LI-Pop	6	18	50	8	23	43	1	6	14	10	26	62	3	11	32	8	26	64	1	8	21
LD-TR	33	192	691	3	14	56	20	115	443	1	6	25	21	99	407	2	29	129	44	117	350
LI-TR	9	51	170	2	34	88	1	13	27	2	32	77	1	7	19	2	40	96	1	20	80
LD-AP	15	55	134	0	3	15	8	44	101	0	9	32	21	55	153	0	0	0	1	41	91
LI-AP	0	7	20	3	17	31	0	2	17	5	20	49	0	7	25	2	17	50	0	0	0

When comparing LD and LI risk models, it is shown that even when considering the same basic risk model, the optimal solutions are clearly different. For example, when looking at the results of Table 7, the optimal solution for LD-Pop leads to an average deviation of 16% from the optimal solution of LI-Pop. While the optimal solution for LI-Pop, leads to an average deviation of even 47% from the optimal solution of LD-Pop. In terms of the overall risk reduction, it is important to look at the difference in the LD risk value. It indicates how much the risk can further be reduced if the varying load capacity is considered. Table 10 shows the average deviation (over all 4 VM) from LD risk value and shows how much further improvement is possible by including load in the risk model.

Table 10 - Average deviation in risk of the LI risk models in comparison to the LD risk model

	Min Z7 LI-Pop	Min Z9 LI-TR	Min Z 11 LI-AP
Average deviation from the optimal LD risk value	62% (LD-Pop)	106% (LD-TR)	51% (LD-AP)

One disadvantage of the solutions obtained by minimizing a LD risk model is an overall higher average value for travelled distance than solutions based on a LI risk model even when the fleet size is restricted.

6. Conclusions

This paper analyzes the influence of the path generation on the results of the HMVRP in urban areas. Six different load-dependent and load-independent risk models are compared.

The results show that different risk models lead to different optimal solutions for the SPP as well as for the HMVRP. To obtain the best solutions, the same risk model should be used for the SPP and the HMVRP. When dealing with an HMVRP, considering the vehicle load in the risk model can help to further minimize the risk. In addition, a decision maker should also consider the fleet size. Even a small increase in fleet size can strongly improve the solutions of LD risk models. These findings suggest that for further work and research on the HMVRP the focus should not only be on the most suited risk model, but also on the path generation and the fleet size.

Limitations and possible further research: This approach does not consider the possibility of an increased risk during the unloading phase. During the service phase, the vehicle stops for a short amount of time while the hazmat is unloaded. The unloading process involves accessing the cargo and may thereby increase the risk of an unwanted event.

The load-dependent risk model prioritizes the customers with a high demand. The influence of the decreasing load-capacity on the fuel consumption and thereby on the operating costs was not included in this approach. Further investigation can be of interest, to create additional incentives for hazmat carriers.

The test instances are all based on networks located in highly populated urban areas. Therefore, population exposure is the only measure for the consequences. An investigation for rural areas and the consideration of other consequences (e.g. damage to the natural environment, like water pollution or forest fires) can be promising. Further work could include different risk dimensions or modelling, such as the comparison of different dimensions for the consequences or different shapes of the impact area.

When a compromise solution between an economical goal and a risk goal is needed, the VM for each objective should be investigated first to find the extreme points of the solution space. If no satisfying solution for the HMVRP can be found based on one of these VM, then a new VM can be constructed by using a multi-criteria shortest path approach. A further investigation of solution methods to construct satisfying pareto frontiers will be promising.

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V

**A Hybrid Genetic Algorithm for the Bi-Objective
Hazardous Materials Vehicle Routing Problem in
Urban Areas**

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A Hybrid Genetic Algorithm for the Bi-Objective Hazardous Materials Vehicle Routing Problem in Urban Areas

Abstract: *The transportation of hazardous materials (hazmat) has attracted much attention in the last decades. The dangerous nature of the cargo and the resulting threat for population, environment and infrastructure require the inclusion of risk in the decision problem. For the purpose of safety, hazmat vehicles should avoid to drive through regions with a high population density. However, hazardous materials like heating oil, fuel gas or gasoline often need to be distributed in highly populated urban areas and to multiple customers. In this paper, the bi-objective hazardous materials vehicle routing problem (HMVRP) with multiple customers in urban areas is addressed. The varying quantity of hazardous cargo during a trip is incorporated into the risk model. A hybrid genetic algorithm metaheuristic framework is adapted to the HMVRP and applied on a random generated but realistic road network of an urban area. The multi-criteria conflict between travel distance and risk minimization is addressed and a pareto front is constructed.*

Keywords: *hazardous materials, vehicle routing, hybrid genetic algorithm, safety, bi-objective optimization*

1. Introduction and literature review

The transportation of hazardous materials (hazmat) has become an indispensable component for satisfying industrial as well as consumer demand in our modern society. The definition given by the German legislator considers any materials or objects as hazmat, that by their very nature, characteristics or state, when transported, pose risk to public safety or order, in particular, to the general public, the life and health of persons, animals and objects (GGBeFG, 2015). Incidents involving the release of hazmat receive a large echo throughout the media and the public awareness of the risk emitted by hazmat transportation is very high. By providing strict laws and regulations, the government and local authorities aim to ensure the safety of the transportation process. Nevertheless, a total safety guarantee is not possible and the risk of an accident with a release of the hazardous cargo will always remain. Depending

on the nature of the hazmat, such an unintended release can result in a catastrophic incident like an explosion, a fire or a toxic gas cloud. To reduce the number of potential casualties to a minimum, hazmat vehicles should avoid driving through highly populated regions. However, certain hazmat, such as heating oil, fuel gas or gasoline, need to be delivered to consumers residing inside urban areas.

The hazardous materials transportation problem has become a popular research topic in the field of operations research for further safety improvement. Some of the earliest contributions to the research field of hazmat logistics can be tracked down to the seventies, see e.g. (Shappert et al., 1973) or (Kalelkar and Brooks, 1978). The research field since then has grown and a considerable amount of contributions has been made (Erkut et al., 2007; Holeczek, 2019). The majority of these contributions consider a large variety of risk assessment and shortest path problems. However, more recently a trend to NP-hard optimization problems like the network design problem (NDP), the toll-setting problem (ToSP) and the vehicle routing problem (VRP) can be observed. Hazmat can be transported by rail, road, air, ship or pipeline. Especially, risk modelling for road transportation has received a lot of attention. A large majority of risk modelling approaches is considering shipments that only supply one single customer. Therefore, most risk models do not need to consider the varying amount of vehicle load in their risk model and use load-independent (LI) risk models. Only few approaches incorporate a load-dependent (LD) risk model. However, when dealing with the VRP vehicles serve multiple customers. In consequence, their load size alters during the delivery trip and a LD risk model becomes more accurate than a LI risk model (Androutsopoulos and Zografos, 2012; Bula et al., 2016).

The classical VRP was first introduced by Dantzig and Ramser (1959) as an extension of the travelling salesman problem. Since then, the problem has become a popular research topic and many different extensions have been proposed (Domschke and Scholl, 2010). Tarantilis and Kiranoudis (2001) were among the first to adapt the VRP to the requirements of hazmat transportation. Ever since, the HMVRP has grown in popularity. Zografos and Androutsopoulos (2002; 2004; 2008), as well as Pradhananga et al. (2010b; 2010a; 2014) introduce extensions to the HMVRP with customer time windows. Zheng (2010) as well as Bula et al. (2016; 2017) consider heterogeneous vehicles in their approach. An extension with multiple depot nodes is considered by Zhao and Zhu (2016) and Du et al. (2017). Link capacity constraints are considered by Zhang et al. (2005) and Ma et al. (2012). However, only the approaches by Androutsopoulos and Zografos (2012), Bula et al. (2016; 2017) and

Hu et al. (2018) are dealing with VRP variants that include a LD risk model. In addition, some LD risk model can be found when dealing with the location and routing problem (LRP), e.g. Nema and Gupta (1999; 2003), Alumur and Kara (2007), Zhao and Zhao (2010) and Samanlioglu (2013). The LRP aims to optimize routing as well as the location planning for facilities necessary for the transportation of hazardous materials (Erkut et al., 2007).

This article addresses the bi-objective HMVRP and aims to minimize the total travel distance as well as the total risk, while including the vehicle load quantity into the risk model. A hybrid genetic algorithm (HGA) is proposed to find a set of good solutions in a short amount of time. The paper is organized as follows: In section two, the problem is characterized and a mathematical model of the problem is provided. In section three, the hybrid genetic algorithm is described. In section four the experimental outcomes are discussed.

2. The hazardous materials vehicle routing problem

2.1. Problem characterization

This paper considers a bi-objective HMVRP in which a given number of customers have to be supplied with hazardous materials. All customers are located in a highly populated urban area. For the distribution process, a fleet of identical vehicles with restricted load capacity is available. Each vehicle has to start and end its tour at the depot and only one depot is available. Each customer can only be visited once and has to be served by only one vehicle. The set of customers as well as the optimal customer serving order for each vehicle has to be determined in the way that the bi-objective function values of travel distance and risk are optimized. The two objectives for the HMVRP are the minimization of the total distance traveled by all vehicles as well as the minimization of the total risk. While the traveled distance is self-explanatory, the selection of the right model for an approach is challenging and has a direct influence on the solution outcome (Erkut et al., 2007). The risk model used in this approach is a load-dependent population exposure model.

Risk modelling is the essential aspect of hazmat transportation. The most common risk models consider either probability of an accident with hazmat spill or the consequences of such an incident. In most approaches, the consequences are measured by the resident population affected in cases of a hazmat accident, but also other consequences like infrastructural damages or pollution of the natural environment are possible (Holeczek, 2019). Among the most widely used risk models are the accident probability model, the population

exposure model and the traditional risk model. The accident probability model aims to minimize the probability of an accident with a release of the hazardous cargo. The population exposure model considers the societal risk and aims to minimize the numbers of fatalities in case of an unwanted hazmat incident (Erkut et al., 2007). The traditional risk model accounts risk as the product of the probability and the consequences of an unwanted incident (Covello and Merkhofer, 1993). A detailed overview of the most common risk models can be found in Erkut et al. (2007). The choice of the risk model has a direct effect on the solution outcome (Erkut and Verter, 1998; Holeczek et al., 2018). The high population density in cities as well as the difficulty to get accurate accident probability data for single road segments make the population exposure model more accurate and thereby more suitable for risk modelling in urban areas. In consequence, a population exposure risk model was selected for this approach. The population exposure for all direct connections between all customers and depot was determined by using a fixed bandwidth approach. This approach is commonly used and very popular for risk assessment. The radius λ of the danger zone is dependent on the category and the amount of hazmat loaded (Erkut et al., 2007). The length of an arc (i,j) is denoted by l_{ij} . Each arc represents a road segment of a transportation network. The bandwidth can represent the evacuation area of the people affected by a hazmat incident. Figure 1 shows the most important models and their shape (Erkut et al., 2007).

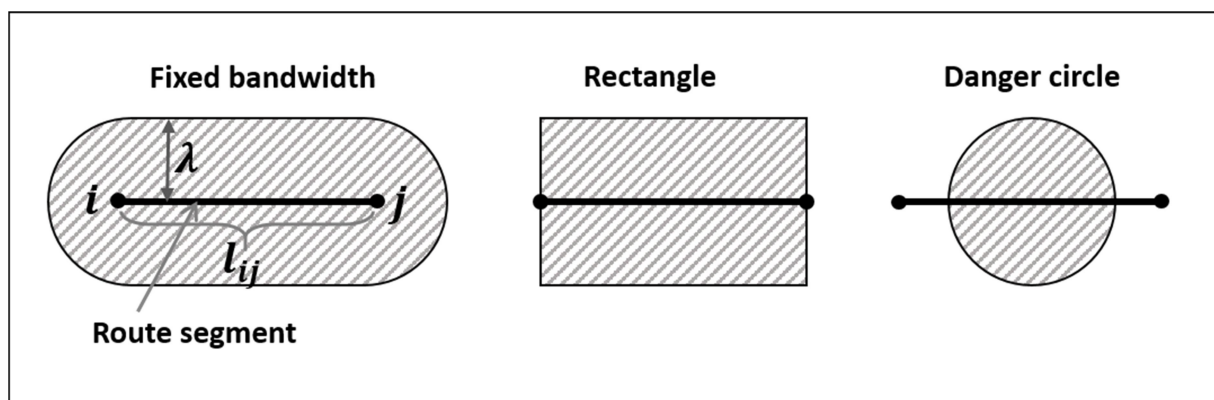


Figure 1 – Popular shapes of the impact area

The choice of a suitable radius λ is important for the accuracy of the risk model. There are different papers dealing with the health effects of the adjacent population and evacuation zones in case of a hazmat incident. However, many approaches are not adapted to the particularities of urban areas such as a greatly varying population density or people caught in congestion (Lozano et al., 2010). The population density in urban areas can vary strongly, even over a short distance. While one road segment can lead through a highly frequented

district with a lot of traffic and many pedestrians, another road segment only a few blocks further away can lead through an industrial district with a significantly lower population density. If the bandwidth of the danger zone is chosen too large it risks to falsify the average population density and to not properly account the particular population patterns of a metropolitan area.

For this approach, a small bandwidth of 50 meters is chosen. This bandwidth represents the direct impact zone in case of a hazmat incident and the people caught in the immediate danger zone in case of a fire or an explosion. Lozano et al. (2011) show that 50 meter bands can be of advantage in urban areas.

The population value for an arc (i,j) is represented by pop_{ij} and stands for the population at risk inside the danger zone. The population value is selected in a way that it represents the danger zone for a fully loaded vehicle. For measuring the total population exposure of all travelled arcs, two popular approximation models are shown in Table 1. N is the node set of the transportation network. The load-independent (LI) risk model has received more attention in the literature so far, but does not include the varying load quantity in case of the HMVRP.

Table 1 - Population exposure based risk models

Model	Approximation approach	References
Load-independent population exposure	$\sum_{i \in N} \sum_{j \in N} pop_{ij}$	Batta and Chiu (1988); ReVelle et al. (1991); Zhao and Zhu (2016)
Load-dependent population exposure	$\sum_{i \in N} \sum_{j \in N} w_{ij} \times pop_{ij}$	Alumur and Kara (2007); Zhao and Zhao (2010); Samanlioglu (2013)

The HMVRP with a load-dependent (LD) risk model needs to incorporate the variable w_{ij} representing the quantity of hazmat transported on the arc from node i to node j . Consequently, the LD risk value for an arc (i,j) is obtained as the product of the load quantity w_{ij} and the population value of this arc pop_{ij} . The total risk value is obtained by summing up the risk values of all arcs. With respect to the maximum vehicle capacity, w_{ij} cannot exceed the maximum load Q . Figure 2 shows how the danger zone (or the region of impact) of a hazmat transport vehicle alters when a load-dependent risk model is used and after a customer is visited and a part of the cargo is unloaded.

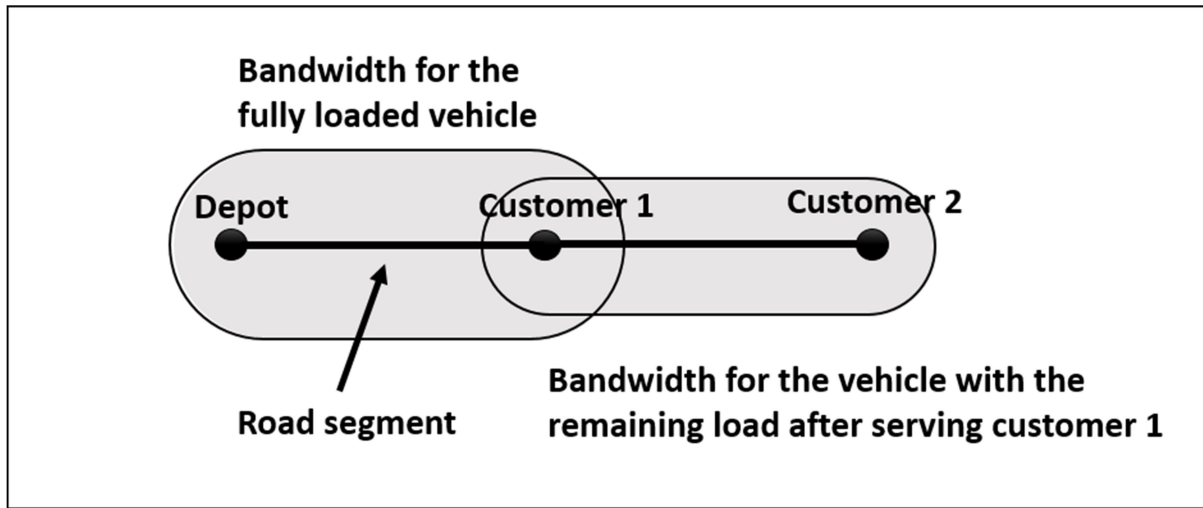


Figure 2 - The LD danger zone

It is noteworthy to mention that the LD risk model used in this approach follows the assumption that the risk value is decreasing linear with the load capacity. However, this approximation is not suitable for all categories of hazmat. For example when dealing with radioactive materials, the radioactive contamination will not automatically disappear once the cargo is unloaded. The risk model in this approach considers the transportation of petrochemicals. Consequently the linear decreasing risk model is appropriate. The total risk for the HMVRP will be expressed by:

$$\sum_{i \in N} \sum_{j \in N} w_{ij} \times pop_{ij} \quad (1)$$

This risk model is a simplification of the model incorporating the load quantity as a percentage value of the maximum load quantity in regard to the vehicle capacity.

$$\sum_{i \in N} \sum_{j \in N} w_{ij} / Q \times pop_{ij} \quad (2)$$

The arc population weight represents the population at risk for a fully loaded vehicle. Thereby, w_{ij} / Q represent the percentage amount of risk, if the vehicle is not fully loaded. However, the load capacity Q is not decision relevant and can be removed. (2) can serve as a more intuitive performance indicator or be of help when comparing a LD and a LI risk model, but is not necessary for solving the HMVRP.

2.2. Mathematical Modell of the HMVRP

The model in this article is an adaptation of the model proposed by Androutsopoulos and Zografos (2012). The HMVRP is defined on a complete graph $G(N, A)$. The node set

$N = \{0,1,2, \dots n\}$ includes the depot node 0 and the set of customer nodes $C = \{1,2, \dots n\}$. Each customer $i \in C$ has a known demand value d_i and is connected with each other node $j \in C$ by an arc $(i, j) \in A$. Each arc (i, j) represents the direct connections between these nodes and is associated with a length value denoted by l_{ij} as well as risk value representing the population at risk pop_{ij} . The number of vehicles available to serve the customers is denoted by K . All vehicles have the same maximal loading capacity denoted by Q . For solving the problem two types of decision variables are defined:

w_{ij} : amount of hazmat transported on the arc from node i to node j

x_{ij} : $\begin{cases} 1, & \text{if a vehicle uses the arc from node } i \text{ to node } j \\ 0, & \text{otherwise} \end{cases}$

The total distance traveled by all vehicles is represented by Z1 in (3). The total load-dependent population exposure caused by all vehicles is represented by Z2 in (4).

$$Z1 = \sum_{i \in N} \sum_{j \in N} x_{ij} \times l_{ij} \quad (3)$$

$$Z2 = \sum_{i \in N} \sum_{j \in N} w_{ij} \times pop_{ij} \quad (4)$$

The HMVRP is formulated as:

$$Min \begin{Bmatrix} Z1 \\ Z2 \end{Bmatrix} \quad (5)$$

Subject to :

$$\sum_{i \in N} x_{ij} = 1, \forall j \in C \quad (6)$$

$$\sum_{j \in N} x_{ij} = 1, \forall i \in C \quad (7)$$

$$\sum_{i \in N} w_{ij} - \sum_{i \in N} w_{ji} = d_j, \quad \forall j \in C \quad (8)$$

$$w_{ih} - w_{hj} + (1 - x_{ih})M \geq d_h, \quad \forall i, j \in N, \forall h \in C, h \neq i, h \neq j \quad (9)$$

$$w_{i0} = 0, \quad \forall i \in C \quad (10)$$

$$w_{ij} \leq Q \times x_{ij}, \quad \forall i, j \in N \quad (11)$$

$$\sum_{i \in N} x_{0i} \leq K \quad (12)$$

$$w_{ij} \geq 0, \forall i, j \in N \quad (13)$$

$$x_{ij} \in \{0, 1\}, \forall i, j \in N \quad (14)$$

The objective function (5) aims to minimize travel distance as well as risk. (6) and (7) state that each customer node is entered and left only once. (8) ensure the continuity of the load flow and guarantee together with (9) customer satisfaction. Furthermore, (9) prevent the formation of sub tours. (10) assure that each truck returns to the depot empty. (8) together with (9) and (10) guarantee that only the minimum required load quantity to satisfy all customers of a tour is transported by the vehicles and that the initial load of each truck does not exceed this required minimum load quantity. (11) ensure that the maximum loading capacity is not exceeded and that the load can only flow on arcs that are visited by a vehicle. (12) restrict the maximum number of vehicles.

2.3. Solution approach

The single objective standard VRP problem is a NP-hard problem (Domschke and Scholl, 2010), thus the more complex bi-objective HMVRP is also NP-hard. A heuristic solution procedure is recommended to find a good solution in a reasonable amount of time (Laporte et al., 2014). A heuristic approach becomes even more important when a set of multiple solutions is required. In this paper, a hybrid genetic algorithm is proposed to find a set of (heuristically) efficient solutions. The bi-objective conflict is addressed by finding a set of different, non-dominated solutions. The set of non-dominated solutions found by the HGA can then be presented to a decision maker in form of a simple 2 dimensional line graph. To speed up the HGA and to improve the quality of the generated solution set, the following assumptions are made concerning the decision maker:

A decision maker with a strong focus on risk minimization will have little interest in increasing the risk in favor of an economic goal such as cost, distance or travel time. For example, the transportation of nuclear spent fuel is solely driven by the risk minimization aspect. This happens to guarantee the maximum safety of the transportation process and to calm the public opinion. However, a decision maker who is primarily focused on economic goals will tend to only fulfil the legally required minimum to reduce the transportation risk, in order to save money. Especially, the oil industry, and thus the distribution of hazmat like heating oil or gasoline, is a highly competitive market where cost minimization is of great

importance. Thereby, in order to increase the willingness of the decision makers to include risk in their routing decision, it becomes mandatory to show them alternatives that, on the one hand, improve the risk objective considerably, but on the other hand, only worsen the economic aspect as little as possible. Risk reduction, while considering the economic operating boundaries, can generally improve the process quality and the public opinion and indirectly even reduce other economic factors such as compensations in case of an accident or insurance costs.

In this article, the HGA should support the decision maker in case of a heating oil delivery. Consequently, the HGA will focus on finding good solutions regarding the distance value in the initialization phase and then will progress to find good compromise solutions between distance and risk. Additionally, the weights for the fitness function are selected with a strong focus on distance minimization. The test instances used for this article are dealing with the distribution of heating oil. However, the problem as well as the presented solution approach can as well be used for other categories of hazmat, such as hydrogen, butane or gasoline.

3. The hybrid genetic algorithm

3.1. Algorithm overview

Genetic algorithms are part of the population-based algorithms and take their inspiration from the theory of evolution. The first applications date back to the mid-seventies (Holland, 1975). The method of Prins (2004) was one of the first successful adaptations of a genetic algorithm to the VRP (Laporte et al., 2014). In this approach, the solution is represented by a giant tour chromosome without any trip delimiters. The giant tour chromosome is then decoded by a shortest path approach for finding the delimiters of the solution. This procedure is called SPLIT. Vidal et al. (2014) extend the work of Prins (2004) to an unified solution framework. To improve the solution quality, many genetic algorithms incorporate local search components for a more extensive investigation of the local neighborhood. The combination of a simple genetic algorithm and local search procedures is referred as a hybrid genetic algorithm (Laporte et al., 2014). In this paper a giant tour based hybrid-genetic algorithm is adapted to a bi-objective HMVRP with a load-dependent risk model. Figure 3 provides the flowchart of the entire HGA. The chart shows the entire program flow and highlights all the different tasks that the HGA performs during each iteration. A detailed description of the different phases is then provided in the following sections.

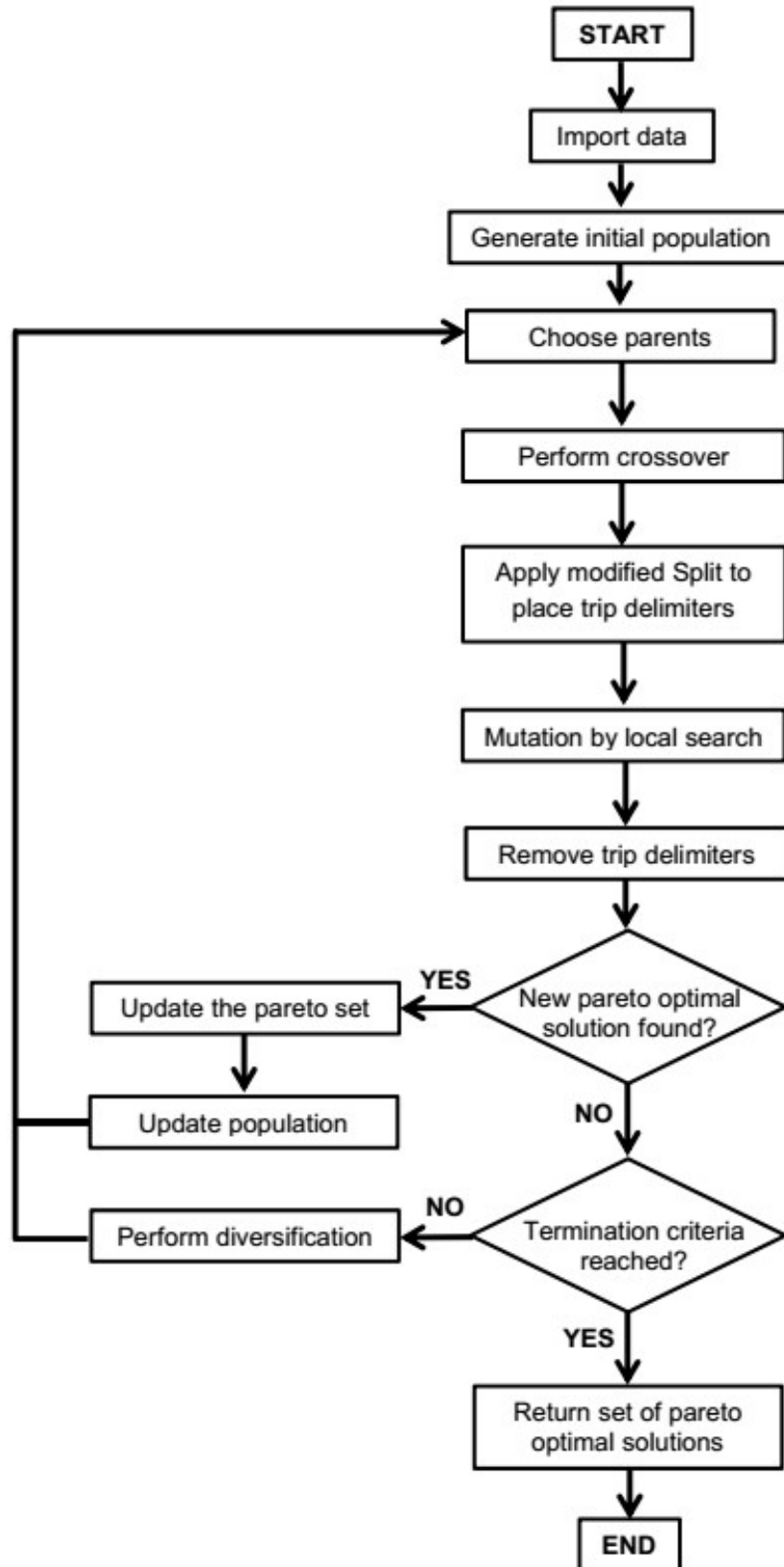


Figure 3 – Flowchart of the Hybrid Genetic Algorithm¹

¹ Note that the HGA in this article is set to stop only after no new pareto optimal solution can be obtained, if another stopping criteria is preferred, the flowchart need to be slightly modified.

3.2. Giant tour chromosome and fitness function

The giant tour chromosome is a simple sequence (permutation) of all client nodes. Trip delimiters, like depot visits or vehicle assignments, are not part of the chromosome. According to Prins (2004), it can be interpreted as the order in which all customers are visited if only one vehicle is used. The length of the chromosomes is thereby always equal to the number of customers. Figure 4 gives an example of a giant tour chromosome with 8 customers. The ranks mark the fixed positions of the chromosome and are necessary for the crossover and the local search phase.

<i>Rank:</i>	1	2	3	4	5	6	7	8
<i>Chromosome:</i>	2	1	3	6	4	5	7	8

Figure 4 - Example of a giant tour chromosome

The fitness function of a solution is defined as the weighted sum of the total risk value and the total distance value. The weights of the two objectives Z1 and Z2 are represented by α_1 and α_2 . The weights are set so that $\alpha_1 + \alpha_2 = 1$. The fitness function is denoted as:

$$fit = \alpha_1 \times Z1 + \alpha_2 \times Z2, \quad \forall \alpha_1, \alpha_2 \geq 0 \quad (15)$$

3.3. Initial population

The initial population is constructed in two steps. In a first step, eight different solutions are constructed by using a simplified version of the greedy algorithm proposed by Holeczek et al. (2018) (a detailed description is provided in the appendix) with different order rules. In a second step, the initial population pool is filled with random but feasible solutions. The random solutions are constructed as follows: First, a random permutation of all customer nodes is generated. Second, the modified SPLIT algorithm is applied and a tour is constructed. Only if a solution is feasible in terms of capacity and vehicle restrictions, the chromosome is added to the parent pool. Furthermore, each chromosome must be different from the other chromosomes. Identical chromosomes are not allowed in the population. This method is repeated until a pool of P parent chromosomes is obtained.

3.4. Parent selection

During each iteration of the algorithm $P/4$ crossovers are performed and each crossover requires two parent chromosomes. The parents are selected according to the tournament selection rule. The deterministic tournament selection is a method where a number of parents are selected from the population pool to participate in a tournament. After the selection, the chromosome with the best fitness value becomes the tournament winner. Then, the tournament winner is selected for the crossover. For each crossover, both parent chromosomes are selected by independent tournaments. The tournament selection is often implemented and allows a simple adjustment of the crossover likelihood by adapting the size of the tournament (Blickle and Thiele, 1996). In this approach the tournament size is set to five participants. Furthermore, only the winner is removed from the current population pool (so that it can only be chosen for one crossover during an iteration) but not the other tournament participants. This helps to reduce the number of identical chromosomes in the new population for the next iteration and to generate child chromosomes with more variety.

3.5. The crossover

An order crossover (OX) was adopted, as recommended by Vidal et al. (2014) for load-dependent problems. Due to the lack of delimiters in the giant tour encoding, all chromosomes have the same length n . This allows an uncomplicated crossover. The OX first select two cutting points i and j to define a subsequence of customers to be inherited by the child chromosome. This subsequence is transferred from the first parent chromosome (P1) to the new child (C1). The missing customers are inserted from the second parent chromosome (P2) starting from position $j+1$ and by preserving the relative order of the customer positions in P2. Figure 5 gives an example of how the OX constructs a child. Two cutting points i and j are randomly selected (here $i=3$ and $j=5$). The subsequence $P1((i) \dots P1(j))$ is then transferred into C1. The missing customers are transferred to C1 from P2 starting from $j+1$ and by preserving the relative order from P2. The circled numbers in Figure 5 indicate the order in which the customers are transferred. By switching the roles of P1 and P2 the second child C2 is constructed. In the here presented approach, the length of the subsequences is chosen at random as an integer number with a minimum of 2 and a maximum of $\lfloor n/2 \rfloor$.

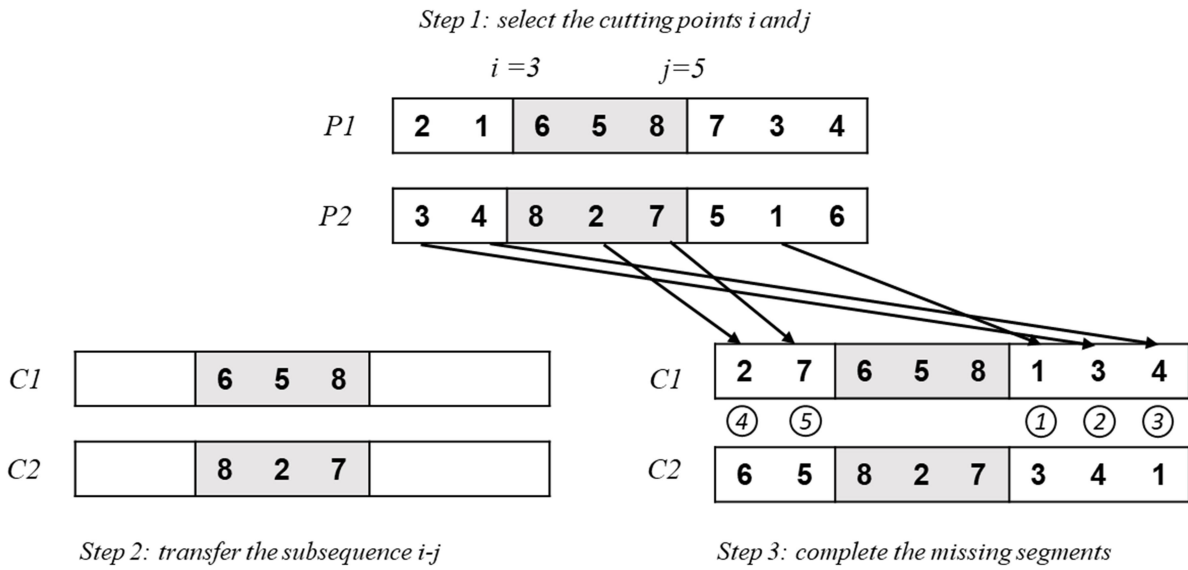


Figure 5 - Example of the OX crossover

3.6. The modified split function

Split, first proposed by Prins (2004) is a splitting procedure, to get the best delimited VRP solution by respecting the sequence of the giant tour chromosome. For any giant tour containing all customers, the splitting problem is considered as a shortest path problem on a directed acyclic auxiliary graph. Vidal et al. (2014) extended the work of Prins (2004) to an unified framework, in the way that split also works when the number of vehicles is restricted. In this approach the split by Prins (2004) is extended by an additional step. If no feasible solution is found due the vehicle restriction, customers that are not assigned to any tour are allocated to the last vehicle. This last step decreases the number of infeasible solution and allows more children to be further investigated by the local search phase. The modified split is applied to each giant tour chromosome (c) by considering the vehicle capacity (Q) and the maximum number of vehicles (K):

The modified Split

Step 1 - For each node j in c , construct a fully loaded tour starting with node j and by adding all consecutive successors of j in c as long as the vehicle capacity constraint is not violated. Calculate the objective function value for the tour by using the fitness function. If all customers of chromosome c have been added to at least one tour without violating the capacity constraint, end Step 1.

Step 2 - Sort all tours constructed in Step 1 in ascending order of their objective function value to a list (*tl*).

Step 3 - Choose the tour from *tl* with the best objective function value, assign it to a selection list (*sl*) and set the vehicle counter (*vc*) to one. Add the objective function value of the selected tour to the total objective function value.

While $vc < K$: choose the next best tour from *tl* that has no common customer nodes with the nodes assigned to *sl* so far and attach the selected tour to *sl*. Add the objective function value of the selected tour to the total objective function value and update the vehicle counter. If all customers have been assigned to *sl*, end the adapted split.

If $vc = K$, and not all customers have been assigned to *sl* yet. Modify the last tour by adding all non-assigned customers to the tour in descending order of the customer demand. Add the last tour to *sl* and add the objective value of the last tour to the total objective value. If the capacity constraint of the last tour is violated before the last customer is assigned, the chromosome is considered as infeasible. If all customers have been assigned to *sl*, end the adapted split.

After the split procedure, the giant tour chromosome becomes a chromosome containing the client nodes and the depot nodes that are working as trip delimiters. Figure 6 shows an example of the tour chromosome with “0” (representing the depot node) as trip delimiter.

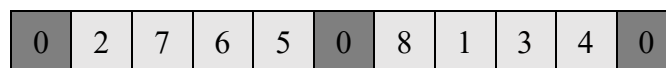


Figure 6 - Tour chromosome with delimiters

3.7. Mutation by local search

In classical genetic algorithms the mutation phase often consists of few simple moves such as inserting and swapping some nodes. However, for vehicle routing problems the performance can be improved by replacing the simple mutation by a local search procedure (LS) (Prins, 2004). The HGA in this article replaces the mutation phase by a LS. The LS is performed after the insertion of the trip delimiters. Each child resulting from the OX crossover is improved by the LS. The different simple local search procedures proposed by Prins (2004) are tested. A combination between a simple insertion-based local search and a double swap local search provided the best results regarding the solution quality and runtime.

Each iteration of the local search examines all possible pairs of distinct nodes $(i; j)$, from a chromosome with trip delimiters cd , with x and y being the successors of i and j in their respective trips. These nodes might belong to different trips or the same trip. The local search phase is performed for each child chromosome:

Local search phase

Step 1 - For all possible pairs of distinct nodes $(i; j)$: If i is a customer node, remove i then insert it after j . After each insertion calculate the fitness function value. If the new fitness value is better than the current best fitness value of the child, immediately update fitness value and the cd and restart *Step 1*.

Step 2 - For all possible pairs of distinct nodes $(i; j)$ and $(x; y)$: If $(i; x)$ and $(j; y)$ are customer nodes, swap $(i; x)$ and $(j; y)$. After each swap calculate the fitness function value. If the new fitness value is better than the current best fitness value of the child chromosome, immediately update fitness value and the cd and return to *Step 1*.

3.8. Update population, perform diversification and update pareto set

After each iteration the pareto set and the population pool are updated. To speed up the search for a suitable pareto front a separated set of all non-dominated solutions is kept. This set is independent from the population pool. The parent chromosomes of the first generation and all newly generated children are checked for pareto optimality. This check is independent from the fitness value of a child and only considers the solution values of travelled distance and risk. If a new non-dominated solution is found at the end of the local search phase, it is added to the pareto set. If a new solution dominates one or more existing solutions, the dominated solutions are removed from the set.

If a new solution was added to the pareto set during an iteration, then a normal population update is performed. The new population consists of the parent chromosomes selected by the tournament method and their children. To guarantee the diversity, the fitness value and the objective function values for distance and risk are checked and identical chromosomes are removed. In addition, it is guaranteed that the best known solution is kept in the population pool. If the population pool is missing individuals, new feasible parents are generated randomly to fill the pool.

If after an iteration no new pareto optimal solution is found, a diversification phase is initiated (Vidal et al., 2014). In this phase only the 35% best chromosomes from the parent pool are kept and the remaining individuals are replaced by new randomly generated solutions. This diversification phase introduces new genetic material to the parent pool.

In addition, after each iteration the weights of fitness function α_1 and α_2 can be adapted. An adjustment of the weights leads to a more extensive investigation of the pareto front and can be of interest when the decision maker has no clear preference.

4. Experimental outcomes

4.1. Test instances

A major problem when dealing with the HMVRP is the lack of benchmark instances. Adapting existing VRP instances by adding a risk dimension leads to an unrealistic assessment of risk values (Holeczek, 2019). This becomes even more important when dealing with the peculiarities of an urban area, due to the strong variation in the population density. In this article the HMVRP test instances are based on realistic but random generated networks and have been created by using a two-step approach.

In a first step, a realistic urban transportation network has been generated by using a network generator especially developed for hazmat transportation networks. For this purpose, the road networks suitable for hazmat transportation of the Bavarian city of Munich and some other smaller Bavarian cities were analyzed and evaluated. Based on the pattern of this evaluation, the generator is able to create realistic transportation networks. These networks include highways, motorways and city road segments all distributed according to a realistic pattern. Additionally, inner city regions are placed in the networks for a more realistic distribution of population values. These regions contain a higher population density and also a denser road network than the rest of the network. Each network contains a given number of weighted, undirected arcs representing road segments (suitable for hazmat transportation) and a given number of nodes representing intersections and crossroads of the transportation network. From all nodes, a subset of nodes is selected marking the locations of the customers and the depot. While the depot node is always located in the outskirts region of the network, customer nodes are distributed randomly all over the network.

In a second step, a Floyd-Warshall algorithm (Floyd, 1962) was used to find the best connections between all customer nodes and the depot node. This resulted in a value matrix containing the distance as well as the risk values for all direct connections. These are used for the parameters in the mathematical model.

The test instances are dealing with the distribution of heating oil in an urban area. The strong fluctuation of the oil price has a direct impact on the petrochemical market. Depending on the current price and season, customer demand can vary strongly. Therefore, the test instances are generated with a size ranging from 13 up to 40 customers. The demand value for each customer is generated based on real demand values. The minimum order quantity requires 600 liter, the average demand value is 2,500 liters and the maximum order quantity equals to 20,000 liters, which corresponds to the maximum vehicle capacity (Q).

For all problem instances the fleet size is restricted and is varying between 2 and 5 vehicles. The restricted fleet size K is calculated as the rounded up quotient of the sum of the customer demand values d_i divided by the vehicle capacity (Q), so that:

$$K = \left\lceil \frac{\sum_{i \in C} d_i}{Q} \right\rceil \quad (16)$$

All HMVRP test instances used in this article can be found under <https://git.io/JfTvh>.

4.2. Results of the experiments

The HGA has been implemented in Python 3.7 and executed on a Core i5-6600K with 8 GB of ram and a Microsoft Windows10 64-bit operating system. For the test results, the HGA has been run 20 times for each test instance. As termination criteria the algorithm was set to stop after three consecutive iterations where no new pareto optimal solution was found. The weights for the fitness function are not altered during an execution. The weights have been selected according to the assumption made in section 2.3 concerning the decision maker. The weights are unstandardized and selected with $\alpha_1 = 0.998$ and $\alpha_2 = 0.002$.

To check the quality of the results found by the HGA, the optimal distance values (ZI) for all instances were calculated with the CPLEX solver. To guarantee that the solutions found by CPLEX are pareto optimal, a lexicographic approach with risk minimization as second goal has been used. Different settings for the population pool were tested, including 20, 30, 40 and 50 parents. A pool size of 40 parent chromosomes proved to be the most reliable considering the number of pareto optimal solutions and runtime.

Table 2 shows the average results of the HGA after being executed 20 times for each test instance. For all instances the average deviation from the optimal distance value is less than 2%. The strong performance regarding the optimal distance value is guaranteed through the greedy approach in the initialization phase. This reliability is important for the decision maker who is primarily focused on an economic goal. The decision process can be supported when the decision maker knows the best value for the distance and in consequence can focus on the tradeoff between cost and risk.

The HGA's runtime offers possibilities for further improvement. However, each run returns between 3 and 8 non-dominated solutions, making the HGA way more effective than computing multiple solution points with the CPLEX solver.

Table 2 - HGA results

Instance	Number of customers	Avg. deviation from the optimal distance value	Avg. number of pareto optimal solutions	Avg. runtime in seconds
S1	13	0.0%	4.4	35
S2	15	<0.1%	5.2	64
S3	16	<0.1%	4.8	66
S4	18	<0.1%	4.1	72
S5	20	<0.1%	3.8	87
S6	22	<1.6%	4.4	101
S7	25	<0.1%	5.1	138
S8	30	<1.2%	5.3	186
S9	35	<1.3%	4.4	234
S10	40	<1.9%	5.2	275

The main goal for the HGA is to support a decision maker responsible for the distribution of hazmat. The different non-dominated solutions found by the HGA can be presented to the decision maker in form of a simple 2 dimensional graph. To provide an illustrate example, the tradeoff line of instance is S7 is presented in Figure 7. For the example, the HGA was run multiple times with different weight settings to provide a more illustrative example of the tradeoff line.

In addition, to show the difference between a load-dependent and a load-independent risk model, the same problem instance was solved with a LI risk model. The pareto fronts of both models are presented in Figure 7 and Figure 8. Each pareto front contains the heuristic efficient solutions found by the HGA. Additionally, the corner points of the pareto fronts were verified with the CPLEX solver.

Figure 7 shows the pareto front with the LD risk model. When using the LD risk model, an improvement in risk can be achieved quickly with only a small deviation from the optimal distance value. In some scenarios, risk can simply be improved by changing only the order of a few customers with high demand value. An early reduction of the load quantity consequently has a positive effect on the risk dimension for the remaining tour.

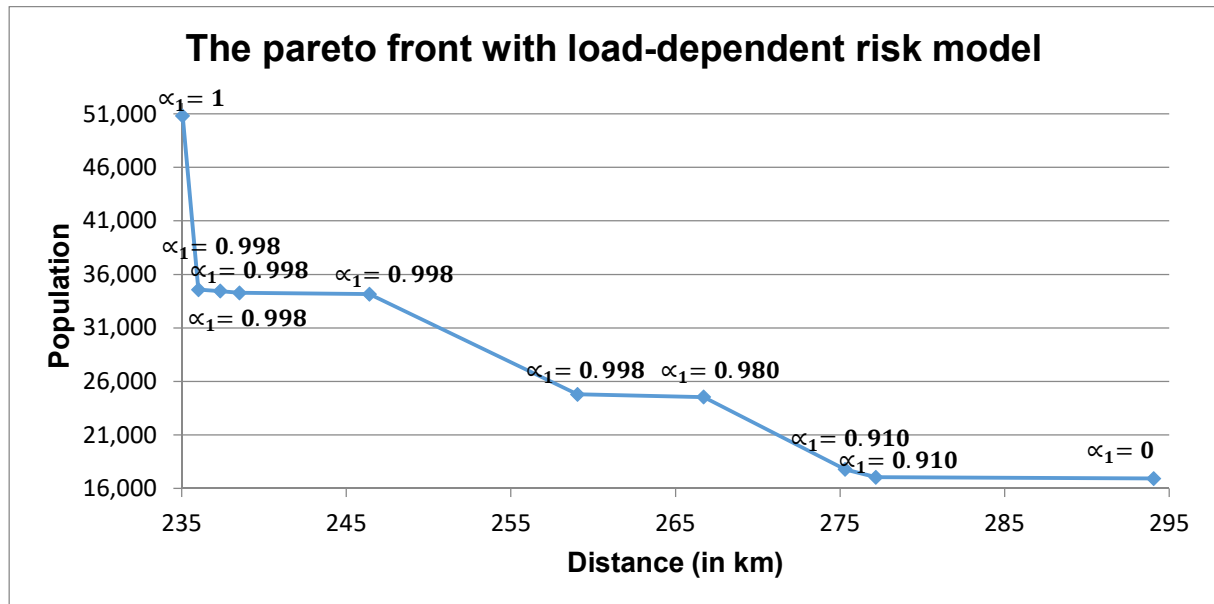


Figure 7 - Example with load-dependent risk model

Figure 8 shows the pareto front with the LI risk model. The LI risk model does not include the vehicle load and thus accounts the risk (in form of population exposure) for all arcs as if a fully loaded vehicle would be used. This includes the return trip to the depot of an empty vehicle. Consequently, the overall population exposure is way higher than with the LD risk model. The trade-off between risk and cost is more linear with the LI risk model than with the LD risk model. For achieving the same amount of risk reduction as with the LD risk model, a much larger trade-off regarding the distance is necessary.

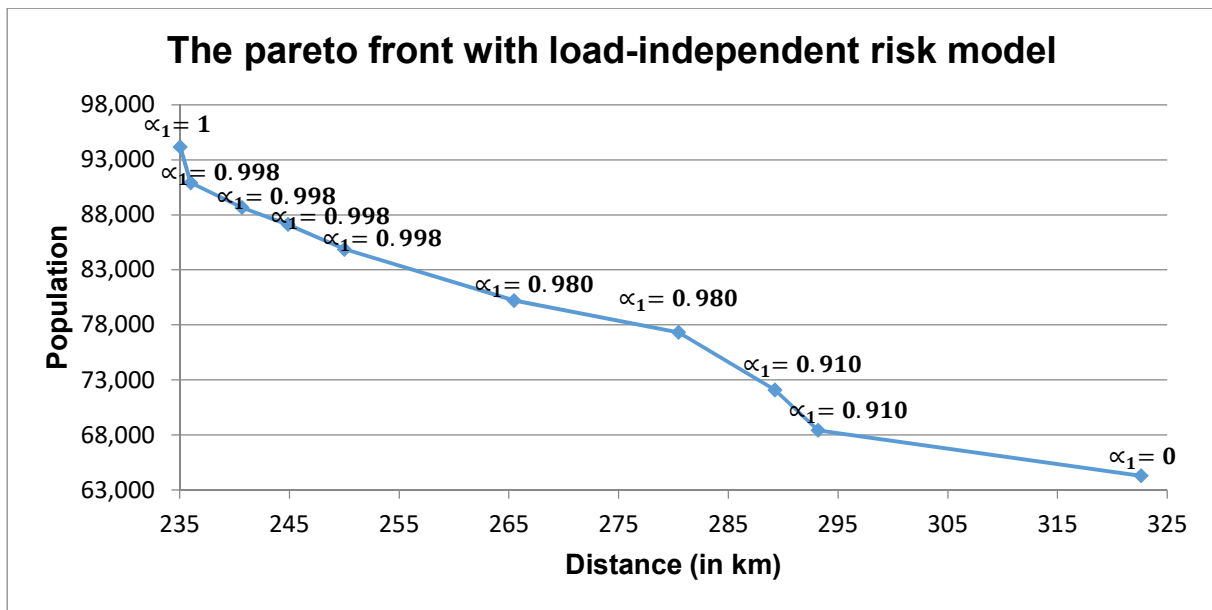


Figure 8 - Example with load-independent risk model

The comparison between both risk models shows that the LD risk model allows a more precise approach and is therefore better suited for the HMVRP. In addition, the economically motivated decision maker can easier be convinced to incorporate risk into his routing decision, when the tradeoff between risk and distance is better.

Table 3 shows some compromise solutions and their tradeoff between distance and population. The solutions are selected to represent a good tradeoff corresponding to the preferences of the decision maker described above. To improve the risk objective considerably while only worsen the distance objective as little as possible.

The distance value represents the combined distance travelled by the entire fleet to serve all customers and to return to the depot. The population value represents the total number of people in the immediate danger zone during the entire distribution process. The left section of the Table 3 represents the optimal solution values when distance only is minimized. These values were calculated exactly with the CPLEX solver. The middle section of Table 3 shows a good compromise solution found by the HGA for each problem instance. The compromise is determined by choosing a solution with a strong risk reduction and only a little increase in distance. The exact tradeoff in percent is shown in the right section of Table 3. It can be observed that with a small sacrifice in terms of distance a huge improvement in terms of population exposure can be achieved for all problem instances. In average a 2.4% increase in distance can reduce the population at risk by 37%.

Table 3 - Good compromise solutions found by the HGA

Instance	Optimal values for distance minimization		Good compromise solution values found		Tradeoff in percent	
	Distance (in km)	Population	Distance (in km)	Population	Distance	Population
S1	138.72	24,384	142.20	13,099	2.5%	-46.3%
S2	196.43	31,332	200.84	18,053	2.2%	-42.4%
S3	178.55	38,593	184.84	18,543	3.5%	-51.9%
S4	179.84	35,388	183.81	25,259	2.2%	-28.6%
S5	211.50	20,854	215.05	17,428	1.7%	-16.4%
S6	239.34	40,389	243.11	23,102	1.6%	-42.8%
S7	221.21	34,437	233.49	23,641	5.5%	-31.3%
S8	276.73	30,793	281.62	18,343	1.8%	-40.4%
S9	235.05	50,814	236.05	34,573	1.0%	-31.2%
S10	351.23	56,718	361.78	35,158	3.0%	-38.0%
Average					2.4%	-37.0%

5. Conclusions

This paper investigates the bi-objective HMVRP with a load-dependent risk model. A hybrid genetic algorithm is proposed to solve the problem and to find a set of pareto optimal solutions. The concept of the algorithm and its different components are explained. Multiple test instances dealing with the distributions of hazardous materials in an urban area are solved by the HGA.

The experimental outcomes show that including a load-dependent risk model, even with a very low weighting for the risk goal, can improve the safety of the transportation process. A severe risk reduction in terms of population exposure is possible with only a small increase in travel distance. The visualization of the pareto front of the bi-objective problem shows that the LD risk models, due to the exponential decrease of the risk value, allows a better trade-off between risk and distance than the LI risk model. Not only is the LD risk model more accurate for the HMVRP but also more suitable when dealing with the tradeoff between distance and risk. Especially, when dealing with the decision maker who is strongly focused on an economical goal, the LD risk model is more persuasive.

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Appendix

The Greedy method by Holeczek et al. 2018

The heuristic algorithm consists of an initialization phase and a customer list based improvement phase. In the initialization phase, a first solution is generated by using sorted customers and a greedy method for assigning customers to vehicles.

Phase 1: Initialization

Select an ordering rule and set the number of iterations for the customer list based improvement phase. Sort the customers according to the chosen ordering rule and add them to a customer list (Co). Construct an initial feasible solution using the customer greedy method. If no feasible solution is possible with the initial customer list, sort the customers in descending order of their demand and apply the customer greedy method. If this does not yield a feasible solution, stop and analyze the problem data. Initialize the best solution with the solution found and the best customer order with the corresponding customer order.

Customer Greedy Method:

Step 1: Select the first customer from the customer list Co .

Step 2: Sort all vehicles to a temporary vehicle list (Vl) in ascending order of the distance from the last customer served by the vehicle (or depot if the vehicle is still unused) to the selected customer.

Step 3: Select the first vehicle in the vehicle order list.

Step 4: If the vehicle has enough load capacity for serving the selected customer, assign the customer to the selected vehicle and update the vehicle load. Select the next customer in Co and return to *Step 2*.

Step 5: If the customer demand exceeds the vehicle capacity, select the next vehicle in Vl and return to *Step 4*.

In the customer list based improvement phase for finding better solutions first a shift phase in which each customer is inserted in all other possible positions is applied to the initial customer order. After the shift phase, a swap phase is performed in which each customer is swapped with all other customers. Each time a better feasible solution is found, the customer order is updated immediately.

Phase 2: Customer List Based Improvement

Step 1: Shift each customer to each other possible position in Co . After each shift construct a new solution using the customer greedy method. If a new best solution is found, immediately update the best solution and the Co .

Step 2: Swap each customer with each other customer in Co . After each swap construct a new solution using the customer greedy method. If a new best solution is found, immediately update the best solution and the Co .

Step 3: Convert the Co from the best solution to a giant tour chromosome by applying the modified split function and calculate the risk, the distance and the fitness value.

The different sorting rules for the greedy method:

1. Order by ascending distance from the customers to the depot.
2. Order by and descending distance from the customers to the depot.
3. Order by ascending customer demand (load) value.
4. Order by and descending customer demand (load) value.
5. Order by ascending distance to the depot divided by customer demand value.
6. Order by and descending distance to the depot divided by customer demand value.
7. Order by ascending risk from the customers to the depot.
8. Order by and descending risk from the customers to the depot.

Appendix A: Results of Study 2

The following table contains the results of study 2, section 5.2. Table A1 shows the results found by the heuristic for the test instance N1_30, N1_40, N2_30 and N2_40. For each problem instance (inst), four different value matrices are created by applying a shortest paths approach with four different objective functions. The different objective functions are the minimization of the total distance traveled (Dist), the minimization of the total population at risk (Pop), the minimization of the total accident probability (AP), and the minimization of the traditional risk value (Risk). The matrices served as basis for the capacitated hazardous materials vehicle routing problem (CHMVRP). For each value matrix the CHMVRP was solved by using the presented heuristic algorithm. The algorithm has been applied four times on each matrix, each time satisfying another one of the four objective functions mentioned above. The tables present a detailed overview over the results obtained for all combinations of objective functions in the two phases of the solution approach, as well as the percentage of deviation from the best object value (DFO) found over all matrices.

Table A1 – Results found by the heuristic for instance N1 with 30 customers

Inst	Matrix		Objective Min. Distance	DFO %	Objective Min. Population	DFO %	Objective Min. AP	DFO %	Objective Min. Risk	DFO %
N1-30c	Dist Matrix	Distance (km)	279.46	0.00	287.23	2.78	296.06	5.94	318.20	13.86
		Population	55,433	30.10	46,142	8.30	47,095	10.53	46,851	9.96
		AP (*10E-5)	6.19	19.04	5.62	8.08	5.55	6.73	5.80	11.54
		Risk (*10E-3)	16.65	70.25	11.97	22.39	11.74	20.04	11.10	13.50
	Pop Matrix	Distance (km)	297.92	6.61	315.17	12.78	300.36	7.48	315.17	12.78
		Population	45,749	7.37	42,607	0.00	43,733	2.64	42,607	0.00
		AP (*10E-5)	5.87	12.88	5.67	9.04	5.51	5.96	5.67	9.04
		Risk (*10E-3)	11.96	22.29	9.84	0.61	10.47	7.06	9.84	0.61
	AP Matrix	Distance (km)	291.52	4.32	307.40	10.00	301.89	8.03	312.10	11.68
		Population	50,807	19.25	47,487	11.45	48,712	14.33	47,560	11.62
		AP (*10E-5)	5.32	2.31	5.35	2.88	5.20	0.00	5.33	2.50
		Risk (*10E-3)	12.70	29.90	10.88	11.25	11.37	16.26	10.58	8.18
	Risk Matrix	Distance (km)	312.37	11.78	316.75	13.34	308.33	10.33	323.64	15.81
		Population	43,175	1.33	43,114	1.19	43,649	2.45	44,060	3.41
		AP (*10E-5)	5.46	5.00	5.54	6.54	5.51	5.96	5.50	5.77
		Risk (*10E-3)	9.94	1.64	9.90	1.23	10.30	5.32	9.78	0.00

Table A1. (continued)

Inst	Matrix		Objective Min. Distance	DFO %	Objective Min. Population	DFO %	Objective Min. AP	DFO %	Objective Min. Risk	DFO %
N1-40c	Dist Matrix	Distance (km)	331.60	0.00	381.75	15.12	346.74	4.57	381.75	15.12
Population		74,100	35.76	59,153	8.38	60,615	11.06	59,153	8.38	
AP (*10E-5)		7.83	26.49	6.93	11.95	6.67	7.75	6.93	11.95	
Risk (*10E-3)		23.62	76.66	14.75	10.32	16.45	23.04	14.75	10.32	
Pop Matrix	Distance (km)	345.16	4.09	354.95	7.04	353.83	6.70	363.75	9.70	
	Population	64,088	17.42	54,579	0.00	54,834	0.47	54,855	0.50	
	AP (*10E-5)	7.35	18.74	6.53	5.49	6.43	3.88	6.51	5.17	
	Risk (*10E-3)	20.54	53.63	13.70	2.47	13.83	3.44	13.49	0.90	
AP Matrix	Distance (km)	356.66	7.56	361.20	8.93	360.12	8.60	370.18	11.63	
	Population	65,355	19.74	57,055	4.53	57,758	5.82	58,034	6.33	
	AP (*10E-5)	6.71	8.40	6.31	1.94	6.19	0.00	6.35	2.58	
	Risk (*10E-3)	17.58	31.49	13.98	4.56	13.96	4.41	13.70	2.47	
Risk Matrix	Distance (km)	355.65	7.25	364.74	9.99	362.86	9.43	362.86	9.43	
	Population	62,773	15.01	54,964	0.70	54,991	0.75	54,991	0.75	
	AP (*10E-5)	7.00	13.09	6.45	4.20	6.39	3.23	6.39	3.23	
	Risk (*10E-3)	17.41	30.22	13.41	0.30	13.37	0.00	13.37	0.00	
N2-30c	Dist Matrix	Distance (km)	276.90	0.00	322.27	16.38	281.95	1.82	322.27	16.38
Population		69,163	45.89	50,929	7.43	61,067	28.81	50,929	7.43	
AP (*10E-5)		6.79	15.87	6.61	12.80	6.30	7.51	6.61	12.80	
Risk (*10E-3)		24.61	76.29	15.48	10.89	20.45	46.49	15.48	10.89	
Pop Matrix	Distance (km)	288.67	4.25	323.66	16.89	309.92	11.92	323.66	16.89	
	Population	52,480	10.70	47,407	0.00	48,523	2.35	47,407	0.00	
	AP (*10E-5)	6.22	6.14	6.62	12.97	6.16	5.12	6.62	12.97	
	Risk (*10E-3)	17.05	22.13	14.45	3.51	14.49	3.80	14.45	3.51	
AP Matrix	Distance (km)	296.62	7.12	317.65	14.72	311.16	12.37	345.76	24.87	
	Population	57,265	20.79	50,023	5.52	54,440	14.84	51,223	8.05	
	AP (*10E-5)	5.95	1.54	5.88	0.34	5.86	0.00	6.23	6.31	
	Risk (*10E-3)	17.81	27.58	14.63	4.80	16.14	15.62	14.29	2.36	
Risk Matrix	Distance (km)	315.35	13.89	318.84	15.15	318.34	14.97	341.28	23.25	
	Population	56,462	19.10	47,799	0.83	50,030	5.53	49,467	4.35	
	AP (*10E-5)	6.45	10.07	6.07	3.58	6.04	3.07	6.30	7.51	
	Risk (*10E-3)	17.80	27.51	14.23	1.93	14.99	7.38	13.96	0.00	
N2-40c	Dist Matrix	Distance (km)	347.40	0.00	392.20	12.90	392.20	12.90	430.00	23.78
Population		103,244	61.99	68,492	7.47	68,492	7.47	69,511	9.06	

Table A1. (continued)

Inst	Matrix		Objective Min. Distance	DFO %	Objective Min. Population	DFO %	Objective Min. AP	DFO %	Objective Min. Risk	DFO %
		AP (*10E-5)	9.13	26.81	7.70	6.94	7.70	6.94	8.03	11.53
		Risk (*10E-3)	39.30	104.79	21.25	10.73	21.25	10.73	20.58	7.24
	Pop Matrix	Distance (km)	398.37	14.67	403.02	16.01	403.02	16.01	409.11	17.76
		Population	78,293	22.84	64,344	0.96	64,344	0.96	65,158	2.23
		AP (*10E-5)	8.42	16.94	7.66	6.39	7.66	6.39	7.67	6.53
		Risk (*10E-3)	26.33	37.21	19.67	2.50	19.67	2.50	19.46	1.41
	AP Matrix	Distance (km)	387.95	11.67	394.76	13.63	394.76	13.63	411.12	18.34
		Population	83,400	30.86	65,264	2.40	65,264	2.40	65,617	2.95
		AP (*10E-5)	8.16	13.33	7.20	0.00	7.20	0.00	7.30	1.39
		Risk (*10E-3)	28.33	47.63	19.78	3.07	19.78	3.07	20.32	5.89
	Risk Matrix	Distance (km)	403.90	16.26	411.01	18.31	411.01	18.31	411.01	18.31
		Population	74,207	16.43	63,734	0.00	63,734	0.00	63,734	0.00
		AP (*10E-5)	7.91	9.86	7.56	5.00	7.56	5.00	7.56	5.00
		Risk (*10E-3)	23.53	22.62	19.19	0.00	19.19	0.00	19.19	0.00

Appendix B: Results of Study 3

The following tables contain the results of study 3.

For each problem instance (inst), four different value matrices are created by applying a shortest paths approach with four different objective functions. The different objective functions are the minimization of the total distance traveled (Dist), the minimization of the total population at risk (Pop), the minimization of the total accident probability (AP), and the minimization of the traditional risk value (Risk). The matrices served as basis for the hazardous materials vehicle routing problem (HMVRP). For each value matrix the HMVRP was solved in GAMS using the CPLEX solver. For each matrix the problem was solved seven times, each time satisfying another objective function. The different objective functions are the minimization of the total distance traveled (Dist), the minimization of the load-dependent population value (LD-Pop), the minimization of the load-independent population value (LI-Pop), the minimization of the load-dependent traditional risk value (LD-Risk), the minimization of the load-independent traditional risk value (LI-Risk), the minimization of the load-dependent accident probability value (LD-AP), the minimization of the load-independent accident probability value (LI-AP). Table B1 contains the results for the instances when the number of vehicles was restricted. Table B2 contains the results when the number is not restricted. Table B3 show how the LD risk value alters when the fleet size is increases one by one.

Table B1 – Results found by the CPLEX solver with restricted number of vehicles

Inst	Matrix		Objective Min Dist.	Objective Min LD-Pop	Objective Min LI-Pop	Objective Min LD-Risk	Objective Min LI-Risk	Objective Min LD-AP	Objective Min LI-AP
N1-i1 13c	Dist. Matrix	Distance	160.02	203.31	169.81	203.31	227.99	164.34	165.72
		LD-Pop	18,983.90	11,110.85	18,150.13	11,110.85	18,034.68	14,405.86	13,979.14
		LI-Pop	51,931.07	58,653.47	38,530.76	58,653.47	38,681.39	50,407.89	40,538.42
		LD-Risk	1,363.55	415.26	1,443.42	415.26	930.51	1,025.92	1,001.30
		LI-Risk	4,565.31	5,177.96	2,836.72	5,177.96	2,092.75	4,542.33	3,262.59
		LD-AP	1.63	1.45	1.52	1.45	2.07	1.31	1.33
		LI-AP	3.97	4.86	3.55	4.86	4.29	3.88	3.52
	Vehicles	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
	Pop Matrix	Distance	214.02	235.79	219.62	235.79	220.42	235.79	219.62
		LD-Pop	18,424.43	10,157.13	15,612.96	10,157.13	20,443.04	10,157.13	15,125.49
		LI-Pop	40,445.92	40,060.24	36,534.55	40,060.24	36,550.07	40,060.24	36,534.55
		LD-Risk	1,060.78	372.35	660.80	372.35	1,294.15	372.35	641.54
		LI-Risk	2,435.35	2,237.92	2,004.53	2,237.92	1,988.76	2,237.92	2,004.53
		LD-AP	1.96	1.40	2.01	1.40	2.03	1.40	1.93
		LI-AP	4.25	4.38	4.08	4.38	4.08	4.38	4.08
	Vehicles	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00

Table B1. (continued)

Inst	Matrix		Objective Min Dist.	Objective Min LD-Pop	Objective Min LI-Pop	Objective Min LD-Risk	Objective Min LI-Risk	Objective Min LD-AP	Objective Min LI-AP
	Risk Matrix	Distance	239.02	260.40	239.02	260.40	239.14	260.40	239.14
		LD-Pop	20,002.90	11,148.80	20,945.65	11,148.80	14,137.30	11,148.80	22,000.22
		LI-Pop	38,671.88	43,288.82	38,671.88	43,288.82	39,034.17	43,288.82	39,034.17
		LD-Risk	1,055.00	360.42	1,079.09	360.42	558.95	360.42	1,272.05
		LI-Risk	1,968.17	2,184.49	1,968.17	2,184.49	1,967.40	2,184.49	1,967.40
		LD-AP	2.03	1.41	2.15	1.41	1.61	1.41	2.11
		LI-AP	4.07	4.43	4.07	4.43	4.05	4.43	4.05
	Vehicles	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
	AP Matrix	Distance	162.57	212.39	224.98	212.39	231.47	198.81	174.34
		LD-Pop	18,357.19	11,125.41	20,536.94	11,125.41	20,560.13	11,785.25	14,781.65
		LI-Pop	50,009.13	41,296.90	37,714.18	41,296.90	38,446.34	46,177.60	39,613.28
		LD-Risk	1,270.30	379.06	1,258.80	379.06	1,251.36	619.89	994.67
		LI-Risk	4,355.26	2,985.30	1,976.30	2,985.30	1,971.30	3,846.53	2,811.98
		LD-AP	1.59	1.41	1.99	1.41	1.98	1.30	1.30
LI-AP		3.86	4.10	4.01	4.10	4.02	4.17	3.42	
Vehicles	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	
N1-i2 13c	Dist. Matrix	Distance	139.82	176.45	161.26	200.52	206.46	156.82	155.15
		LD-Pop	26,355.84	6,872.24	18,968.24	7,384.40	9,858.52	7,267.24	9,127.16
		LI-Pop	43,942.20	40,025.29	30,990.73	34,300.33	33,698.55	45,920.73	31,558.33
		LD-Risk	2,459.12	293.94	1,197.53	222.71	297.77	373.69	354.93
		LI-Risk	3,885.00	2,990.99	1,637.56	1,608.99	1,585.62	3,497.37	1,661.95
		LD-AP	1.85	0.91	1.66	1.00	1.36	0.81	0.95
		LI-AP	3.37	3.78	3.20	3.79	3.85	3.66	3.10
	Vehicles	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
	Pop Matrix	Distance	163.01	181.88	163.01	200.37	165.35	181.88	163.01
		LD-Pop	7,478.64	5,794.51	7,728.94	6,216.97	17,263.37	5,794.51	17,310.07
		LI-Pop	27,986.36	30,922.61	27,986.36	32,767.50	28,252.84	30,922.61	27,986.36
		LD-Risk	273.11	189.47	279.43	182.20	1,022.95	189.47	1,028.97
		LI-Risk	1,403.85	1,542.93	1,403.85	1,559.69	1,398.58	1,542.93	1,403.85
		LD-AP	0.91	0.78	0.94	0.83	1.71	0.78	1.73
		LI-AP	3.06	3.48	3.06	3.71	3.11	3.48	3.06
	Vehicles	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
	Risk Matrix	Distance	167.67	210.25	167.67	228.18	170.25	210.25	167.67
		LD-Pop	17,140.38	6,087.13	16,769.93	6,378.80	8,178.91	6,087.13	8,027.56
		LI-Pop	29,047.13	32,717.04	29,047.13	35,098.47	29,275.15	32,717.04	29,047.13
		LD-Risk	994.70	179.84	985.93	176.82	277.85	179.84	280.05
		LI-Risk	1,388.65	1,500.11	1,388.65	1,521.25	1,384.60	1,500.11	1,388.65
		LD-AP	1.59	0.75	1.54	0.79	0.97	0.75	0.93
		LI-AP	3.01	3.67	3.01	3.89	3.07	3.67	3.01
	Vehicles	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
	AP Matrix	Distance	146.97	182.86	162.95	209.85	184.17	169.33	162.95
		LD-Pop	12,098.51	6,372.53	8,441.47	6,811.74	8,978.76	6,476.08	8,191.17
		LI-Pop	39,231.24	35,760.91	30,607.11	36,055.87	31,553.68	35,479.60	30,607.11
		LD-Risk	1,060.97	222.23	289.16	193.25	297.42	243.66	282.84
LI-Risk		3,736.74	2,007.82	1,467.80	1,633.24	1,433.79	2,066.83	1,467.80	
LD-AP		1.06	0.74	0.91	0.82	1.05	0.72	0.87	
LI-AP		3.11	3.50	2.91	3.77	3.26	3.22	2.91	
Vehicles	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	
N1-i3 15c	Dist. Matrix	Distance	140.48	150.67	140.48	150.97	150.63	150.67	140.55
		LD-Pop	18,527.87	6,953.37	18,666.03	7,131.80	19,302.26	6,953.37	19,191.84
		LI-Pop	33,062.43	42,421.67	33,062.43	42,574.58	35,124.73	42,421.67	33,275.81
		LD-Risk	1,497.91	362.36	1,502.23	360.46	1,468.14	362.36	1,511.86
		LI-Risk	2,430.26	3,015.40	2,430.26	3,011.28	2,419.57	3,015.40	2,430.27
		LD-AP	1.58	0.69	1.60	0.71	1.64	0.69	1.65

Table B1. (continued)

Inst	Matrix		Objective Min Dist.	Objective Min LD-Pop	Objective Min LI-Pop	Objective Min LD-Risk	Objective Min LI-Risk	Objective Min LD-AP	Objective Min LI-AP	
		LI-AP	2.90	3.51	2.90	3.53	3.07	3.51	2.90	
		Vehicles	2.00	2.00	2.00	2.00	2.00	2.00	2.00	
	Pop Matrix	Distance	143.55	171.25	143.55	203.61	143.55	171.25	143.55	
		LD-Pop	12,001.29	6,929.17	12,001.29	7,709.65	12,077.17	6,929.17	12,329.96	
		LI-Pop	32,680.59	35,230.68	32,680.59	41,190.38	32,680.59	35,230.68	32,680.59	
		LD-Risk	836.74	359.60	836.74	331.99	837.14	359.60	844.25	
		LI-Risk	2,390.77	2,517.18	2,390.77	2,667.86	2,390.77	2,517.18	2,390.77	
		LD-AP	1.05	0.69	1.05	0.82	1.06	0.69	1.10	
		LI-AP	2.92	3.33	2.92	3.83	2.92	3.33	2.92	
		Vehicles	2.00	2.00	2.00	2.00	2.00	2.00	2.00	
	Risk Matrix	Distance	169.28	187.71	169.53	229.62	174.31	187.71	169.64	
		LD-Pop	20,900.70	7,998.47	20,845.90	8,516.45	14,063.57	8,728.69	20,982.75	
		LI-Pop	36,263.60	37,938.84	36,080.87	45,855.04	36,695.21	37,938.84	36,443.16	
		LD-Risk	1,436.65	365.52	1,437.30	306.98	772.86	422.31	1,435.69	
		LI-Risk	2,270.29	2,404.50	2,270.18	2,489.41	2,267.11	2,404.50	2,269.41	
		LD-AP	1.80	0.79	1.81	0.86	1.24	0.75	1.79	
		LI-AP	3.16	3.40	3.17	4.01	3.18	3.40	3.16	
		Vehicles	2.00	2.00	2.00	2.00	2.00	2.00	2.00	
	AP Matrix	Distance	142.44	171.23	142.44	201.40	142.80	171.23	142.80	
		LD-Pop	19,661.64	7,082.84	12,713.53	8,469.70	20,891.51	7,082.84	11,769.61	
		LI-Pop	34,468.75	36,274.24	34,468.75	43,611.47	34,648.31	36,274.24	34,648.31	
		LD-Risk	1,531.48	361.58	862.48	336.39	1,555.30	361.58	840.73	
		LI-Risk	2,472.13	2,549.93	2,472.13	2,632.12	2,471.25	2,549.93	2,471.25	
		LD-AP	1.57	0.67	1.09	0.86	1.70	0.67	0.98	
		LI-AP	2.88	3.27	2.88	3.77	2.87	3.27	2.87	
		Vehicles	2.00	2.00	2.00	2.00	2.00	2.00	2.00	
	N1-i4 15c	Dist. Matrix	Distance	173.74	182.87	194.22	182.87	195.83	190.50	195.83
			LD-Pop	13,072.42	10,130.34	14,901.95	10,130.34	16,166.09	11,854.81	15,293.83
			LI-Pop	38,343.59	41,191.22	32,085.78	41,191.22	32,420.41	40,006.93	32,420.41
			LD-Risk	608.16	337.79	622.99	337.79	639.36	511.35	615.56
			LI-Risk	2,704.19	2,794.37	1,503.35	2,794.37	1,483.05	2,678.03	1,483.05
			LD-AP	1.33	1.17	1.59	1.17	1.68	1.17	1.57
LI-AP			3.45	3.53	3.40	3.53	3.32	3.57	3.32	
Pop Matrix		Vehicles	2.00	2.00	2.00	2.00	2.00	2.00	2.00	
		Distance	200.19	225.82	201.04	225.82	200.19	215.85	200.19	
		LD-Pop	14,072.84	9,617.89	14,085.51	9,617.89	14,072.84	10,107.87	14,211.70	
		LI-Pop	31,071.37	32,813.54	30,980.65	32,813.54	31,071.37	32,667.95	31,071.37	
		LD-Risk	592.30	315.89	599.68	315.89	592.30	340.70	594.08	
		LI-Risk	1,455.79	1,566.12	1,470.86	1,566.12	1,455.79	1,509.75	1,455.79	
		LD-AP	1.49	1.22	1.53	1.22	1.49	1.15	1.50	
		LI-AP	3.29	3.69	3.35	3.69	3.29	3.49	3.29	
		Vehicles	2.00	2.00	2.00	2.00	2.00	2.00	2.00	
		Risk Matrix	Distance	205.47	246.51	205.47	254.48	205.47	225.25	205.47
			LD-Pop	15,171.07	10,097.48	14,442.39	11,152.47	15,309.92	10,678.42	14,438.25
			LI-Pop	31,963.75	35,486.58	31,963.75	43,515.12	31,963.75	34,527.11	31,963.75
			LD-Risk	725.17	310.84	593.75	308.24	726.95	328.08	590.74
LI-Risk			1,445.41	1,504.56	1,445.41	2,096.81	1,445.41	1,470.53	1,445.41	
LD-AP			1.58	1.21	1.51	1.21	1.59	1.14	1.50	
LI-AP			3.29	3.76	3.29	4.10	3.29	3.45	3.29	
Vehicles			2.00	2.00	2.00	2.00	2.00	2.00	2.00	
AP Matrix		Distance	184.85	227.53	196.48	227.53	196.48	212.20	196.48	
		LD-Pop	14,079.39	10,359.18	15,064.16	10,359.18	14,750.72	10,485.69	14,750.72	
		LI-Pop	39,612.86	34,992.86	32,602.22	34,992.86	32,602.22	33,904.74	32,602.22	
		LD-Risk	608.17	315.95	725.25	315.95	594.37	331.15	594.37	
		LI-Risk	2,635.34	1,563.16	1,455.06	1,563.16	1,455.06	1,462.28	1,455.06	

Table B1. (continued)

Inst	Matrix		Objective Min Dist.	Objective Min LD-Pop	Objective Min LI-Pop	Objective Min LD-Risk	Objective Min LI-Risk	Objective Min LD-AP	Objective Min LI-AP
		LD-AP	1.33	1.17	1.51	1.17	1.45	1.12	1.45
		LI-AP	3.31	3.58	3.19	3.58	3.19	3.30	3.19
		Vehicles	2.00	2.00	2.00	2.00	2.00	2.00	2.00
N1-i5	Dist.	Distance	190.73	230.48	207.33	235.92	209.18	234.19	208.53
18c	Matrix	LD-Pop	21,599.67	11,949.19	23,475.29	12,246.62	19,746.44	13,342.68	17,604.70
		LI-Pop	54,369.40	58,884.59	43,895.37	55,411.40	44,311.49	68,584.86	45,704.56
		LD-Risk	1,621.03	617.38	1,670.41	582.28	1,469.62	860.82	910.94
		LI-Risk	4,475.51	4,388.54	2,600.56	4,248.31	2,584.01	5,178.73	3,134.59
		LD-AP	1.68	1.30	2.03	1.35	1.65	1.21	1.78
		LI-AP	4.43	5.21	4.20	4.99	4.18	5.46	4.15
		Vehicles	3.00	3.00	3.00	3.00	3.00	3.00	3.00
	Pop Matrix	Distance	198.12	267.63	211.99	317.73	215.78	265.83	214.74
		LD-Pop	19,079.25	11,742.42	20,658.86	12,280.41	16,801.38	12,858.31	16,397.38
		LI-Pop	49,401.91	51,623.07	43,729.73	55,036.10	44,118.78	51,044.90	44,155.37
		LD-Risk	1,351.92	539.66	1,519.73	507.12	762.52	683.67	840.55
		LI-Risk	3,862.24	3,374.77	2,598.05	3,080.38	2,582.18	3,105.20	2,881.42
		LD-AP	1.68	1.33	1.79	1.43	1.76	1.26	1.77
		LI-AP	4.44	5.19	4.23	5.80	4.22	5.04	4.20
	Risk Matrix	Distance	220.16	272.09	220.47	332.10	220.47	274.01	220.38
		LD-Pop	26,223.37	12,170.86	20,011.87	12,554.80	23,567.44	13,039.20	20,645.01
		LI-Pop	55,242.38	55,111.11	44,797.10	57,022.85	44,797.10	52,129.53	44,824.90
		LD-Risk	1,691.04	511.88	1,469.53	495.03	1,654.61	681.40	1,689.52
		LI-Risk	3,651.51	3,464.67	2,574.20	3,041.14	2,574.20	3,095.17	2,872.43
		LD-AP	2.18	1.34	1.66	1.38	1.98	1.26	1.67
		LI-AP	4.75	5.21	4.22	5.69	4.22	5.05	4.20
	AP Matrix	Distance	199.53	272.15	216.86	315.86	213.50	275.26	216.69
		LD-Pop	20,603.29	12,131.29	25,412.66	14,377.76	17,555.51	12,991.14	19,825.68
		LI-Pop	54,489.51	52,914.22	45,040.54	61,040.83	45,384.38	58,441.50	47,235.59
		LD-Risk	1,560.51	612.62	1,916.66	557.90	766.45	773.78	1,094.79
		LI-Risk	4,375.71	3,621.47	2,895.57	3,654.99	2,589.96	3,965.19	3,137.69
		LD-AP	1.65	1.28	2.12	1.56	1.69	1.19	1.85
LI-AP		4.30	5.03	4.14	5.68	4.10	5.09	4.06	
		Vehicles	3.00	3.00	3.00	3.00	3.00	3.00	
N1-i6 18c	Dist. Matrix	Distance	213.74	254.62	232.30	234.33	234.11	249.52	224.30
		LD-Pop	17,850.77	8,683.20	18,334.89	9,268.35	14,220.32	9,503.60	21,245.43
		LI-Pop	43,876.84	62,312.76	34,363.84	47,978.99	34,591.73	59,581.79	35,318.93
		LD-Risk	875.32	282.08	1,039.55	244.44	707.43	392.01	1,398.53
		LI-Risk	3,076.55	5,155.95	1,847.46	3,303.27	1,843.68	4,851.91	2,010.74
		LD-AP	1.88	1.07	2.03	1.08	1.56	1.03	2.11
		LI-AP	3.93	5.18	3.76	4.32	3.75	5.00	3.63
	Pop Matrix	Distance	231.18	299.95	231.18	246.78	242.14	246.78	232.44
		LD-Pop	14,579.01	8,452.77	15,494.92	8,887.89	19,040.70	8,887.89	10,673.74
		LI-Pop	31,608.15	38,706.77	31,608.15	33,450.38	32,876.70	33,450.38	31,963.30
		LD-Risk	736.88	235.10	750.10	230.40	981.46	230.40	280.52
		LI-Risk	1,661.20	1,849.06	1,661.20	1,683.92	1,554.57	1,683.92	1,658.70
		LD-AP	1.73	1.06	1.83	1.03	2.12	1.03	1.32
		LI-AP	3.63	4.66	3.63	3.78	3.74	3.78	3.62
	Risk Matrix	Distance	246.18	325.31	246.18	261.96	250.68	261.96	246.18
		LD-Pop	16,468.15	8,661.53	16,759.81	9,067.70	17,742.02	9,067.70	14,779.78
		LI-Pop	33,335.17	42,579.08	33,335.17	35,385.23	33,878.09	35,385.23	33,335.17

Table B1. (continued)

Inst	Matrix		Objective Min Dist.	Objective Min LD-Pop	Objective Min LI-Pop	Objective Min LD-Risk	Objective Min LI-Risk	Objective Min LD-AP	Objective Min LI-AP
		LD-Risk	749.60	231.18	763.02	225.57	978.91	225.57	709.54
		LI-Risk	1,539.56	1,732.36	1,539.56	1,568.59	1,539.04	1,568.59	1,539.56
		LD-AP	1.83	1.03	1.90	1.00	1.79	1.00	1.57
		LI-AP	3.63	4.70	3.63	3.79	3.64	3.79	3.63
		Vehicles	3.00	3.00	3.00	3.00	3.00	3.00	3.00
	AP Matrix	Distance	217.96	307.38	228.29	247.41	243.12	271.21	229.82
		LD-Pop	22,372.78	8,879.53	11,738.93	9,259.61	13,761.08	9,726.86	14,505.16
		LI-Pop	37,461.31	44,164.75	34,743.08	37,148.64	35,659.89	46,170.11	34,858.70
		LD-Risk	1,782.58	232.22	457.04	229.23	544.54	383.28	583.53
		LI-Risk	2,433.15	2,120.26	1,947.59	1,959.04	1,820.51	2,961.48	1,931.84
		LD-AP	1.90	1.03	1.23	1.00	1.42	0.98	1.63
		LI-AP	3.54	4.55	3.56	3.66	3.62	4.30	3.49
		Vehicles	3.00	3.00	3.00	3.00	3.00	3.00	3.00
	N1-i7 20c	Dist. Matrix	Distance	203.66	237.99	227.70	252.79	228.81	218.81
LD-Pop			25,207.46	17,372.78	25,186.40	18,495.37	25,207.29	17,884.82	23,725.90
LI-Pop			62,667.67	75,473.15	50,868.94	65,717.10	51,038.49	63,622.82	56,726.98
LD-Risk			2,025.24	972.67	1,850.44	840.12	1,593.58	1,086.04	1,804.97
LI-Risk			5,841.25	6,746.75	3,402.24	5,397.59	3,400.36	5,232.72	4,945.26
LD-AP			2.20	1.97	2.27	2.25	2.43	1.77	2.13
LI-AP			4.89	5.91	4.79	5.76	4.81	5.12	4.62
Vehicles			3.00	3.00	3.00	3.00	3.00	3.00	3.00
Pop Matrix		Distance	210.17	242.02	231.42	251.18	262.78	283.36	210.90
		LD-Pop	22,293.25	15,847.23	26,076.51	17,103.75	23,975.71	17,425.92	21,176.41
		LI-Pop	52,807.25	58,194.35	48,669.87	61,033.03	49,035.41	62,541.90	53,008.27
		LD-Risk	1,487.18	726.10	1,919.39	714.38	1,337.90	922.53	1,336.38
		LI-Risk	3,972.40	4,688.62	3,115.10	4,758.61	2,783.00	4,420.70	3,972.47
		LD-AP	2.06	1.94	2.40	2.09	2.55	1.85	2.11
		LI-AP	4.69	5.30	4.81	5.58	5.09	5.89	4.68
		Vehicles	3.00	3.00	3.00	3.00	3.00	3.00	3.00
Risk Matrix		Distance	240.28	283.62	276.82	284.06	278.30	267.39	250.40
		LD-Pop	32,347.62	16,316.30	22,149.38	16,493.19	23,831.62	17,664.55	29,701.38
		LI-Pop	57,979.51	63,496.81	50,673.72	63,628.64	51,041.18	54,088.75	52,577.32
		LD-Risk	2,251.17	705.41	1,141.22	694.34	1,303.59	835.45	1,789.01
		LI-Risk	3,801.44	3,990.04	2,753.16	3,976.20	2,750.88	3,222.68	2,995.46
		LD-AP	2.86	1.89	2.23	1.87	2.40	1.85	2.68
		LI-AP	5.25	5.93	5.01	5.89	4.98	5.14	4.92
		Vehicles	3.00	3.00	3.00	3.00	3.00	3.00	3.00
AP Matrix		Distance	206.47	227.26	222.59	269.78	259.10	226.37	212.96
		LD-Pop	24,363.53	16,773.87	28,139.63	20,102.51	26,173.91	17,037.04	22,521.96
		LI-Pop	53,418.59	60,022.31	50,295.64	60,317.41	51,428.19	63,915.43	54,637.78
		LD-Risk	1,937.57	888.65	2,124.40	866.69	1,522.45	991.02	1,564.53
		LI-Risk	3,992.15	5,171.17	3,380.33	4,528.05	3,044.14	5,282.05	4,268.71
		LD-AP	2.18	1.79	2.40	2.23	2.45	1.75	2.08
	LI-AP	4.67	5.00	4.58	5.42	4.85	5.28	4.54	
	Vehicles	3.00	3.00	3.00	3.00	3.00	3.00	3.00	
N1-i8 20c	Dist. Matrix	Distance	225.78	275.58	242.13	275.55	275.89	252.62	236.58
		LD-Pop	28,416.07	11,719.21	20,525.55	11,782.06	28,080.57	13,161.55	26,724.09
		LI-Pop	56,382.07	72,196.36	47,128.15	72,370.15	51,243.23	72,169.81	47,993.31
		LD-Risk	2,565.87	395.95	1,291.83	388.06	1,557.54	593.28	1,924.57
		LI-Risk	4,827.52	5,256.89	3,042.04	5,232.26	2,810.67	5,716.63	3,173.79
		LD-AP	2.35	1.46	1.94	1.47	2.68	1.40	2.38
		LI-AP	4.58	5.94	4.51	5.98	5.05	5.80	4.50
		Vehicles	4.00	4.00	4.00	4.00	4.00	4.00	4.00
	Pop	Distance	240.58	284.45	268.37	311.98	277.84	280.24	245.45

Table B1. (continued)

Inst	Matrix		Objective Min Dist.	Objective Min LD-Pop	Objective Min LI-Pop	Objective Min LD-Risk	Objective Min LI-Risk	Objective Min LD-AP	Objective Min LI-AP	
N2-i1 13c	Dist. Matrix	Distance	116.41	157.23	118.25	154.99	123.37	148.36	118.25	
		LD-Pop	17,127.03	11,998.97	15,210.42	12,096.74	18,022.82	12,063.22	16,503.09	
		LI-Pop	36,939.80	51,004.93	36,570.20	51,208.90	39,491.11	55,959.99	36,570.20	
		LD-Risk	923.96	589.43	838.84	586.27	1,071.38	661.65	910.47	
		LI-Risk	2,338.24	2,927.01	2,355.16	2,934.69	2,242.18	3,886.87	2,355.16	
		LD-AP	1.58	1.20	1.45	1.21	1.68	1.16	1.52	
		LI-AP	3.41	4.76	3.38	4.70	3.66	5.13	3.38	
		Vehicles	2.00	2.00	2.00	2.00	2.00	2.00	2.00	
	Pop Matrix	Distance	121.08	186.70	131.07	190.28	158.48	143.48	123.20	
		LD-Pop	15,563.35	11,415.36	14,778.01	13,422.11	19,816.39	11,524.06	15,540.96	
		LI-Pop	35,678.94	41,467.17	34,746.10	52,236.76	37,752.32	37,858.04	34,995.71	
		LD-Risk	944.58	633.63	866.63	545.24	954.78	603.37	968.82	
		LI-Risk	2,099.23	2,061.22	2,107.34	2,622.84	1,943.36	2,221.54	2,109.58	
		LD-AP	1.53	1.20	1.57	1.35	1.93	1.16	1.55	
		LI-AP	3.49	4.32	3.57	4.97	3.83	3.87	3.46	
		Vehicles	2.00	2.00	2.00	2.00	2.00	2.00	2.00	
	Risk Matrix	Distance	151.13	206.28	151.13	170.73	164.99	206.28	151.13	
		LD-Pop	18,617.75	12,081.80	15,797.74	12,898.59	19,168.42	12,081.80	19,893.18	
		LI-Pop	38,598.38	45,440.23	38,598.38	41,654.75	39,690.78	45,440.23	38,598.38	
		LD-Risk	816.11	591.39	796.05	502.90	876.47	591.39	872.11	
		LI-Risk	1,810.75	1,937.63	1,810.75	1,922.20	1,769.21	1,937.63	1,810.75	
		LD-AP	1.72	1.19	1.47	1.22	1.76	1.19	1.81	
		LI-AP	3.57	4.30	3.57	3.96	3.68	4.30	3.57	
		Vehicles	2.00	2.00	2.00	2.00	2.00	2.00	2.00	
	AP Matrix	Distance	123.88	196.07	128.03	191.52	168.46	139.05	128.03	
		LD-Pop	15,568.24	11,690.03	16,484.19	13,266.06	20,582.64	11,870.76	17,659.83	
		LI-Pop	36,800.33	44,277.65	36,744.12	46,356.64	40,318.30	39,874.90	36,744.12	
		LD-Risk	816.03	605.50	921.44	540.42	924.07	572.19	922.66	
		LI-Risk	2,273.27	1,983.08	1,983.16	2,098.26	1,867.53	2,144.33	1,983.16	
		LD-AP	1.44	1.14	1.52	1.31	1.85	1.12	1.59	
		LI-AP	3.36	4.13	3.34	4.19	3.67	3.61	3.34	
		Vehicles	2.00	2.00	2.00	2.00	2.00	2.00	2.00	
	N2-i2 13c	Dist. Matrix	Distance	124.65	150.15	140.20	163.33	140.20	164.55	140.20
			LD-Pop	19,978.20	11,823.02	19,213.20	12,362.43	18,339.64	12,039.27	18,941.60
			LI-Pop	43,013.54	53,911.84	40,314.01	56,791.90	40,314.01	58,578.13	40,314.01
			LD-Risk	1,306.03	622.46	986.77	577.26	967.13	606.77	935.61
LI-Risk			2,700.67	3,478.44	2,131.88	3,503.96	2,131.88	3,684.09	2,131.88	
LD-AP			1.87	1.05	1.81	1.08	1.73	1.03	1.72	
LI-AP			3.90	4.81	3.73	5.06	3.73	5.14	3.73	
Vehicles			2.00	2.00	2.00	2.00	2.00	2.00	2.00	
Pop Matrix		Distance	128.33	170.22	142.13	192.83	164.24	157.86	168.87	
		LD-Pop	20,141.96	11,234.61	18,590.66	11,673.80	19,371.38	11,485.49	18,951.41	
		LI-Pop	42,243.98	43,211.44	39,601.53	47,133.81	41,641.15	41,410.15	41,188.72	
		LD-Risk	1,373.98	616.77	1,023.37	576.66	1,059.85	682.08	1,033.14	
		LI-Risk	2,698.17	2,574.49	2,147.60	2,568.44	2,108.09	2,512.64	2,125.71	
		LD-AP	1.86	1.14	1.74	1.15	1.87	1.09	1.76	
		LI-AP	4.01	4.21	3.80	4.52	4.04	3.98	3.76	
		Vehicles	2.00	2.00	2.00	2.00	2.00	2.00	2.00	
Risk Matrix		Distance	140.77	180.10	150.31	181.51	179.14	180.10	179.14	
		LD-Pop	22,941.62	12,149.72	19,685.23	12,321.41	19,577.82	12,149.72	20,835.73	
		LI-Pop	46,709.88	46,434.13	42,507.38	46,924.24	44,070.09	46,434.13	44,070.09	
		LD-Risk	1,248.99	512.43	1,012.74	508.86	864.63	512.43	885.70	
		LI-Risk	2,480.67	2,287.78	1,961.42	2,281.49	1,879.36	2,287.78	1,879.36	
		LD-AP	2.02	1.11	1.85	1.13	1.72	1.11	1.75	

Table B1. (continued)

Inst	Matrix		Objective Min Dist.	Objective Min LD-Pop	Objective Min LI-Pop	Objective Min LD-Risk	Objective Min LI-Risk	Objective Min LD-AP	Objective Min LI-AP	
		LI-AP	4.21	4.18	3.84	4.25	3.79	4.18	3.79	
		Vehicles	2.00	2.00	2.00	2.00	2.00	2.00	2.00	
	AP Matrix	Distance	125.45	201.53	141.96	173.27	169.41	195.51	169.41	
		LD-Pop	16,992.69	11,663.61	19,045.56	11,951.99	19,051.48	12,118.66	20,141.96	
		LI-Pop	43,428.02	50,429.95	41,346.05	45,599.81	42,530.21	50,574.39	42,530.21	
		LD-Risk	873.68	587.99	835.06	518.23	914.58	599.06	936.92	
		LI-Risk	2,420.50	2,893.63	2,024.49	2,345.72	1,986.34	2,707.94	1,986.34	
		LD-AP	1.54	1.10	1.59	1.08	1.66	1.00	1.76	
		LI-AP	3.84	4.66	3.62	4.09	3.56	4.36	3.56	
		Vehicles	2.00	2.00	2.00	2.00	2.00	2.00	2.00	
N2-i3 15c	Dist. Matrix	Distance	83.48	119.40	91.87	110.74	103.89	147.93	91.87	
		LD-Pop	13,669.08	6,740.20	10,644.92	7,278.68	13,856.19	7,139.98	10,644.92	
		LI-Pop	26,338.71	41,692.80	25,540.00	35,479.19	26,594.79	43,015.35	25,540.00	
		LD-Risk	1,069.42	327.34	569.64	308.36	592.98	336.14	569.64	
		LI-Risk	1,817.43	2,809.59	1,380.90	2,206.35	1,233.95	2,525.86	1,380.90	
		LD-AP	1.22	0.71	1.05	0.75	1.36	0.69	1.05	
		LI-AP	2.48	3.90	2.45	3.31	2.56	4.03	2.45	
		Vehicles	2.00	2.00	2.00	2.00	2.00	2.00	2.00	
	Pop Matrix	Distance	87.32	126.80	92.42	120.94	124.74	150.89	92.42	
		LD-Pop	12,560.16	6,605.30	10,319.25	7,233.82	12,281.95	6,842.30	10,822.88	
		LI-Pop	29,453.90	30,483.35	24,441.46	30,179.11	26,580.31	37,483.08	24,441.46	
		LD-Risk	718.73	338.58	563.24	314.08	586.30	338.92	663.97	
		LI-Risk	1,862.20	1,528.50	1,431.11	1,596.21	1,252.64	1,951.22	1,431.11	
		LD-AP	1.27	0.73	1.09	0.75	1.28	0.69	1.09	
		LI-AP	2.88	3.18	2.51	3.14	2.80	3.75	2.51	
		Vehicles	2.00	2.00	2.00	2.00	2.00	2.00	2.00	
	Risk Matrix	Distance	108.38	151.28	113.41	142.83	136.19	149.50	110.23	
		LD-Pop	13,145.51	6,892.49	10,243.87	8,011.51	12,409.67	7,061.19	14,216.61	
		LI-Pop	29,981.30	33,825.47	26,894.02	34,377.91	29,047.88	34,971.86	27,116.04	
		LD-Risk	642.53	324.36	512.88	298.10	572.03	318.12	574.97	
		LI-Risk	1,479.58	1,441.33	1,181.06	1,543.97	1,171.86	1,522.26	1,213.21	
		LD-AP	1.25	0.72	0.97	0.79	1.14	0.70	1.29	
		LI-AP	2.83	3.22	2.59	3.21	2.72	3.26	2.59	
		Vehicles	2.00	2.00	2.00	2.00	2.00	2.00	2.00	
	AP Matrix	Distance	83.60	141.52	92.12	131.32	128.98	160.84	92.12	
		LD-Pop	11,476.83	6,735.41	11,451.30	7,726.18	13,492.26	6,973.76	10,618.04	
		LI-Pop	26,384.51	32,811.30	25,342.69	34,416.76	28,344.54	39,861.91	25,342.69	
		LD-Risk	635.70	329.14	593.70	301.17	560.37	329.37	555.98	
		LI-Risk	1,755.43	1,505.91	1,309.19	1,600.21	1,181.15	1,876.57	1,309.19	
		LD-AP	1.04	0.70	1.02	0.76	1.23	0.67	1.05	
		LI-AP	2.48	3.02	2.43	3.03	2.63	3.63	2.43	
		Vehicles	2.00	2.00	2.00	2.00	2.00	2.00	2.00	
	N2-i4 15c	Dist. Matrix	Distance	131.29	132.87	144.08	142.38	176.51	132.88	143.06
			LD-Pop	14,330.59	12,538.93	24,179.81	13,210.20	27,882.20	12,926.81	23,166.69
			LI-Pop	43,645.20	44,751.06	41,216.38	44,698.09	45,534.29	45,105.49	41,308.97
			LD-Risk	726.64	640.21	1,442.75	604.69	1,395.21	639.05	1,416.43
			LI-Risk	2,790.88	2,938.43	2,419.76	2,817.69	2,272.07	2,935.10	2,419.12
			LD-AP	1.37	1.23	2.29	1.27	2.58	1.22	2.16
			LI-AP	3.95	4.06	3.92	4.08	4.22	4.05	3.89
			Vehicles	2.00	2.00	2.00	2.00	2.00	2.00	2.00
		Pop Matrix	Distance	137.69	169.41	144.46	175.59	153.99	169.49	144.43
			LD-Pop	21,023.21	12,208.87	15,296.96	12,410.27	24,803.77	12,210.54	19,273.78
LI-Pop			40,386.02	40,605.04	38,636.89	40,867.97	39,998.33	40,561.31	38,711.45	
LD-Risk			1,244.65	615.11	785.88	569.60	1,290.82	605.33	1,170.32	

Table B1. (continued)

Inst	Matrix		Objective Min Dist.	Objective Min LD-Pop	Objective Min LI-Pop	Objective Min LD-Risk	Objective Min LI-Risk	Objective Min LD-AP	Objective Min LI-AP
		LI-Risk	2,339.75	2,311.91	2,174.56	2,230.30	2,000.96	2,299.69	2,165.86
		LD-AP	2.03	1.22	1.51	1.25	2.39	1.22	1.88
		LI-AP	3.89	4.01	3.82	4.09	3.90	4.01	3.79
		Vehicles	2.00	2.00	2.00	2.00	2.00	2.00	2.00
	Risk Matrix	Distance	155.99	176.63	168.91	176.63	168.91	176.63	168.91
		LD-Pop	24,090.49	13,881.43	25,987.66	13,881.43	25,090.41	13,881.43	22,705.24
		LI-Pop	43,721.49	44,243.34	42,839.54	44,243.34	42,839.54	44,243.34	42,839.54
		LD-Risk	1,264.42	542.29	1,201.01	542.29	1,133.37	542.29	1,041.48
		LI-Risk	2,054.16	2,025.77	1,877.43	2,025.77	1,877.43	2,025.77	1,877.43
		LD-AP	2.25	1.29	2.39	1.29	2.29	1.29	2.05
		LI-AP	4.03	4.05	3.95	4.05	3.95	4.05	3.95
		Vehicles	2.00	2.00	2.00	2.00	2.00	2.00	2.00
		AP Matrix	Distance	136.34	155.22	150.50	165.65	156.60	155.22
	LD-Pop		17,541.91	12,360.93	17,144.54	13,028.22	17,489.73	12,360.93	15,154.50
	LI-Pop		42,520.21	41,534.90	40,080.90	42,628.91	41,145.26	41,534.90	40,972.39
	LD-Risk		1,020.60	604.53	849.49	567.30	818.18	604.53	843.76
	LI-Risk		2,569.44	2,161.15	2,165.55	2,092.34	1,942.71	2,161.15	2,266.81
	LD-AP		1.60	1.19	1.56	1.22	1.63	1.19	1.36
	LI-AP		3.94	3.85	3.75	3.90	3.78	3.85	3.69
	Vehicles		2.00	2.00	2.00	2.00	2.00	2.00	2.00
	N2-i5 18c	Dist. Matrix	Distance	186.64	218.22	187.08	226.94	199.09	218.22
LD-Pop			23,734.36	19,810.37	29,715.23	20,277.82	28,057.84	19,810.37	24,211.22
LI-Pop			62,421.03	79,764.04	60,350.06	74,095.55	60,975.98	79,764.04	60,968.44
LD-Risk			1,696.85	1,284.08	1,973.24	1,255.00	1,653.61	1,284.08	1,452.89
LI-Risk			4,357.97	5,156.09	3,865.90	4,830.32	3,716.08	5,156.09	3,901.81
LD-AP			2.22	1.88	2.71	1.93	2.66	1.88	2.37
LI-AP			5.86	7.07	5.83	6.75	5.84	7.07	5.80
Vehicles			3.00	3.00	3.00	3.00	3.00	3.00	3.00
Pop Matrix		Distance	193.13	288.18	193.13	287.14	237.17	246.15	194.44
		LD-Pop	25,050.35	19,103.82	21,843.08	19,731.56	23,787.78	19,377.01	27,886.05
		LI-Pop	56,908.55	68,296.59	56,908.55	71,717.69	60,977.85	70,936.35	58,647.46
		LD-Risk	1,640.42	1,179.61	1,407.64	1,072.57	1,323.53	1,097.66	1,768.34
		LI-Risk	3,656.04	4,056.08	3,656.04	4,039.50	3,460.31	4,686.28	3,678.79
		LD-AP	2.51	1.93	2.27	1.92	2.38	1.90	2.71
		LI-AP	5.80	6.77	5.80	6.86	6.02	6.88	5.79
		Vehicles	3.00	3.00	3.00	3.00	3.00	3.00	3.00
Risk Matrix		Distance	201.12	301.54	206.55	302.64	285.10	258.37	215.70
		LD-Pop	24,798.10	19,518.14	27,722.91	20,503.03	30,295.52	20,228.68	27,620.16
		LI-Pop	60,663.04	72,675.40	60,008.11	75,673.84	66,190.81	74,741.41	61,870.24
		LD-Risk	1,386.20	1,142.45	1,522.37	1,026.73	1,260.15	1,038.57	1,446.15
		LI-Risk	3,381.29	3,831.12	3,368.69	3,756.47	3,269.93	4,102.55	3,327.43
		LD-AP	2.40	1.92	2.61	1.89	2.74	1.88	2.59
		LI-AP	5.89	6.82	5.83	6.84	6.11	6.84	5.78
		Vehicles	3.00	3.00	3.00	3.00	3.00	3.00	3.00
AP Matrix		Distance	191.50	289.82	191.90	261.11	240.76	251.52	207.27
		LD-Pop	28,099.52	19,689.09	25,257.99	21,476.69	24,794.83	20,107.76	28,498.70
		LI-Pop	63,178.95	69,564.10	58,149.80	69,097.61	61,663.34	72,997.88	62,068.91
		LD-Risk	1,676.93	1,281.09	1,628.36	1,088.08	1,410.29	1,205.91	1,663.31
	LI-Risk	3,777.38	4,139.86	3,707.99	4,059.96	3,384.83	4,581.65	3,781.65	
	LD-AP	2.52	1.91	2.48	2.05	2.36	1.84	2.57	
	LI-AP	5.96	6.58	5.69	6.50	5.83	6.65	5.66	
	Vehicles	3.00	3.00	3.00	3.00	3.00	3.00	3.00	
N2-i6 18c	Dist. Matrix	Distance	175.32	203.56	185.67	201.88	188.33	203.56	187.91
		LD-Pop	30,750.00	19,349.33	29,822.10	20,232.25	36,233.65	19,349.33	23,595.19

Table B1. (continued)

Inst	Matrix		Objective Min Dist.	Objective Min LD-Pop	Objective Min LI-Pop	Objective Min LD-Risk	Objective Min LI-Risk	Objective Min LD-AP	Objective Min LI-AP	
		LI-Pop	63,000.83	75,119.99	57,896.30	79,449.31	60,907.61	75,119.99	58,524.58	
		LD-Risk	1,823.75	1,091.39	1,834.35	1,064.61	2,151.55	1,091.39	1,366.56	
		LI-Risk	3,796.27	4,672.31	3,617.56	4,849.09	3,474.25	4,672.31	3,753.86	
		LD-AP	2.92	1.79	2.90	1.91	3.36	1.79	2.29	
		LI-AP	5.67	6.47	5.55	6.65	5.72	6.47	5.49	
		Vehicles	3.00	3.00	3.00	3.00	3.00	3.00	3.00	
	Pop Matrix	Distance	197.35	259.92	224.58	226.10	224.74	255.08	202.76	
		LD-Pop	28,276.41	17,915.47	23,106.85	18,626.88	25,565.05	18,485.91	28,274.62	
		LI-Pop	57,727.44	59,255.65	53,076.48	56,703.28	53,327.37	63,506.04	54,918.71	
		LD-Risk	1,765.59	929.02	1,285.69	882.71	1,257.97	959.38	1,830.79	
		LI-Risk	3,754.44	3,232.19	2,695.96	3,135.05	2,691.05	3,631.44	3,366.02	
		LD-AP	2.75	1.76	2.42	1.79	2.61	1.76	2.79	
		LI-AP	5.70	6.01	5.54	5.77	5.51	6.22	5.34	
		Vehicles	3.00	3.00	3.00	3.00	3.00	3.00	3.00	
	Risk Matrix	Distance	209.82	265.44	238.10	235.15	239.00	286.71	234.00	
		LD-Pop	31,150.87	18,938.22	26,291.38	19,432.33	27,230.24	18,964.14	28,665.78	
		LI-Pop	63,997.65	67,219.74	56,410.35	60,773.85	56,799.94	68,444.80	57,529.25	
		LD-Risk	1,611.37	880.19	1,274.54	859.60	1,306.63	887.22	1,367.43	
		LI-Risk	3,216.40	3,236.47	2,648.70	3,012.90	2,633.30	3,212.85	2,808.69	
		LD-AP	2.76	1.73	2.61	1.75	2.71	1.73	2.65	
		LI-AP	5.86	6.12	5.56	5.66	5.59	6.22	5.39	
		Vehicles	3.00	3.00	3.00	3.00	3.00	3.00	3.00	
	AP Matrix	Distance	186.16	253.74	216.77	222.31	216.99	222.31	220.21	
		LD-Pop	33,290.78	18,402.33	31,932.13	19,065.01	24,051.33	18,490.40	29,074.24	
		LI-Pop	67,602.10	65,219.06	55,520.66	61,073.23	55,540.24	61,073.23	57,918.07	
		LD-Risk	2,045.01	889.32	1,600.31	873.09	1,247.00	929.91	1,582.80	
		LI-Risk	4,149.01	3,300.15	2,758.44	3,303.91	2,758.40	3,303.91	2,977.42	
		LD-AP	2.87	1.68	2.96	1.70	2.37	1.67	2.63	
		LI-AP	5.80	5.83	5.23	5.39	5.23	5.39	5.16	
		Vehicles	3.00	3.00	3.00	3.00	3.00	3.00	3.00	
	N2-i7 20c	Dist. Matrix	Distance	182.14	212.62	190.41	217.74	202.92	211.43	190.51
			LD-Pop	32,613.22	18,937.95	25,988.26	19,577.42	28,056.25	19,535.34	28,124.36
			LI-Pop	66,491.81	77,842.87	61,160.53	79,192.52	64,399.95	78,856.50	62,777.96
			LD-Risk	2,359.24	998.49	1,728.96	947.46	1,487.79	1,101.51	1,928.92
			LI-Risk	4,528.73	5,161.60	3,896.64	5,044.31	3,542.47	5,332.08	3,965.80
			LD-AP	2.84	1.75	2.34	1.81	2.48	1.71	2.41
LI-AP			5.79	6.90	5.50	7.03	5.78	6.90	5.47	
Vehicles			4.00	4.00	4.00	4.00	4.00	4.00	4.00	
Pop Matrix		Distance	190.08	242.96	195.97	271.92	241.55	253.47	195.77	
		LD-Pop	32,790.92	18,349.05	26,218.85	19,044.26	26,619.64	18,846.86	28,226.12	
		LI-Pop	61,875.88	70,058.14	56,460.02	74,114.34	58,659.30	71,430.73	56,803.16	
		LD-Risk	2,123.51	1,082.09	1,723.04	919.65	1,473.34	1,011.92	1,864.89	
		LI-Risk	3,726.01	4,509.67	3,497.45	4,130.77	3,171.19	4,287.82	3,492.24	
		LD-AP	2.86	1.75	2.44	1.78	2.64	1.69	2.50	
		LI-AP	5.54	6.36	5.26	6.78	5.62	6.50	5.23	
		Vehicles	4.00	4.00	4.00	4.00	4.00	4.00	4.00	
Risk Matrix		Distance	210.79	327.93	257.82	317.46	251.21	309.69	243.33	
		LD-Pop	35,449.62	19,328.48	27,044.34	19,752.16	31,563.56	19,457.22	26,159.09	
		LI-Pop	68,574.03	80,230.38	61,550.09	79,258.29	62,387.95	76,169.74	62,364.24	
		LD-Risk	1,826.45	902.87	1,247.49	869.88	1,556.40	943.37	1,223.93	
		LI-Risk	3,447.18	3,694.75	2,997.76	3,636.45	2,911.04	3,503.48	2,912.02	
		LD-AP	3.12	1.76	2.55	1.80	2.94	1.72	2.33	
		LI-AP	6.09	7.15	5.57	7.04	5.80	6.77	5.48	
		Vehicles	4.00	4.00	4.00	4.00	4.00	4.00	4.00	
AP		Distance	192.59	249.07	199.31	227.78	242.69	260.17	200.70	

Table B1. (continued)

Inst	Matrix		Objective Min Dist.	Objective Min LD-Pop	Objective Min LI-Pop	Objective Min LD-Risk	Objective Min LI-Risk	Objective Min LD-AP	Objective Min LI-AP
	Matrix	LD-Pop	32,633.59	18,680.08	29,134.18	19,971.84	28,553.79	18,968.59	28,923.57
		LI-Pop	61,337.39	71,557.57	57,327.43	70,583.76	60,886.82	72,770.88	58,221.87
		LD-Risk	1,992.88	1,075.47	1,952.25	921.39	1,535.49	1,006.08	1,941.97
		LI-Risk	3,789.03	4,613.78	3,482.74	4,204.24	3,243.29	4,392.18	3,607.51
		LD-AP	2.76	1.70	2.57	1.83	2.53	1.66	2.51
		LI-AP	5.38	6.23	5.17	6.19	5.27	6.39	5.15
		Vehicles	4.00	4.00	4.00	4.00	4.00	4.00	4.00
N2-i8 25c	Dist. Matrix	Distance	210.81	252.41	217.98	259.21	218.05	251.72	211.64
		LD-Pop	32,809.98	19,816.73	31,280.31	22,894.33	28,672.95	21,021.78	36,599.31
		LI-Pop	70,115.93	100,544.80	67,033.44	94,683.78	68,053.03	106,029.39	68,330.48
		LD-Risk	1,987.18	1,142.61	1,970.44	1,072.76	1,734.89	1,219.51	2,434.60
		LI-Risk	4,496.81	6,520.35	4,081.34	5,691.45	4,040.98	6,889.71	4,263.91
		LD-AP	2.95	1.91	2.86	2.04	2.55	1.78	3.20
		LI-AP	6.08	8.40	6.03	8.05	6.02	8.54	5.93
	Vehicles	4.00	4.00	4.00	4.00	4.00	4.00	4.00	
	Pop Matrix	Distance	225.85	312.65	241.59	283.79	246.04	312.65	231.59
		LD-Pop	26,737.01	17,844.95	29,017.69	20,968.05	28,543.09	17,844.95	26,893.14
		LI-Pop	63,772.87	81,187.89	57,533.60	72,128.28	62,832.92	81,187.89	58,417.49
		LD-Risk	1,485.87	950.62	1,922.85	868.50	1,521.24	950.62	1,311.19
		LI-Risk	3,876.21	4,819.30	3,473.29	3,998.02	3,187.74	4,819.30	3,287.57
		LD-AP	2.75	1.79	3.02	2.06	2.84	1.79	2.56
		LI-AP	6.26	7.92	5.93	7.04	6.02	7.92	5.74
	Vehicles	4.00	4.00	4.00	4.00	4.00	4.00	4.00	
	Risk Matrix	Distance	248.75	401.61	260.72	355.80	262.87	318.32	251.90
		LD-Pop	28,830.44	19,603.03	29,884.23	21,621.50	28,117.08	20,161.38	31,693.71
		LI-Pop	69,162.40	89,145.63	64,311.27	84,854.51	64,425.04	74,975.40	65,159.68
		LD-Risk	1,463.33	877.84	1,263.79	819.09	1,370.90	825.15	1,491.70
		LI-Risk	3,398.86	4,038.79	2,935.50	3,744.84	2,934.83	3,322.81	2,956.13
		LD-AP	2.63	1.82	2.66	1.95	2.62	1.80	2.84
		LI-AP	6.27	7.70	5.81	7.60	5.81	6.59	5.81
	Vehicles	4.00	4.00	4.00	4.00	4.00	4.00	4.00	
	AP Matrix	Distance	213.83	302.50	243.60	309.56	261.56	336.60	239.01
		LD-Pop	32,107.84	18,698.13	32,028.97	22,027.79	28,374.60	20,507.28	35,443.64
		LI-Pop	68,261.47	81,755.29	64,051.28	79,394.69	68,030.62	88,371.55	64,541.07
		LD-Risk	2,032.54	955.02	1,640.21	875.24	1,504.54	1,100.55	1,998.38
		LI-Risk	4,081.94	4,620.53	3,599.82	4,149.75	3,321.47	4,868.22	3,721.07
		LD-AP	2.63	1.79	2.76	1.93	2.57	1.71	2.98
LI-AP		5.80	7.14	5.64	6.83	6.07	7.35	5.45	
Vehicles	4.00	4.00	4.00	4.00	4.00	4.00	4.00		
N3-i1 13c	Dist. Matrix	Distance	127.75	147.45	130.69	140.75	142.36	135.21	130.24
		LD-Pop	18,081.13	15,330.93	19,786.67	16,178.11	22,878.20	15,485.52	21,215.51
		LI-Pop	51,459.49	57,791.13	49,116.69	55,805.42	53,983.69	54,180.86	51,652.15
		LD-Risk	894.66	796.70	1,032.39	727.39	1,094.25	869.82	1,138.03
		LI-Risk	2,911.43	3,421.14	2,620.62	3,044.80	2,541.79	3,115.44	2,756.17
		LD-AP	1.83	1.61	1.97	1.64	2.35	1.55	2.04
		LI-AP	4.98	5.95	5.03	5.63	5.46	5.30	4.97
	Vehicles	3.00	3.00	3.00	3.00	3.00	3.00	3.00	
	Pop Matrix	Distance	136.09	164.41	144.80	178.33	172.26	164.96	142.92
		LD-Pop	19,417.87	13,130.55	20,281.23	13,567.73	21,989.94	13,786.54	19,399.17
		LI-Pop	46,620.62	46,985.76	43,345.11	48,808.95	45,228.02	49,079.01	44,672.53
		LD-Risk	1,077.85	578.27	959.63	578.14	988.11	603.36	1,051.71
		LI-Risk	2,481.39	2,244.22	2,154.72	2,231.56	2,019.34	2,282.11	2,246.97
		LD-AP	2.01	1.48	2.29	1.53	2.43	1.47	2.04
LI-AP		4.93	5.29	4.80	5.53	5.04	5.36	4.68	

Table B1. (continued)

Inst	Matrix		Objective Min Dist.	Objective Min LD-Pop	Objective Min LI-Pop	Objective Min LD-Risk	Objective Min LI-Risk	Objective Min LD-AP	Objective Min LI-AP	
	Risk Matrix	Vehicles	3.00	3.00	3.00	3.00	3.00	3.00	3.00	
		Distance	149.49	176.78	169.25	176.78	169.25	176.78	169.25	
		LD-Pop	15,453.81	13,416.76	19,871.40	13,416.76	17,921.15	13,416.76	16,703.41	
		LI-Pop	48,815.82	49,639.14	45,663.66	49,639.14	45,663.66	49,639.14	45,663.66	
		LD-Risk	751.28	571.75	823.83	571.75	791.36	571.75	712.03	
		LI-Risk	2,425.55	2,142.49	1,935.41	2,142.49	1,935.41	2,142.49	1,935.41	
		LD-AP	1.69	1.51	2.02	1.51	2.02	1.51	1.87	
		LI-AP	5.16	5.51	4.91	5.51	4.91	5.51	4.91	
	AP Matrix	Vehicles	3.00	3.00	3.00	3.00	3.00	3.00	3.00	
		Distance	131.17	146.98	141.20	160.23	154.74	146.98	139.40	
		LD-Pop	27,418.42	13,458.26	19,202.40	13,684.65	21,349.65	13,458.26	19,333.49	
		LI-Pop	49,213.39	50,333.24	45,049.36	49,695.98	45,109.09	50,333.24	46,321.49	
		LD-Risk	1,675.85	597.68	988.13	593.86	990.69	597.68	967.70	
		LI-Risk	2,751.16	2,586.91	2,152.92	2,464.47	2,030.19	2,586.91	2,276.84	
		LD-AP	2.51	1.45	1.96	1.46	2.18	1.45	1.93	
		LI-AP	4.78	5.09	4.61	5.14	4.61	5.09	4.50	
		Vehicles	3.00	3.00	3.00	3.00	3.00	3.00	3.00	
N3-i2 13c	Dist. Matrix	Distance	131.61	140.06	131.61	168.55	140.75	156.13	131.61	
		LD-Pop	20,150.55	17,648.69	21,290.68	17,838.39	21,160.81	17,664.76	19,776.67	
		LI-Pop	46,158.97	48,502.49	46,158.97	60,136.55	47,158.92	58,807.47	46,158.97	
		LD-Risk	1,159.62	911.54	1,188.80	906.98	1,110.14	947.39	1,076.77	
		LI-Risk	2,516.52	2,762.84	2,516.52	3,322.57	2,476.74	3,482.42	2,516.52	
		LD-AP	1.93	1.73	2.00	1.80	1.95	1.67	1.85	
		LI-AP	4.33	4.76	4.33	5.91	4.41	5.48	4.33	
	Pop Matrix	Vehicles	2.00	2.00	2.00	2.00	2.00	2.00	2.00	
		Distance	146.99	161.46	149.25	183.91	186.22	150.01	148.25	
		LD-Pop	20,081.30	16,139.22	20,018.21	17,726.56	19,604.62	16,387.22	20,453.40	
		LI-Pop	44,905.75	47,791.08	41,991.18	50,271.68	44,927.57	46,084.71	42,181.81	
		LD-Risk	1,184.22	808.34	1,037.03	668.05	923.49	873.13	1,171.54	
		LI-Risk	2,526.06	2,579.96	2,227.70	2,398.99	2,019.55	2,533.15	2,274.40	
		LD-AP	2.10	1.78	2.20	1.86	2.07	1.75	2.01	
	Risk Matrix	LI-AP	4.82	5.23	4.38	5.37	4.76	4.99	4.31	
		Vehicles	2.00	2.00	2.00	2.00	2.00	2.00	2.00	
		Distance	153.42	236.54	153.42	211.04	185.88	188.62	153.42	
		LD-Pop	20,649.60	16,502.93	19,690.27	17,785.56	19,492.68	17,174.45	20,345.67	
		LI-Pop	43,901.25	54,092.19	43,901.25	51,656.51	45,875.68	51,803.59	43,901.25	
		LD-Risk	910.54	696.28	896.02	654.03	848.86	832.63	917.53	
		LI-Risk	2,088.60	2,119.54	2,088.60	2,220.02	1,905.87	2,277.07	2,088.60	
	AP Matrix	LD-AP	2.08	1.85	2.04	1.86	2.03	1.79	2.07	
		LI-AP	4.38	5.75	4.38	5.38	4.74	5.36	4.38	
		Vehicles	2.00	2.00	2.00	2.00	2.00	2.00	2.00	
		Distance	137.24	148.59	144.86	173.54	183.55	141.87	139.58	
		LD-Pop	20,123.45	16,705.73	19,028.86	18,286.03	20,925.46	17,064.00	19,811.62	
		LI-Pop	45,821.48	49,442.48	44,272.97	51,909.09	47,441.12	48,765.08	44,405.70	
		LD-Risk	1,135.74	836.71	1,089.71	700.83	989.21	909.46	1,095.35	
		LI-Risk	2,500.45	2,870.59	2,400.51	2,570.56	2,148.00	2,820.31	2,420.24	
		LD-AP	1.91	1.69	1.78	1.80	2.00	1.65	1.85	
		LI-AP	4.28	4.69	4.14	4.98	4.60	4.66	4.13	
		Vehicles	2.00	2.00	2.00	2.00	2.00	2.00	2.00	
	N3-i3 15c	Dist. Matrix	Distance	174.14	195.08	186.70	199.35	192.94	200.79	186.70
			LD-Pop	24,116.07	18,808.30	25,823.30	19,432.74	23,312.35	20,549.15	24,471.88
			LI-Pop	56,855.51	59,520.47	51,796.20	60,141.30	52,756.12	60,984.73	51,796.20
LD-Risk			1,073.04	837.39	1,151.91	767.88	996.29	1,096.30	1,193.47	
LI-Risk			2,904.19	2,863.72	2,465.13	2,765.20	2,365.74	3,200.78	2,465.13	

Table B1. (continued)

Inst	Matrix		Objective Min Dist.	Objective Min LD-Pop	Objective Min LI-Pop	Objective Min LD-Risk	Objective Min LI-Risk	Objective Min LD-AP	Objective Min LI-AP	
		LD-AP	2.28	1.92	2.58	2.04	2.43	1.92	2.38	
		LI-AP	5.26	5.91	5.10	6.04	5.33	5.70	5.10	
		Vehicles	3.00	3.00	3.00	3.00	3.00	3.00	3.00	
	Pop Matrix	Distance	192.06	211.58	205.57	223.39	211.64	228.04	205.57	
		LD-Pop	23,692.12	18,243.88	22,978.62	19,306.05	24,261.99	19,424.52	22,978.62	
		LI-Pop	49,057.86	53,426.15	47,252.25	54,742.54	48,397.95	56,380.44	47,252.25	
		LD-Risk	1,087.87	778.70	1,103.18	714.98	927.53	966.65	1,103.18	
		LI-Risk	2,178.50	2,436.10	2,166.76	2,381.74	2,028.61	2,743.37	2,166.76	
		LD-AP	2.42	1.92	2.41	2.10	2.67	1.90	2.41	
		LI-AP	5.04	5.60	5.01	5.80	5.18	5.70	5.01	
		Vehicles	3.00	3.00	3.00	3.00	3.00	3.00	3.00	
		Risk Matrix	Distance	200.97	233.73	200.97	248.25	220.04	237.74	200.97
			LD-Pop	23,786.46	19,080.16	21,388.21	19,707.21	23,246.18	19,146.57	21,388.21
LI-Pop	49,066.89		56,029.49	49,066.89	57,629.24	50,641.40	56,299.13	49,066.89		
LD-Risk	1,025.41		738.11	870.57	692.27	929.22	734.72	870.57		
LI-Risk	2,020.33		2,318.75	2,020.33	2,239.69	1,953.98	2,316.48	2,020.33		
LD-AP	2.60		2.02	2.28	2.15	2.50	2.02	2.28		
LI-AP	5.35		5.99	5.35	6.28	5.50	5.98	5.35		
Vehicles	3.00		3.00	3.00	3.00	3.00	3.00	3.00		
AP Matrix	Distance		179.07	201.06	195.27	206.03	203.90	209.48	195.27	
	LD-Pop		21,524.46	18,428.16	22,839.15	19,088.70	24,451.32	18,929.43	21,975.44	
	LI-Pop		52,201.23	54,293.34	47,529.50	54,780.64	48,357.82	56,409.47	47,529.50	
	LD-Risk		915.79	828.87	1,039.67	723.52	1,106.49	888.29	1,040.33	
	LI-Risk		2,603.82	2,566.36	2,207.98	2,481.57	2,113.41	2,656.86	2,207.98	
	LD-AP	2.09	1.89	2.29	2.04	2.43	1.83	2.21		
	LI-AP	4.86	5.44	4.74	5.35	4.95	5.33	4.74		
Vehicles	3.00	3.00	3.00	3.00	3.00	3.00	3.00			
N3-i4 15c	Dist. Matrix	Distance	187.29	206.82	191.47	214.52	204.79	198.17	190.02	
		LD-Pop	35,342.02	24,874.98	28,805.68	25,735.31	35,686.32	25,678.20	31,644.84	
		LI-Pop	67,692.17	73,102.85	65,198.57	71,221.32	66,502.02	72,404.94	67,216.29	
		LD-Risk	1,936.16	1,297.97	1,578.12	1,218.70	1,747.31	1,402.96	1,776.35	
		LI-Risk	3,737.74	3,900.19	3,384.11	3,882.20	3,334.61	4,075.01	3,676.02	
		LD-AP	3.31	2.69	3.04	2.76	3.54	2.54	3.01	
		LI-AP	6.59	7.33	6.67	7.23	6.88	6.92	6.58	
	Vehicles	3.00	3.00	3.00	3.00	3.00	3.00	3.00		
	Pop Matrix	Distance	211.36	228.71	217.20	267.66	229.21	222.87	218.01	
		LD-Pop	28,468.72	23,057.68	25,406.07	25,817.86	28,505.95	23,441.97	26,086.75	
		LI-Pop	58,563.04	61,154.64	55,765.75	73,202.52	56,914.46	63,951.93	55,830.52	
		LD-Risk	1,479.27	1,174.69	1,305.10	1,089.10	1,524.04	1,150.91	1,298.15	
		LI-Risk	3,094.10	3,028.60	2,844.91	3,705.02	2,816.74	3,277.79	2,844.14	
		LD-AP	3.06	2.56	2.77	2.85	3.12	2.53	2.86	
		LI-AP	6.24	6.55	6.01	7.82	6.16	6.79	5.99	
	Vehicles	3.00	3.00	3.00	3.00	3.00	3.00	3.00		
	Risk Matrix	Distance	230.65	239.10	231.68	239.10	230.77	239.89	231.68	
		LD-Pop	30,748.91	24,670.56	28,388.97	24,670.56	27,635.63	24,791.68	27,842.10	
		LI-Pop	63,235.06	64,381.18	59,419.41	64,381.18	59,901.84	67,231.96	59,419.41	
		LD-Risk	1,383.21	998.84	1,214.93	998.84	1,171.44	1,034.45	1,238.28	
		LI-Risk	2,742.94	2,794.38	2,620.21	2,794.38	2,551.45	3,054.63	2,620.21	
		LD-AP	3.14	2.63	2.95	2.63	2.76	2.63	2.81	
		LI-AP	6.63	6.77	6.10	6.77	6.26	6.97	6.10	
	Vehicles	3.00	3.00	3.00	3.00	3.00	3.00	3.00		
	AP Matrix	Distance	210.15	240.27	217.05	300.22	238.18	223.21	216.75	
		LD-Pop	32,645.69	24,489.01	26,549.02	26,703.93	29,174.81	25,210.81	30,663.98	
		LI-Pop	62,140.31	64,483.63	58,973.13	75,231.28	61,204.48	67,647.84	59,284.72	
		LD-Risk	1,681.04	1,155.71	1,189.70	1,054.54	1,359.06	1,216.12	1,437.65	

Table B1. (continued)

Inst	Matrix		Objective Min Dist.	Objective Min LD-Pop	Objective Min LI-Pop	Objective Min LD-Risk	Objective Min LI-Risk	Objective Min LD-AP	Objective Min LI-AP	
		LI-Risk	3,156.85	3,027.80	2,754.00	3,695.69	2,715.51	3,411.14	2,822.53	
		LD-AP	3.10	2.52	2.65	2.72	3.04	2.44	2.84	
		LI-AP	6.01	6.41	5.81	7.47	6.19	6.51	5.78	
		Vehicles	3.00	3.00	3.00	3.00	3.00	3.00	3.00	
N3-i5 16c	Dist. Matrix	Distance	168.54	190.43	170.01	199.58	171.81	190.10	170.01	
		LD-Pop	23,512.30	14,471.39	22,965.10	15,944.47	21,533.84	15,528.22	20,182.45	
		LI-Pop	49,683.11	59,160.99	44,382.61	57,111.56	44,818.13	60,696.35	44,382.61	
		LD-Risk	1,233.75	697.15	1,112.59	659.16	1,067.78	735.19	891.35	
		LI-Risk	2,479.31	3,101.09	2,080.71	2,856.70	2,079.58	3,168.17	2,080.71	
		LD-AP	2.36	1.54	2.36	1.75	2.23	1.53	2.12	
		LI-AP	4.93	5.77	4.62	5.81	4.71	5.76	4.62	
		Vehicles	3.00	3.00	3.00	3.00	3.00	3.00	3.00	
	Pop Matrix	Distance	179.79	221.07	179.79	228.22	191.43	221.07	185.22	
		LD-Pop	20,998.20	13,739.73	20,998.20	14,960.70	22,254.19	13,739.73	21,557.07	
		LI-Pop	41,603.46	50,697.88	41,603.46	52,993.37	43,204.03	50,697.88	43,061.48	
		LD-Risk	1,116.86	627.52	1,116.86	578.50	1,084.78	627.52	1,111.92	
		LI-Risk	2,070.65	2,331.27	2,070.65	2,434.36	2,050.87	2,331.27	2,150.97	
		LD-AP	2.22	1.49	2.22	1.69	2.43	1.49	2.17	
		LI-AP	4.50	5.21	4.50	5.72	4.74	5.21	4.43	
		Vehicles	3.00	3.00	3.00	3.00	3.00	3.00	3.00	
	Risk Matrix	Distance	197.77	223.53	197.77	223.53	198.19	218.68	198.19	
		LD-Pop	22,210.24	15,077.81	22,948.93	15,077.81	22,826.25	15,225.68	21,892.09	
		LI-Pop	44,537.02	53,737.45	44,537.02	53,737.45	44,949.87	53,300.64	44,949.87	
		LD-Risk	1,003.80	538.19	999.64	538.19	1,016.37	625.51	989.80	
		LI-Risk	1,854.52	2,171.04	1,854.52	2,171.04	1,853.62	2,220.37	1,853.62	
		LD-AP	2.35	1.68	2.45	1.68	2.39	1.65	2.31	
		LI-AP	4.83	5.67	4.83	5.67	4.82	5.66	4.82	
		Vehicles	3.00	3.00	3.00	3.00	3.00	3.00	3.00	
	AP Matrix	Distance	180.04	215.45	182.07	226.14	205.51	215.11	189.00	
		LD-Pop	25,319.21	13,776.08	17,594.93	15,423.52	20,114.31	14,832.91	21,331.82	
		LI-Pop	47,506.84	50,927.82	42,188.71	54,999.26	47,390.07	52,463.17	45,115.58	
		LD-Risk	1,278.48	626.33	799.75	577.06	876.03	664.37	959.95	
		LI-Risk	2,338.95	2,463.90	2,031.26	2,673.99	2,011.08	2,530.98	2,130.67	
		LD-AP	2.45	1.48	1.84	1.65	2.07	1.48	2.06	
		LI-AP	4.72	5.08	4.38	5.42	4.85	5.07	4.38	
		Vehicles	3.00	3.00	3.00	3.00	3.00	3.00	3.00	
	N3-i6 18c	Dist. Matrix	Distance	213.45	263.30	221.67	261.92	234.82	261.58	221.67
			LD-Pop	24,410.03	14,746.23	26,072.33	15,105.03	22,685.36	14,864.24	27,227.90
			LI-Pop	57,303.72	72,966.23	55,188.01	72,016.41	56,076.62	73,296.79	55,188.01
LD-Risk			1,235.11	655.20	1,369.07	610.77	1,020.00	648.31	1,406.74	
LI-Risk			2,834.28	3,670.06	2,719.34	3,123.43	2,497.39	3,543.38	2,719.34	
LD-AP			2.67	1.74	2.80	1.83	2.44	1.70	2.93	
LI-AP			6.12	7.87	5.96	7.82	6.13	7.92	5.96	
Vehicles			4.00	4.00	4.00	4.00	4.00	4.00	4.00	
Pop Matrix		Distance	223.91	283.19	231.56	285.85	233.38	292.11	231.52	
		LD-Pop	22,768.68	14,575.42	26,737.61	14,950.23	26,463.83	14,641.59	28,761.44	
		LI-Pop	55,724.40	66,929.95	52,806.10	65,405.64	53,460.07	66,981.01	53,339.29	
		LD-Risk	1,042.20	614.69	1,307.16	598.61	1,138.58	612.18	1,375.61	
		LI-Risk	2,600.57	3,004.17	2,404.65	2,759.03	2,283.38	2,957.26	2,392.87	
		LD-AP	2.69	1.73	2.87	1.80	3.11	1.73	3.15	
		LI-AP	6.35	7.74	5.97	7.44	6.16	7.70	5.95	
		Vehicles	4.00	4.00	4.00	4.00	4.00	4.00	4.00	
Risk Matrix		Distance	229.36	298.35	236.46	290.06	273.54	305.43	240.28	
		LD-Pop	28,833.28	15,417.14	26,141.00	15,949.10	28,502.34	15,636.88	25,128.77	

Table B1. (continued)

Inst	Matrix		Objective Min Dist.	Objective Min LD-Pop	Objective Min LI-Pop	Objective Min LD-Risk	Objective Min LI-Risk	Objective Min LD-AP	Objective Min LI-AP	
		LI-Pop	58,297.67	71,282.12	55,160.68	68,550.76	56,760.00	71,284.94	55,206.85	
		LD-Risk	1,204.80	586.61	1,112.40	552.15	1,109.26	581.25	1,141.40	
		LI-Risk	2,384.35	2,900.24	2,222.09	2,601.99	2,154.37	2,820.55	2,294.72	
		LD-AP	3.07	1.76	2.85	1.85	3.12	1.72	2.67	
		LI-AP	6.26	7.75	6.05	7.47	6.37	7.72	6.02	
		Vehicles	4.00	4.00	4.00	4.00	4.00	4.00	4.00	
	AP Matrix	Distance	222.16	283.33	229.21	294.07	239.65	296.67	231.82	
		LD-Pop	27,094.55	15,099.23	25,592.81	15,901.91	27,454.26	15,230.50	26,303.90	
		LI-Pop	57,334.16	70,722.38	54,805.90	67,075.99	55,905.50	71,269.01	55,711.57	
		LD-Risk	1,306.09	635.68	1,339.79	601.92	1,278.24	630.32	1,119.33	
		LI-Risk	2,745.95	3,620.06	2,640.02	2,990.67	2,408.81	3,562.53	2,504.50	
		LD-AP	2.74	1.67	2.68	1.73	2.84	1.66	2.70	
		LI-AP	5.90	7.35	5.79	6.91	5.95	7.36	5.73	
		Vehicles	4.00	4.00	4.00	4.00	4.00	4.00	4.00	
N3-i7 18c	Dist. Matrix	Distance	208.04	227.29	216.50	227.29	235.99	218.64	212.91	
		LD-Pop	25,453.40	19,881.75	29,679.37	19,881.75	30,546.70	21,295.56	23,761.17	
		LI-Pop	57,007.11	61,695.35	55,735.54	61,695.35	58,838.32	57,943.95	56,711.37	
		LD-Risk	1,344.76	832.48	1,411.46	832.48	1,260.24	960.60	1,202.56	
		LI-Risk	2,950.70	2,705.87	2,692.16	2,705.87	2,504.29	2,776.18	3,008.68	
		LD-AP	2.80	2.33	3.17	2.33	3.33	2.32	2.65	
		LI-AP	6.16	6.65	6.10	6.65	6.35	6.27	6.05	
	Pop Matrix	Vehicles	3.00	3.00	3.00	3.00	3.00	3.00	3.00	
		Distance	213.04	239.88	224.93	294.20	252.94	239.88	224.93	
		LD-Pop	24,857.55	19,717.34	24,355.50	21,056.72	26,416.46	19,717.34	27,704.30	
		LI-Pop	54,909.25	58,755.33	53,275.77	62,002.23	55,640.03	58,755.33	53,275.77	
		LD-Risk	1,098.64	841.11	1,116.80	794.29	1,187.28	841.11	1,260.39	
		LI-Risk	2,487.10	2,669.52	2,460.59	2,437.56	2,326.51	2,669.52	2,460.59	
		LD-AP	2.92	2.30	2.78	2.52	2.91	2.30	3.23	
	Risk Matrix	LI-AP	6.23	6.67	6.04	7.16	6.35	6.67	6.04	
		Vehicles	3.00	3.00	3.00	3.00	3.00	3.00	3.00	
		Distance	223.45	242.21	236.20	284.73	267.80	243.45	236.20	
		LD-Pop	27,250.67	20,890.55	25,743.08	21,731.31	28,622.54	21,593.98	28,816.36	
		LI-Pop	57,927.76	61,752.66	56,422.79	64,942.24	60,937.86	57,372.79	56,422.79	
		LD-Risk	1,078.29	789.96	1,078.99	766.36	1,062.57	906.62	1,187.29	
		LI-Risk	2,421.33	2,544.49	2,357.30	2,421.20	2,248.66	2,370.43	2,357.30	
	AP Matrix	LD-AP	3.03	2.34	2.73	2.45	3.05	2.25	3.09	
		LI-AP	6.26	6.55	6.10	6.98	6.53	6.17	6.10	
		Vehicles	3.00	3.00	3.00	3.00	3.00	3.00	3.00	
		Distance	215.71	239.19	222.22	287.56	234.50	236.06	226.28	
		LD-Pop	28,419.40	20,638.89	29,528.18	22,432.80	29,007.58	21,648.65	29,119.67	
		LI-Pop	57,783.82	61,431.16	55,671.32	64,727.92	57,027.54	58,038.87	56,525.20	
		LD-Risk	1,480.99	923.99	1,443.83	820.95	1,265.59	944.96	1,476.61	
		LI-Risk	2,896.34	3,023.97	2,733.00	2,890.25	2,410.44	2,849.24	2,826.57	
		LD-AP	2.99	2.25	3.15	2.46	2.96	2.22	3.04	
LI-AP		5.99	6.36	5.83	6.75	6.02	5.91	5.82		
Vehicles		3.00	3.00	3.00	3.00	3.00	3.00	3.00		
N3-i8 20c		Dist. Matrix	Distance	221.13	275.11	221.69	271.42	245.65	286.05	221.69
			LD-Pop	40,527.10	28,461.03	39,818.68	28,907.97	37,377.55	29,224.97	38,825.68
			LI-Pop	84,308.51	102,518.33	84,053.44	101,733.37	87,440.72	109,000.40	84,053.44
	LD-Risk		2,351.17	1,486.39	2,222.95	1,422.92	1,767.12	1,588.48	2,146.10	
	LI-Risk		4,731.93	5,856.98	4,683.29	5,699.99	4,383.99	6,266.56	4,683.29	
	LD-AP		3.88	2.83	3.78	2.93	3.83	2.78	3.74	
	LI-AP		8.09	10.13	8.04	10.07	8.89	10.52	8.04	
Vehicles	5.00	5.00	5.00	5.00	5.00	5.00	5.00			

Table B1. (continued)

Inst	Matrix		Objective Min Dist.	Objective Min LD-Pop	Objective Min LI-Pop	Objective Min LD-Risk	Objective Min LI-Risk	Objective Min LD-AP	Objective Min LI-AP	
	Pop Matrix	Distance	251.59	341.14	262.72	332.33	287.76	341.14	256.13	
		LD-Pop	34,135.62	23,720.85	32,649.73	25,218.79	32,015.61	23,720.85	34,874.48	
		LI-Pop	75,072.20	87,800.39	70,081.41	90,560.01	72,947.24	87,800.39	74,069.43	
		LD-Risk	1,884.41	1,205.91	1,734.38	1,124.59	1,497.28	1,205.91	1,874.41	
		LI-Risk	4,087.23	4,659.40	3,465.37	4,682.16	3,332.47	4,659.40	3,940.51	
		LD-AP	3.28	2.44	3.32	2.65	3.29	2.44	3.37	
		LI-AP	7.43	9.02	7.34	9.49	7.53	9.02	7.21	
	Vehicles	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	
	Risk Matrix	Distance	265.86	388.82	277.79	387.53	277.79	327.35	271.50	
		LD-Pop	36,354.45	24,612.12	34,402.02	26,630.61	34,264.90	25,029.65	36,156.89	
		LI-Pop	78,308.68	93,309.49	73,174.39	98,909.81	73,174.39	86,520.26	73,409.09	
		LD-Risk	1,677.31	1,191.53	1,419.88	1,093.05	1,426.77	1,240.20	1,625.99	
		LI-Risk	3,554.18	4,170.68	3,182.71	4,244.83	3,182.71	3,849.33	3,202.91	
		LD-AP	3.72	2.52	3.57	2.80	3.59	2.51	3.72	
		LI-AP	8.16	9.77	7.71	10.55	7.71	8.94	7.61	
	Vehicles	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	
	AP Matrix	Distance	247.61	337.46	259.47	352.37	291.62	336.73	253.18	
		LD-Pop	34,037.76	24,204.21	30,365.93	25,188.92	35,454.17	24,283.10	31,115.30	
		LI-Pop	79,060.76	89,407.89	71,682.79	94,053.72	76,211.72	90,622.86	71,917.49	
		LD-Risk	1,958.44	1,200.31	1,599.14	1,127.18	1,590.25	1,223.19	1,657.32	
		LI-Risk	4,494.84	4,469.38	3,745.34	4,640.75	3,459.51	4,768.23	3,765.54	
		LD-AP	3.24	2.40	2.96	2.56	3.52	2.39	3.08	
		LI-AP	7.49	8.83	7.03	9.34	7.60	8.80	6.94	
	Vehicles	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	
	N3-19 20c	Dist. Matrix	Distance	244.17	289.66	261.73	286.42	287.80	275.26	260.27
			LD-Pop	40,961.35	27,898.07	34,173.34	27,906.98	38,683.38	28,296.25	36,231.00
			LI-Pop	83,995.90	86,171.27	74,889.38	86,073.17	76,763.55	88,227.58	75,080.27
			LD-Risk	2,087.63	1,239.21	1,592.02	1,213.06	1,660.27	1,354.54	1,615.29
LI-Risk			4,377.38	4,323.74	3,593.27	4,276.61	3,378.85	4,664.27	3,606.65	
LD-AP			3.84	2.82	3.34	2.86	3.97	2.75	3.52	
LI-AP			7.82	8.37	7.37	8.42	7.77	8.40	7.29	
Vehicles		4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	
Pop Matrix		Distance	266.14	332.08	279.79	344.24	313.89	330.47	279.79	
		LD-Pop	30,255.53	25,796.25	30,907.06	26,642.87	29,236.90	26,060.57	31,107.62	
		LI-Pop	71,385.15	73,003.61	65,069.24	73,938.87	66,879.26	70,588.75	65,069.24	
		LD-Risk	1,427.35	1,189.48	1,206.06	1,049.38	1,285.71	1,182.84	1,599.40	
		LI-Risk	3,747.31	3,234.70	2,940.73	3,025.22	2,704.60	2,922.26	2,940.73	
		LD-AP	3.07	2.71	3.26	2.95	3.13	2.61	3.17	
		LI-AP	7.36	8.07	6.76	8.18	7.18	7.48	6.76	
Vehicles		4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	
Risk Matrix		Distance	290.00	372.07	296.36	344.61	317.17	372.07	295.95	
		LD-Pop	33,574.15	26,371.19	31,681.34	26,835.89	34,279.13	26,371.19	32,828.88	
		LI-Pop	70,421.56	76,998.06	67,221.53	74,613.71	67,712.24	76,998.06	67,374.71	
		LD-Risk	1,424.39	1,120.69	1,251.55	1,042.63	1,281.63	1,120.69	1,331.63	
		LI-Risk	2,992.27	3,029.41	2,748.45	2,989.73	2,645.02	3,029.41	2,799.88	
		LD-AP	3.44	2.77	3.40	2.92	3.67	2.77	3.57	
		LI-AP	7.34	8.34	7.26	8.09	7.31	8.34	7.18	
Vehicles		4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	
AP Matrix		Distance	264.20	344.23	276.13	320.48	311.12	324.83	274.34	
		LD-Pop	41,371.53	26,223.16	31,586.25	26,709.04	36,954.63	26,228.15	31,356.30	
		LI-Pop	86,526.83	74,884.33	66,286.65	74,247.56	68,052.14	71,863.66	67,181.85	
		LD-Risk	2,401.68	1,181.95	1,421.18	1,098.17	1,481.25	1,182.91	1,567.18	
	LI-Risk	4,829.71	3,099.41	2,982.08	3,235.14	2,814.89	3,117.76	3,113.97		
	LD-AP	3.69	2.57	3.13	2.71	3.73	2.56	3.00		
LI-AP	7.87	7.59	6.60	7.38	6.86	7.17	6.56			

Table B1. (continued)

Inst	Matrix		Objective Min Dist.	Objective Min LD-Pop	Objective Min LI-Pop	Objective Min LD-Risk	Objective Min LI-Risk	Objective Min LD-AP	Objective Min LI-AP	
		Vehicles	4.00	4.00	4.00	4.00	4.00	4.00	4.00	
N3-i10 22c	Dist. Matrix	Distance	229.32	263.66	233.09	259.09	263.35	260.63	233.09	
		LD-Pop	34,486.32	18,907.69	27,561.33	20,434.29	28,745.73	19,047.98	29,589.40	
		LI-Pop	67,747.04	81,199.10	59,378.99	76,979.00	65,202.26	81,632.46	59,378.99	
		LD-Risk	1,825.37	758.21	1,288.14	716.61	1,186.51	757.80	1,331.88	
		LI-Risk	3,529.15	3,857.47	2,805.09	3,570.10	2,699.69	3,996.82	2,805.09	
		LD-AP	3.40	2.03	3.00	2.16	3.17	2.01	3.10	
		LI-AP	6.87	8.26	6.35	7.86	7.08	8.10	6.35	
		Vehicles	5.00	5.00	5.00	5.00	5.00	5.00	5.00	
	Pop Matrix	Distance	244.35	300.27	244.35	299.84	270.86	285.18	244.35	
		LD-Pop	24,137.68	17,827.93	23,917.67	19,009.90	27,227.57	18,055.49	24,655.42	
		LI-Pop	55,004.53	73,574.78	55,004.53	68,149.23	59,985.10	72,698.24	55,004.53	
		LD-Risk	1,086.07	685.42	1,080.28	635.80	1,039.23	718.50	1,021.44	
		LI-Risk	2,432.61	3,470.48	2,432.61	2,813.80	2,306.86	3,389.31	2,432.61	
		LD-AP	2.60	1.95	2.58	2.06	3.01	1.93	2.68	
		LI-AP	6.04	8.04	6.04	7.38	6.52	7.79	6.04	
		Vehicles	5.00	5.00	5.00	5.00	5.00	5.00	5.00	
	Risk Matrix	Distance	248.86	306.99	249.53	328.79	274.64	310.11	265.07	
		LD-Pop	25,285.29	18,029.37	27,057.15	18,696.95	28,033.86	18,535.78	26,527.01	
		LI-Pop	59,753.56	70,749.71	56,748.60	81,704.79	61,046.80	69,384.60	57,718.33	
		LD-Risk	1,010.07	628.70	1,111.88	622.22	1,028.82	656.54	1,062.72	
		LI-Risk	2,504.05	2,742.84	2,348.36	3,187.32	2,251.69	2,661.54	2,325.84	
		LD-AP	2.80	1.92	2.95	1.96	3.04	1.91	2.87	
		LI-AP	6.40	7.46	6.23	8.56	6.57	7.36	6.17	
		Vehicles	5.00	5.00	5.00	5.00	5.00	5.00	5.00	
	AP Matrix	Distance	242.74	291.41	244.65	325.14	276.11	304.77	244.65	
		LD-Pop	30,938.74	18,089.00	26,220.05	18,946.84	29,717.15	19,325.32	27,981.60	
		LI-Pop	63,160.63	77,469.38	58,672.66	84,122.49	63,691.02	77,081.84	58,672.66	
		LD-Risk	1,456.48	644.11	1,170.73	632.44	1,239.04	744.51	1,344.59	
		LI-Risk	3,003.56	3,455.76	2,673.67	3,488.53	2,492.66	3,391.04	2,673.67	
		LD-AP	3.10	1.91	2.58	1.96	3.01	1.89	2.76	
		LI-AP	6.28	7.51	5.83	8.16	6.52	7.41	5.83	
		Vehicles	5.00	5.00	5.00	5.00	5.00	5.00	5.00	
	N3-i11 25c	Dist. Matrix	Distance	209.14	276.43	214.99	278.82	275.26	263.93	214.99
			LD-Pop	29,817.99	18,937.72	27,177.37	20,364.98	27,491.66	18,980.46	28,360.72
			LI-Pop	59,264.69	83,577.39	59,040.66	75,856.73	63,392.28	80,502.26	59,040.66
LD-Risk			1,539.45	811.20	1,245.86	741.90	1,121.89	812.24	1,326.94	
LI-Risk			2,948.80	4,322.42	2,871.70	3,549.04	2,729.01	4,291.75	2,871.70	
LD-AP			2.85	1.92	2.69	2.18	2.92	1.88	2.76	
LI-AP			5.73	8.03	5.70	7.64	6.55	7.85	5.70	
Vehicles			5	5	5	5	5	5	5	
Pop Matrix		Distance	231.11	348.49	231.11	324.51	239.03	316.73	231.11	
		LD-Pop	26,858.23	18,271.82	24,229.00	19,302.78	23,502.78	18,584.35	24,923.24	
		LI-Pop	52,550.88	73,349.02	52,550.88	79,864.44	54,117.98	74,611.33	52,550.88	
		LD-Risk	1,309.41	756.90	1,164.84	709.01	972.74	732.78	1,178.76	
		LI-Risk	2,401.03	3,279.16	2,401.03	3,601.40	2,386.13	3,305.45	2,401.03	
		LD-AP	3.00	1.95	2.72	2.11	2.50	1.89	2.69	
		LI-AP	5.71	8.00	5.71	8.55	5.93	7.84	5.71	
		Vehicles	5.00	5.00	5.00	5.00	5.00	5.00	5.00	
Risk Matrix		Distance	231.05	265.95	231.53	295.77	231.53	265.95	231.53	
		LD-Pop	23,091.78	18,736.11	27,064.93	19,872.82	25,422.34	18,736.11	27,092.56	
		LI-Pop	55,388.67	68,442.67	55,331.64	72,142.13	55,331.64	68,442.67	55,331.64	
		LD-Risk	935.42	735.00	1,129.34	688.62	1,095.25	735.00	1,216.19	
		LI-Risk	2,325.26	2,896.36	2,307.47	2,772.39	2,307.47	2,896.36	2,307.47	

Table B1. (continued)

Inst	Matrix		Objective Min Dist.	Objective Min LD-Pop	Objective Min LI-Pop	Objective Min LD-Risk	Objective Min LI-Risk	Objective Min LD-AP	Objective Min LI-AP
		LD-AP	2.38	1.91	2.81	2.09	2.55	1.91	2.73
		LI-AP	5.67	6.91	5.66	7.29	5.66	6.91	5.66
		Vehicles	5.00	5.00	5.00	5.00	5.00	5.00	5.00
	AP Matrix	Distance	226.87	263.86	226.87	296.91	242.08	326.20	226.87
		LD-Pop	26,448.02	18,842.88	25,529.04	20,009.49	29,004.42	18,937.94	28,781.60
		LI-Pop	55,617.69	70,973.68	55,617.69	84,653.37	58,619.17	79,312.01	55,617.69
		LD-Risk	1,255.95	725.82	1,158.68	700.63	1,237.42	730.14	1,413.63
		LI-Risk	2,544.87	3,216.00	2,544.87	3,859.14	2,449.38	3,404.45	2,544.87
		LD-AP	2.57	1.95	2.46	2.00	2.80	1.84	2.67
		LI-AP	5.40	6.86	5.40	8.01	5.81	7.55	5.40
Vehicles	5.00	5.00	5.00	5.00	5.00	5.00	5.00		
N4-i1 13c	Dist. Matrix	Distance	138.72	148.84	157.59	149.30	168.24	148.84	142.10
		LD-Pop	24,383.98	12,369.93	25,615.83	12,442.20	22,290.91	12,369.93	23,091.04
		LI-Pop	52,246.89	50,458.04	44,513.75	50,549.20	48,302.75	50,458.04	46,497.26
		LD-Risk	1,684.90	527.08	1,535.66	524.64	985.87	527.08	1,413.60
		LI-Risk	3,191.26	2,674.39	2,502.76	2,670.86	2,272.87	2,674.39	2,570.83
		LD-AP	2.15	1.25	2.50	1.25	2.25	1.25	2.06
		LI-AP	4.76	4.62	4.44	4.63	4.71	4.62	4.31
	Vehicles	2.00	2.00	2.00	2.00	2.00	2.00	2.00	
	Pop Matrix	Distance	154.13	179.09	167.96	183.93	194.78	180.26	168.22
		LD-Pop	20,894.58	11,856.38	18,523.87	12,427.53	21,329.11	11,930.28	24,734.30
		LI-Pop	44,135.74	46,537.67	42,655.15	47,802.77	43,939.93	46,721.61	42,728.87
		LD-Risk	1,246.63	536.41	916.30	522.95	1,025.24	536.28	1,459.88
		LI-Risk	2,500.71	2,394.81	2,350.95	2,483.52	2,177.93	2,395.29	2,347.46
		LD-AP	2.12	1.26	2.01	1.36	2.35	1.26	2.52
		LI-AP	4.53	4.74	4.46	5.02	4.68	4.75	4.46
	Vehicles	2.00	2.00	2.00	2.00	2.00	2.00	2.00	
	Risk Matrix	Distance	166.44	191.49	192.16	191.95	214.15	192.65	176.78
		LD-Pop	19,213.29	13,090.34	25,969.07	13,162.61	14,174.20	13,164.24	28,799.37
		LI-Pop	50,604.75	50,441.03	48,149.97	50,532.18	50,590.38	50,624.97	48,543.48
		LD-Risk	738.32	468.95	1,132.12	466.51	564.32	468.82	1,324.17
		LI-Risk	2,195.55	2,137.23	2,011.03	2,133.69	1,987.04	2,137.71	2,083.54
		LD-AP	1.83	1.25	2.50	1.25	1.39	1.25	2.67
		LI-AP	4.72	4.78	4.67	4.78	4.98	4.78	4.56
	Vehicles	2.00	2.00	2.00	2.00	2.00	2.00	2.00	
	AP Matrix	Distance	146.90	157.90	168.88	157.92	177.41	158.63	148.52
		LD-Pop	27,144.63	12,987.81	23,560.37	13,096.15	23,333.83	13,097.78	22,309.62
		LI-Pop	49,846.09	46,818.98	45,837.05	51,307.17	48,661.23	51,399.95	46,045.12
		LD-Risk	1,579.66	489.01	1,376.32	473.13	1,136.98	475.44	1,364.01
LI-Risk		2,812.73	2,307.52	2,365.73	2,537.34	2,157.10	2,541.36	2,459.16	
LD-AP		2.46	1.22	2.16	1.21	2.16	1.21	1.99	
LI-AP		4.52	4.38	4.19	4.53	4.46	4.53	4.15	
Vehicles	2.00	2.00	2.00	2.00	2.00	2.00	2.00		
N4-i2 13c	Dist. Matrix	Distance	130.56	154.27	135.50	153.83	135.50	154.27	135.50
		LD-Pop	14,834.24	10,064.46	17,779.04	12,099.50	10,146.37	10,064.46	21,452.29
		LI-Pop	42,547.47	44,999.02	33,789.01	41,539.20	33,789.01	44,999.02	33,789.01
		LD-Risk	826.82	393.05	829.91	359.22	366.06	393.05	1,081.56
		LI-Risk	2,578.14	2,238.42	1,558.91	1,825.01	1,558.91	2,238.42	1,558.91
		LD-AP	1.38	0.96	1.74	1.12	1.02	0.96	2.12
		LI-AP	3.97	4.10	3.34	3.85	3.34	4.10	3.34
	Vehicles	2.00	2.00	2.00	2.00	2.00	2.00	2.00	
	Pop Matrix	Distance	134.71	196.66	135.26	196.66	187.27	197.29	135.89
		LD-Pop	15,792.53	9,518.39	12,051.98	9,518.39	18,259.55	9,624.61	18,685.02
		LI-Pop	32,960.61	39,673.62	32,842.58	39,673.62	38,593.80	39,856.66	33,025.63

Table B1. (continued)

Inst	Matrix		Objective Min Dist.	Objective Min LD-Pop	Objective Min LI-Pop	Objective Min LD-Risk	Objective Min LI-Risk	Objective Min LD-AP	Objective Min LI-AP	
		LD-Risk	710.33	338.70	471.37	338.70	610.36	339.28	958.95	
		LI-Risk	1,533.21	1,518.74	1,538.59	1,518.74	1,472.96	1,519.50	1,539.35	
		LD-AP	1.64	0.95	1.24	0.95	1.86	0.95	1.85	
		LI-AP	3.35	4.11	3.29	4.11	3.93	4.09	3.28	
		Vehicles	2.00	2.00	2.00	2.00	2.00	2.00	2.00	
	Risk Matrix	Distance	160.07	205.79	160.07	206.83	196.42	206.83	161.12	
		LD-Pop	19,007.18	10,491.70	19,007.18	10,637.14	22,944.75	10,637.14	17,645.44	
		LI-Pop	38,897.42	43,609.88	38,897.42	43,845.56	41,730.15	43,845.56	39,133.10	
		LD-Risk	790.69	314.06	790.69	312.52	771.13	312.52	487.38	
		LI-Risk	1,350.65	1,325.95	1,350.65	1,323.85	1,311.83	1,323.85	1,348.55	
		LD-AP	1.83	0.91	1.83	0.91	2.19	0.91	1.53	
		LI-AP	3.57	3.97	3.57	3.96	3.84	3.96	3.56	
		Vehicles	2.00	2.00	2.00	2.00	2.00	2.00	2.00	
	AP Matrix	Distance	138.09	167.74	138.09	167.74	199.32	167.74	138.09	
		LD-Pop	19,178.36	10,563.15	13,379.40	10,563.15	20,958.88	10,563.15	15,594.08	
		LI-Pop	34,706.16	42,458.40	34,706.16	42,458.40	43,340.25	42,458.40	34,706.16	
		LD-Risk	963.84	332.50	470.07	332.50	805.13	332.50	721.66	
		LI-Risk	1,540.15	1,858.22	1,540.15	1,858.22	1,491.31	1,858.22	1,540.15	
		LD-AP	1.79	0.85	1.12	0.85	1.85	0.85	1.41	
		LI-AP	3.10	3.56	3.10	3.56	3.67	3.56	3.10	
		Vehicles	2.00	2.00	2.00	2.00	2.00	2.00	2.00	
	N4-i3 15c	Dist. Matrix	Distance	196.43	200.83	203.90	227.93	199.76	201.48	196.80
			LD-Pop	31,331.67	18,052.90	23,695.58	19,403.60	28,172.50	18,106.63	27,332.89
			LI-Pop	56,177.87	67,419.31	55,383.48	73,440.48	57,449.77	67,520.81	55,873.02
			LD-Risk	1,636.08	1,053.38	1,307.86	787.86	1,375.36	1,053.50	1,547.83
			LI-Risk	3,088.73	3,771.55	3,239.14	3,972.53	3,049.86	3,771.89	3,061.90
			LD-AP	3.01	1.79	2.35	1.91	2.76	1.76	2.59
			LI-AP	5.33	6.16	5.36	6.74	5.51	6.13	5.29
Vehicles			3.00	3.00	3.00	3.00	3.00	3.00	3.00	
Pop Matrix		Distance	205.86	234.48	209.78	253.34	209.78	235.12	209.78	
		LD-Pop	26,948.79	17,635.07	22,347.77	18,511.10	25,101.56	17,701.48	22,347.77	
		LI-Pop	50,155.39	57,833.88	47,717.48	59,775.89	47,717.48	57,935.37	47,717.48	
		LD-Risk	1,681.03	1,010.77	877.48	708.67	1,171.31	1,010.93	877.48	
		LI-Risk	2,684.09	2,932.04	2,085.39	2,651.38	2,085.39	2,932.38	2,085.39	
		LD-AP	2.64	1.72	2.33	1.94	2.49	1.68	2.33	
		LI-AP	5.00	5.73	4.83	5.99	4.83	5.70	4.83	
		Vehicles	3.00	3.00	3.00	3.00	3.00	3.00	3.00	
Risk Matrix		Distance	219.73	241.78	219.73	280.76	219.73	262.47	219.73	
		LD-Pop	27,650.63	19,919.04	25,766.84	21,268.43	25,380.68	20,296.21	28,961.72	
		LI-Pop	52,769.68	58,421.60	52,769.68	63,219.87	52,769.68	66,464.07	52,769.68	
		LD-Risk	1,133.09	699.90	850.55	653.72	1,071.15	781.26	1,139.44	
		LI-Risk	1,969.83	2,231.17	1,969.83	2,233.33	1,969.83	2,498.89	1,969.83	
		LD-AP	2.50	1.85	2.34	1.98	2.33	1.78	2.64	
		LI-AP	4.81	5.42	4.81	5.84	4.81	6.11	4.81	
		Vehicles	3.00	3.00	3.00	3.00	3.00	3.00	3.00	
AP Matrix		Distance	214.51	246.06	225.54	264.18	225.54	246.36	225.54	
		LD-Pop	29,535.35	19,649.02	27,987.27	21,267.56	24,673.69	19,751.01	27,987.27	
		LI-Pop	55,203.26	63,649.49	54,295.88	64,144.84	54,295.88	63,835.75	54,295.88	
		LD-Risk	1,464.79	1,017.03	948.12	719.59	878.18	1,020.78	948.12	
		LI-Risk	2,771.75	2,966.89	2,091.57	2,568.97	2,091.57	2,972.29	2,091.57	
		LD-AP	2.51	1.61	2.37	1.77	2.08	1.61	2.37	
	LI-AP	4.73	5.47	4.62	5.48	4.62	5.47	4.62		
	Vehicles	3.00	3.00	3.00	3.00	3.00	3.00	3.00		
N4-i4	Dist.	Distance	178.55	213.13	204.43	222.89	204.43	193.00	203.22	

Table B1. (continued)

Inst	Matrix		Objective Min Dist.	Objective Min LD-Pop	Objective Min LI-Pop	Objective Min LD-Risk	Objective Min LI-Risk	Objective Min LD-AP	Objective Min LI-AP	
16c	Matrix	LD-Pop	38,592.95	18,463.19	27,307.31	20,275.56	24,089.57	19,253.35	26,688.73	
		LI-Pop	61,827.28	68,656.71	51,797.57	59,736.95	51,797.57	66,178.44	51,936.17	
		LD-Risk	2,633.84	886.74	1,212.83	772.96	1,291.38	979.28	1,457.14	
		LI-Risk	3,885.06	4,415.27	2,521.67	3,146.93	2,521.67	4,284.05	2,590.12	
		LD-AP	3.44	1.82	2.66	2.19	2.34	1.79	2.50	
		LI-AP	5.54	6.31	5.05	5.84	5.05	5.94	4.99	
		Vehicles	3.00	3.00	3.00	3.00	3.00	3.00	3.00	
	Pop Matrix	Distance	195.00	265.17	204.12	234.85	301.19	236.03	203.33	
		LD-Pop	32,592.71	18,433.46	24,697.27	19,100.30	24,130.24	18,461.35	22,096.38	
		LI-Pop	59,905.10	53,475.79	46,170.29	52,699.84	54,461.29	51,333.46	46,193.33	
		LD-Risk	2,005.71	882.38	938.35	739.61	933.49	922.80	1,075.14	
		LI-Risk	3,461.84	2,330.04	2,004.47	2,252.95	1,952.26	2,407.23	2,005.69	
		LD-AP	3.14	1.82	2.67	2.05	2.62	1.80	2.21	
		LI-AP	5.84	5.71	4.87	5.56	6.03	5.43	4.86	
	Risk Matrix	Distance	219.93	294.63	220.72	255.60	220.72	305.63	219.93	
		LD-Pop	23,734.27	19,216.26	25,042.88	22,399.81	24,929.89	19,257.68	25,119.40	
		LI-Pop	49,756.65	60,021.68	49,733.60	56,065.39	49,733.60	61,272.79	49,756.65	
		LD-Risk	816.14	812.11	1,002.06	707.39	1,048.83	793.68	998.88	
		LI-Risk	1,851.46	1,988.68	1,850.24	1,960.24	1,850.24	1,999.85	1,851.46	
		LD-AP	2.32	1.91	2.54	2.24	2.52	1.89	2.55	
		LI-AP	4.97	5.99	4.98	5.65	4.98	6.00	4.97	
	AP Matrix	Distance	189.57	237.52	205.53	237.38	257.44	258.45	205.53	
		LD-Pop	35,643.22	18,579.08	26,716.78	21,186.28	28,507.37	19,487.50	24,314.70	
		LI-Pop	61,793.88	55,235.65	48,463.08	54,381.45	54,004.68	55,974.13	48,463.08	
		LD-Risk	2,230.49	921.24	943.72	751.85	849.82	982.14	1,136.28	
		LI-Risk	3,783.72	2,380.79	2,003.61	2,163.61	1,978.86	2,269.44	2,003.61	
		LD-AP	3.15	1.80	2.64	2.12	2.73	1.77	2.27	
		LI-AP	5.46	5.11	4.64	5.11	5.13	5.07	4.64	
	Vehicles	3.00	3.00	3.00	3.00	3.00	3.00	3.00		
	N4-i5 18c	Dist. Matrix	Distance	179.84	199.25	187.15	213.67	200.48	213.67	188.23
			LD-Pop	35,388.17	23,506.34	29,478.19	23,829.37	26,842.86	23,829.37	29,165.97
			LI-Pop	66,129.15	70,067.47	61,054.56	80,007.23	68,768.62	80,007.23	61,982.48
			LD-Risk	2,215.53	1,135.89	1,785.17	1,131.55	1,359.58	1,131.55	1,718.86
LI-Risk			4,224.85	4,081.02	3,986.30	4,699.16	3,836.46	4,699.16	3,845.95	
LD-AP			3.38	2.34	2.85	2.30	2.63	2.30	2.82	
LI-AP			6.13	6.66	5.87	7.35	6.49	7.35	5.87	
Pop Matrix		Distance	194.43	255.61	212.08	255.51	232.14	245.83	212.08	
		LD-Pop	27,112.86	22,106.57	25,921.36	22,926.74	28,565.96	22,117.34	25,529.08	
		LI-Pop	63,259.40	69,055.65	55,131.50	69,955.63	60,295.98	69,901.27	55,131.50	
		LD-Risk	1,534.71	1,086.89	1,452.66	1,019.80	1,302.03	1,026.72	1,412.41	
		LI-Risk	3,890.38	3,606.47	3,067.90	3,519.02	2,944.81	3,549.67	3,067.90	
		LD-AP	2.53	2.35	2.49	2.34	2.92	2.20	2.64	
		LI-AP	6.00	6.94	5.56	7.00	5.98	6.92	5.56	
Risk Matrix		Distance	229.68	284.60	235.36	319.20	235.36	284.60	235.36	
		LD-Pop	27,775.33	23,424.92	28,257.82	25,352.97	28,257.82	23,424.92	28,183.58	
		LI-Pop	60,522.05	74,669.42	60,101.27	81,413.48	60,101.27	74,669.42	60,101.27	
		LD-Risk	1,223.49	987.63	1,254.98	934.28	1,254.98	987.63	1,249.87	
		LI-Risk	2,751.47	3,356.81	2,695.93	3,291.83	2,695.93	3,356.81	2,695.93	
		LD-AP	2.73	2.24	2.69	2.42	2.69	2.24	2.79	
		LI-AP	5.87	7.21	5.87	7.87	5.87	7.21	5.87	
Vehicles		3.00	3.00	3.00	3.00	3.00	3.00	3.00		

Table B1. (continued)

Inst	Matrix		Objective Min Dist.	Objective Min LD-Pop	Objective Min LI-Pop	Objective Min LD-Risk	Objective Min LI-Risk	Objective Min LD-AP	Objective Min LI-AP
	AP Matrix	Distance	197.50	234.45	218.12	249.80	236.09	234.45	218.12
		LD-Pop	33,445.81	23,143.43	32,193.21	25,099.50	33,230.96	23,143.43	27,302.67
		LI-Pop	64,359.02	73,720.87	58,096.61	75,420.51	63,454.98	73,720.87	58,096.61
		LD-Risk	2,047.11	1,038.43	1,773.23	1,027.97	1,649.18	1,038.43	1,454.35
		LI-Risk	3,913.09	3,986.62	3,094.82	3,977.83	2,994.36	3,986.62	3,094.82
		LD-AP	3.08	2.13	2.89	2.21	2.97	2.13	2.47
		LI-AP	5.93	6.59	5.29	6.79	5.69	6.59	5.29
		Vehicles	3.00	3.00	3.00	3.00	3.00	3.00	3.00
N4-i6 20c	Dist. Matrix	Distance	211.50	258.05	237.65	245.77	238.01	258.05	227.16
		LD-Pop	20,853.99	15,647.14	29,787.71	16,751.42	28,047.15	15,647.14	21,492.47
		LI-Pop	67,137.63	76,626.17	54,957.79	71,494.04	55,122.56	76,626.17	55,236.11
		LD-Risk	861.67	606.73	1,205.46	591.54	1,056.88	606.73	833.71
		LI-Risk	3,393.33	3,793.95	2,185.17	3,261.69	2,181.46	3,793.95	2,366.39
		LD-AP	1.89	1.55	2.87	1.56	2.54	1.55	2.03
		LI-AP	5.97	7.04	5.17	6.30	5.15	7.04	5.13
	Vehicles	4.00	4.00	4.00	4.00	4.00	4.00	4.00	
	Pop Matrix	Distance	225.35	250.48	234.84	278.75	242.41	249.25	236.80
		LD-Pop	31,028.93	14,970.18	23,823.15	16,128.20	30,091.68	15,047.35	32,348.56
		LI-Pop	51,916.10	52,166.31	49,888.64	55,746.83	51,465.89	51,872.35	50,641.68
		LD-Risk	1,464.29	555.88	1,023.26	497.70	1,249.49	555.85	1,377.18
		LI-Risk	2,314.04	2,198.81	2,177.26	2,100.36	1,952.96	2,196.27	2,093.53
		LD-AP	2.82	1.45	2.52	1.52	2.81	1.44	3.03
		LI-AP	4.96	5.02	4.89	5.37	4.96	5.00	4.85
	Vehicles	4.00	4.00	4.00	4.00	4.00	4.00	4.00	
	Risk Matrix	Distance	244.77	270.48	250.53	269.06	253.05	289.12	253.05
		LD-Pop	28,433.98	16,952.97	28,371.98	17,453.93	33,291.54	17,000.15	31,837.86
		LI-Pop	63,793.06	57,325.21	55,457.89	57,463.72	55,466.17	63,050.31	55,466.17
		LD-Risk	1,137.61	470.42	924.34	462.88	1,223.28	474.73	1,175.14
		LI-Risk	2,505.22	1,946.69	1,832.34	1,937.57	1,822.32	2,153.13	1,822.32
		LD-AP	2.46	1.49	2.48	1.49	2.94	1.48	2.77
		LI-AP	5.45	5.10	4.91	5.08	4.89	5.62	4.89
	Vehicles	4.00	4.00	4.00	4.00	4.00	4.00	4.00	
	AP Matrix	Distance	236.00	265.78	250.23	296.26	274.90	265.78	252.50
		LD-Pop	34,617.66	17,190.31	31,895.33	18,375.85	24,869.29	17,227.04	31,506.54
		LI-Pop	61,930.84	58,417.98	56,070.43	62,935.11	60,048.02	58,417.98	56,888.34
		LD-Risk	1,443.82	560.52	1,307.92	512.05	773.07	560.77	1,265.44
		LI-Risk	2,663.20	2,212.04	2,096.83	2,138.97	1,988.67	2,212.04	2,088.79
		LD-AP	2.94	1.35	2.69	1.45	2.10	1.34	2.55
LI-AP		5.22	4.73	4.63	5.09	4.85	4.73	4.60	
Vehicles	4.00	4.00	4.00	4.00	4.00	4.00	4.00		
N4-i7 20c	Dist. Matrix	Distance	266.98	296.94	294.77	315.44	296.51	305.89	294.15
		LD-Pop	43,009.44	30,690.58	39,169.97	32,566.96	44,607.11	31,734.42	51,827.58
		LI-Pop	103,691.96	101,538.18	92,405.89	104,823.61	99,555.29	107,042.89	92,689.73
		LD-Risk	2,669.40	1,677.47	2,246.05	1,520.55	2,045.12	1,617.56	3,121.79
		LI-Risk	6,340.27	5,902.06	5,461.22	5,455.48	5,087.01	5,880.47	5,457.50
		LD-AP	4.04	3.06	3.77	3.19	4.13	3.05	4.87
		LI-AP	9.58	9.58	8.79	9.77	9.25	9.92	8.78
	Vehicles	4.00	4.00	4.00	4.00	4.00	4.00	4.00	
	Pop Matrix	Distance	312.75	352.60	339.86	391.90	388.33	352.60	339.86
		LD-Pop	46,693.05	28,256.57	37,057.99	30,553.65	40,321.85	28,256.57	37,630.94
		LI-Pop	86,695.58	87,504.81	78,501.27	88,798.88	85,237.59	87,504.81	78,501.27
		LD-Risk	2,485.46	1,285.27	1,939.48	1,210.36	1,550.93	1,285.27	1,831.27
		LI-Risk	4,416.59	4,397.73	3,882.05	4,019.63	3,621.15	4,397.73	3,882.05
		LD-AP	4.58	2.90	3.52	3.11	4.10	2.90	3.68

Table B1. (continued)

Inst	Matrix		Objective Min Dist.	Objective Min LD-Pop	Objective Min LI-Pop	Objective Min LD-Risk	Objective Min LI-Risk	Objective Min LD-AP	Objective Min LI-AP
		LI-AP	8.48	8.65	7.60	8.90	8.60	8.65	7.60
		Vehicles	4.00	4.00	4.00	4.00	4.00	4.00	4.00
	Risk Matrix	Distance	354.92	439.99	360.63	459.49	391.32	420.10	365.80
		LD-Pop	46,884.42	30,690.20	34,915.65	34,664.19	40,115.91	30,717.02	38,303.14
		LI-Pop	86,261.09	97,800.16	84,986.06	102,839.78	87,061.72	91,690.18	85,149.34
		LD-Risk	2,062.21	1,184.08	1,361.57	1,151.65	1,556.41	1,205.42	1,678.64
		LI-Risk	3,686.85	3,830.62	3,609.42	4,141.41	3,397.27	3,572.25	3,492.60
		LD-AP	4.40	2.96	3.38	3.34	3.80	2.94	3.66
		LI-AP	8.27	9.32	8.23	9.86	8.20	8.76	8.11
		Vehicles	4.00	4.00	4.00	4.00	4.00	4.00	4.00
	AP Matrix	Distance	316.19	365.23	338.68	386.86	393.84	368.00	352.79
		LD-Pop	45,960.29	29,997.22	42,229.55	35,204.06	47,716.66	31,649.66	47,647.80
		LI-Pop	90,865.72	92,657.08	83,575.14	98,876.93	87,366.41	89,192.20	84,102.73
		LD-Risk	2,357.36	1,284.50	2,110.69	1,218.74	1,901.92	1,384.98	2,101.41
		LI-Risk	4,488.35	4,374.18	4,029.05	4,334.98	3,670.98	4,083.58	3,944.42
		LD-AP	4.12	2.79	3.73	3.16	4.11	2.78	4.06
		LI-AP	8.10	8.26	7.37	8.88	7.66	7.76	7.30
		Vehicles	4.00	4.00	4.00	4.00	4.00	4.00	4.00
N4-i8 22c	Dist. Matrix	Distance	239.34	260.28	265.90	261.84	268.81	263.27	247.99
		LD-Pop	40,388.75	21,960.75	29,693.36	22,958.92	30,758.95	22,012.62	23,937.34
		LI-Pop	72,921.53	85,429.98	70,635.38	82,618.70	71,876.63	85,096.51	73,142.57
		LD-Risk	2,608.70	1,067.51	1,490.27	1,023.15	1,469.68	1,084.01	1,179.94
		LI-Risk	4,209.67	4,939.72	3,685.63	4,794.80	3,601.02	4,893.31	3,865.55
		LD-AP	3.73	2.21	2.91	2.37	3.00	2.21	2.42
		LI-AP	6.99	7.99	6.91	7.76	7.06	7.99	6.83
	Pop Matrix	Vehicles	4.00	4.00	4.00	4.00	4.00	4.00	4.00
		Distance	248.16	292.60	264.57	290.76	319.37	292.60	275.60
		LD-Pop	37,343.93	21,056.88	31,558.49	22,585.99	36,926.63	21,056.88	27,703.78
		LI-Pop	69,348.43	72,590.72	64,935.09	73,756.44	73,003.92	72,590.72	66,104.10
		LD-Risk	2,061.71	1,068.93	1,602.91	1,008.11	1,450.07	1,068.93	1,551.59
		LI-Risk	3,654.53	3,546.60	3,457.45	3,705.30	3,128.47	3,546.60	3,471.91
		LD-AP	3.74	2.17	3.34	2.38	3.90	2.17	2.84
	Risk Matrix	LI-AP	7.09	7.37	6.71	7.39	7.55	7.37	6.68
		Vehicles	4.00	4.00	4.00	4.00	4.00	4.00	4.00
		Distance	280.13	394.51	288.21	404.67	332.61	389.50	288.21
		LD-Pop	32,878.54	24,297.18	31,181.50	25,560.53	39,883.05	24,403.10	35,833.06
		LI-Pop	77,913.77	90,365.67	74,277.79	90,917.15	77,543.78	85,968.22	74,277.79
		LD-Risk	1,395.27	947.69	1,266.93	934.76	1,359.60	983.69	1,608.12
		LI-Risk	3,437.67	3,431.05	3,107.76	3,303.19	2,898.09	3,152.99	3,107.76
	AP Matrix	LD-AP	3.10	2.32	2.92	2.47	3.94	2.30	3.43
		LI-AP	7.47	8.80	7.11	8.74	7.48	8.37	7.11
		Vehicles	4.00	4.00	4.00	4.00	4.00	4.00	4.00
		Distance	248.38	305.77	273.76	308.57	310.53	305.77	284.88
		LD-Pop	35,356.72	23,003.97	33,159.39	24,020.40	36,986.62	23,003.97	31,024.67
		LI-Pop	72,651.71	79,031.72	70,513.32	83,067.15	75,867.39	79,031.72	71,345.30
		LD-Risk	1,920.41	1,070.24	1,493.18	1,017.04	1,464.27	1,070.24	1,494.35
	Risk Matrix	LI-Risk	3,836.06	3,618.14	3,404.41	4,104.14	3,103.74	3,618.14	3,429.65
		LD-AP	3.36	2.12	3.00	2.19	3.41	2.12	2.79
LI-AP		6.78	7.12	6.59	7.48	6.99	7.12	6.51	
Vehicles		4.00	4.00	4.00	4.00	4.00	4.00	4.00	
LD-Risk		2,188.43	1,079.78	2,286.33	1,023.59	1,793.84	1,433.33	2,546.09	
N4-i9 25c	Dist. Matrix	Distance	221.21	247.92	259.12	244.02	262.44	245.16	223.88
		LD-Pop	34,437.13	22,491.99	34,582.73	22,934.71	32,769.34	23,422.37	35,455.69
		LI-Pop	73,054.63	74,516.83	67,489.38	76,235.03	69,962.21	82,388.38	70,819.62
		LD-Risk	2,188.43	1,079.78	2,286.33	1,023.59	1,793.84	1,433.33	2,546.09

Table B1. (continued)

Inst	Matrix		Objective Min Dist.	Objective Min LD-Pop	Objective Min LI-Pop	Objective Min LD-Risk	Objective Min LI-Risk	Objective Min LD-AP	Objective Min LI-AP
		LI-Risk	4,606.25	4,463.02	3,863.68	4,517.81	3,625.24	4,875.54	4,346.02
		LD-AP	3.25	2.40	3.37	2.41	3.27	2.30	3.41
		LI-AP	7.08	7.20	6.88	7.43	7.04	7.91	6.78
		Vehicles	4.00	4.00	4.00	4.00	4.00	4.00	4.00
	Pop Matrix	Distance	235.36	270.80	254.43	300.44	258.32	276.39	244.78
		LD-Pop	32,180.72	22,274.10	29,387.05	23,429.05	28,338.33	22,987.60	31,948.56
		LI-Pop	71,085.20	70,790.58	63,950.08	73,793.30	66,236.02	72,452.45	64,074.63
		LD-Risk	1,805.25	1,019.52	1,710.56	1,037.63	1,351.31	1,422.08	2,038.54
		LI-Risk	4,229.69	3,678.96	3,390.40	3,694.15	3,195.49	4,168.23	3,701.64
		LD-AP	3.28	2.39	2.90	2.57	2.89	2.31	3.14
		LI-AP	7.12	7.17	6.46	7.63	6.60	7.48	6.39
		Vehicles	4.00	4.00	4.00	4.00	4.00	4.00	4.00
		Risk Matrix	Distance	270.43	327.11	286.89	299.05	285.73	294.64
	LD-Pop		43,631.96	25,302.84	36,419.88	25,454.46	27,835.61	25,447.08	36,054.43
	LI-Pop		81,755.71	84,502.76	71,442.96	78,168.27	71,851.23	77,281.43	71,472.32
	LD-Risk		2,070.77	983.62	1,566.94	931.58	1,158.72	960.82	1,583.95
	LI-Risk		3,812.18	3,523.50	3,021.48	3,267.12	2,994.67	3,217.91	3,001.36
	LD-AP		4.25	2.50	3.48	2.54	2.73	2.51	3.45
	LI-AP		7.86	8.17	6.88	7.54	6.84	7.38	6.83
	Vehicles		4.00	4.00	4.00	4.00	4.00	4.00	4.00
	AP	Distance	235.80	306.21	262.27	264.26	279.40	274.94	240.71
	Matrix	LD-Pop	41,317.06	23,452.58	30,513.08	23,921.82	35,142.03	23,754.54	38,113.01
		LI-Pop	77,898.44	80,765.39	67,146.51	75,240.44	70,506.88	78,210.77	68,257.54
		LD-Risk	2,421.41	1,056.88	1,697.41	1,025.39	1,611.98	1,457.81	2,096.79
		LI-Risk	4,589.66	3,882.48	3,452.30	3,780.21	3,233.10	4,178.28	3,600.44
		LD-AP	3.82	2.34	2.91	2.30	3.35	2.25	3.43
		LI-AP	7.33	7.72	6.39	7.05	6.68	7.28	6.25
		Vehicles	4.00	4.00	4.00	4.00	4.00	4.00	4.00
N5-i1 15c	Dist. Matrix	Distance	144.08	191.85	170.52	215.53	176.89	185.96	149.92
		LD-Pop	20,331.43	10,013.32	21,075.21	10,781.73	16,606.91	11,354.18	23,059.79
		LI-Pop	43,239.53	52,857.53	37,835.40	55,847.56	39,057.76	56,996.41	43,943.75
		LD-Risk	1,416.67	548.01	1,794.89	412.16	790.27	774.26	1,817.11
		LI-Risk	3,373.99	3,635.08	2,580.11	3,251.95	2,090.86	4,185.16	3,380.65
		LD-AP	1.55	1.17	1.62	1.26	1.66	1.09	1.66
		LI-AP	3.29	4.33	3.34	4.66	3.44	4.39	3.24
	Vehicles	3.00	3.00	3.00	3.00	3.00	3.00	3.00	
	Pop Matrix	Distance	152.66	201.43	158.22	203.38	158.88	201.43	154.60
		LD-Pop	18,425.96	8,375.07	15,084.95	8,493.90	17,629.17	8,375.07	11,953.70
		LI-Pop	32,229.73	36,738.83	31,823.95	37,009.49	31,966.31	36,738.83	32,500.38
		LD-Risk	1,353.57	334.80	1,036.15	332.11	1,117.07	334.80	594.00
		LI-Risk	2,003.15	1,875.05	1,782.86	1,865.92	1,773.09	1,875.05	1,994.02
		LD-AP	1.55	1.00	1.38	1.00	1.55	1.00	1.16
		LI-AP	2.95	3.93	3.02	3.92	3.01	3.93	2.94
		Vehicles	3.00	3.00	3.00	3.00	3.00	3.00	3.00
	Risk Matrix	Distance	165.62	207.60	165.62	207.60	166.21	207.60	166.21
		LD-Pop	11,575.04	8,984.79	19,749.62	8,984.79	17,855.19	8,984.79	19,157.81
		LI-Pop	34,402.06	40,890.04	34,402.06	40,890.04	34,471.56	40,890.04	34,471.56
		LD-Risk	463.49	315.74	1,066.98	315.74	995.07	315.74	1,054.32
		LI-Risk	1,708.09	1,736.04	1,708.09	1,736.04	1,707.21	1,736.04	1,707.21
		LD-AP	1.16	0.99	1.59	0.99	1.49	0.99	1.56
		LI-AP	3.02	3.78	3.02	3.78	3.01	3.78	3.01
		Vehicles	3.00	3.00	3.00	3.00	3.00	3.00	3.00
	AP Matrix	Distance	154.68	212.43	161.21	213.76	205.18	212.43	158.65
		LD-Pop	21,787.94	9,156.47	19,099.47	9,257.57	19,932.73	9,156.47	11,587.63
		LI-Pop	37,111.44	41,343.03	34,576.37	41,559.11	40,848.07	41,343.03	35,318.81

Table B1. (continued)

Inst	Matrix		Objective Min Dist.	Objective Min LD-Pop	Objective Min LI-Pop	Objective Min LD-Risk	Objective Min LI-Risk	Objective Min LD-AP	Objective Min LI-AP	
		LD-Risk	1,709.38	322.27	1,061.41	321.96	893.28	322.27	587.68	
		LI-Risk	2,574.92	1,752.82	1,735.01	1,751.02	1,717.53	1,752.82	1,961.95	
		LD-AP	1.61	0.99	1.54	0.99	1.75	0.99	1.07	
		LI-AP	2.99	3.76	2.97	3.77	3.59	3.76	2.89	
		Vehicles	3.00	3.00	3.00	3.00	3.00	3.00	3.00	
N5-i2 16c	Dist. Matrix	Distance	189.02	204.07	209.61	268.39	215.03	204.07	199.52	
		LD-Pop	17,507.46	12,632.80	22,246.64	16,433.05	20,648.41	12,632.80	25,233.52	
		LI-Pop	61,869.61	61,133.23	41,024.78	52,509.98	41,535.44	61,133.23	46,786.77	
		LD-Risk	1,047.71	681.86	1,434.33	649.13	1,267.73	681.86	2,071.19	
		LI-Risk	4,620.81	4,369.45	2,534.76	2,841.08	2,521.82	4,369.45	3,330.44	
		LD-AP	1.42	1.21	2.13	1.96	1.95	1.21	1.91	
		LI-AP	4.28	4.45	4.02	5.24	3.97	4.45	3.86	
		Vehicles	3.00	3.00	3.00	3.00	3.00	3.00	3.00	
	Pop Matrix	Distance	202.18	219.90	214.19	219.90	219.90	219.90	219.90	205.56
		LD-Pop	18,441.71	10,933.98	14,524.04	10,933.98	21,424.42	10,933.98	16,038.94	
		LI-Pop	36,748.99	38,371.90	36,564.60	38,371.90	38,371.90	38,371.90	36,839.00	
		LD-Risk	1,107.58	445.19	765.48	445.19	1,080.03	445.19	816.85	
		LI-Risk	2,037.34	1,912.55	2,039.65	1,912.55	1,912.55	1,912.55	2,028.78	
		LD-AP	1.99	1.25	1.55	1.25	2.09	1.25	1.63	
LI-AP		3.84	4.09	4.03	4.09	4.09	4.09	3.83		
Vehicles		3.00	3.00	3.00	3.00	3.00	3.00	3.00		
	Risk Matrix	Distance	225.72	225.72	225.72	229.21	229.21	225.72	225.72	
		LD-Pop	16,511.29	11,307.09	11,940.63	11,427.08	20,787.28	11,307.09	21,921.24	
		LI-Pop	39,631.54	39,631.54	39,631.54	39,684.59	39,684.59	39,631.54	39,631.54	
		LD-Risk	792.63	428.71	445.20	428.13	946.05	428.71	1,107.42	
		LI-Risk	1,864.37	1,864.37	1,864.37	1,862.74	1,862.74	1,864.37	1,864.37	
		LD-AP	1.76	1.24	1.36	1.26	1.90	1.24	2.04	
		LI-AP	4.00	4.00	4.00	4.02	4.02	4.00	4.00	
		Vehicles	3.00	3.00	3.00	3.00	3.00	3.00	3.00	
	AP Matrix	Distance	202.54	218.11	206.04	218.11	221.59	218.11	206.04	
		LD-Pop	16,563.45	11,282.48	19,034.92	11,282.48	21,994.78	11,282.48	18,206.92	
		LI-Pop	42,881.13	40,045.16	38,286.98	40,045.16	40,098.20	40,045.16	38,286.98	
		LD-Risk	811.68	440.20	1,086.75	440.20	975.38	440.20	1,071.88	
		LI-Risk	2,806.43	1,886.33	2,008.53	1,886.33	1,884.70	1,886.33	2,008.53	
		LD-AP	1.50	1.16	1.84	1.16	2.01	1.16	1.75	
LI-AP		3.78	3.86	3.66	3.86	3.88	3.86	3.66		
Vehicles		3.00	3.00	3.00	3.00	3.00	3.00	3.00		
N5-i3 16c	Dist. Matrix	Distance	189.02	204.07	209.61	268.39	215.03	204.07	199.52	
		LD-Pop	17,507.46	12,632.80	22,246.64	16,433.05	20,648.41	12,632.80	25,233.52	
		LI-Pop	61,869.61	61,133.23	41,024.78	52,509.98	41,535.44	61,133.23	46,786.77	
		LD-Risk	1,047.71	681.86	1,434.33	649.13	1,267.73	681.86	2,071.19	
		LI-Risk	4,620.81	4,369.45	2,534.76	2,841.08	2,521.82	4,369.45	3,330.44	
		LD-AP	1.42	1.21	2.13	1.96	1.95	1.21	1.91	
		LI-AP	4.28	4.45	4.02	5.24	3.97	4.45	3.86	
		Vehicles	3.00	3.00	3.00	3.00	3.00	3.00	3.00	
	Pop Matrix	Distance	202.18	219.90	214.19	219.90	219.90	219.90	219.90	205.56
		LD-Pop	18,441.71	10,933.98	14,524.04	10,933.98	21,424.42	10,933.98	16,038.94	
		LI-Pop	36,748.99	38,371.90	36,564.60	38,371.90	38,371.90	38,371.90	36,839.00	
		LD-Risk	1,107.58	445.19	765.48	445.19	1,080.03	445.19	816.85	
		LI-Risk	2,037.34	1,912.55	2,039.65	1,912.55	1,912.55	1,912.55	2,028.78	
		LD-AP	1.99	1.25	1.55	1.25	2.09	1.25	1.63	
LI-AP		3.84	4.09	4.03	4.09	4.09	4.09	3.83		
Vehicles		3.00	3.00	3.00	3.00	3.00	3.00	3.00		
Risk	Distance	225.72	225.72	225.72	229.21	229.21	225.72	225.72		

Table B1. (continued)

Inst	Matrix		Objective Min Dist.	Objective Min LD-Pop	Objective Min LI-Pop	Objective Min LD-Risk	Objective Min LI-Risk	Objective Min LD-AP	Objective Min LI-AP
	Matrix	LD-Pop	16,511.29	11,307.09	11,940.63	11,427.08	20,787.28	11,307.09	21,921.24
		LI-Pop	39,631.54	39,631.54	39,631.54	39,684.59	39,684.59	39,631.54	39,631.54
		LD-Risk	792.63	428.71	445.20	428.13	946.05	428.71	1,107.42
		LI-Risk	1,864.37	1,864.37	1,864.37	1,862.74	1,862.74	1,864.37	1,864.37
		LD-AP	1.76	1.24	1.36	1.26	1.90	1.24	2.04
		LI-AP	4.00	4.00	4.00	4.02	4.02	4.00	4.00
		Vehicles	3.00	3.00	3.00	3.00	3.00	3.00	3.00
	AP Matrix	Distance	202.54	218.11	206.04	218.11	221.59	218.11	206.04
		LD-Pop	16,563.45	11,282.48	19,034.92	11,282.48	21,994.78	11,282.48	18,206.92
		LI-Pop	42,881.13	40,045.16	38,286.98	40,045.16	40,098.20	40,045.16	38,286.98
		LD-Risk	811.68	440.20	1,086.75	440.20	975.38	440.20	1,071.88
		LI-Risk	2,806.43	1,886.33	2,008.53	1,886.33	1,884.70	1,886.33	2,008.53
		LD-AP	1.50	1.16	1.84	1.16	2.01	1.16	1.75
		LI-AP	3.78	3.86	3.66	3.86	3.88	3.86	3.66
Vehicles	3.00	3.00	3.00	3.00	3.00	3.00	3.00		
N5-i4 18c	Dist. Matrix	Distance	185.02	209.06	199.28	211.75	203.52	196.97	199.28
		LD-Pop	35,940.90	10,414.96	18,781.65	10,475.19	16,919.10	14,243.94	17,888.93
		LI-Pop	51,575.77	42,009.02	34,287.47	42,181.84	34,569.20	52,457.32	34,287.47
		LD-Risk	2,310.96	402.14	1,140.55	397.70	857.32	859.07	1,122.47
		LI-Risk	3,225.67	2,440.26	1,980.01	2,435.99	1,976.89	3,225.95	1,980.01
		LD-AP	2.60	1.44	1.71	1.43	2.19	1.24	1.67
		LI-AP	4.06	3.92	3.62	3.91	3.63	4.19	3.62
	Vehicles	3.00	3.00	3.00	3.00	3.00	3.00	3.00	
	Pop Matrix	Distance	198.58	241.59	200.73	241.59	200.73	218.81	200.73
		LD-Pop	17,029.20	10,348.51	16,656.42	10,348.51	18,715.58	13,833.17	18,767.74
		LI-Pop	34,507.54	39,645.15	34,183.52	39,645.15	34,183.52	35,694.82	34,183.52
		LD-Risk	1,096.00	396.21	853.68	396.21	1,145.61	851.60	1,146.75
		LI-Risk	2,003.97	2,181.52	1,977.92	2,181.52	1,977.92	2,029.26	1,977.92
		LD-AP	1.50	1.43	2.17	1.43	1.84	1.24	1.85
		LI-AP	3.71	4.37	3.66	4.37	3.66	3.92	3.66
	Vehicles	3.00	3.00	3.00	3.00	3.00	3.00	3.00	
	Risk Matrix	Distance	215.57	262.82	215.57	262.82	215.57	234.98	215.57
		LD-Pop	19,689.82	11,080.38	20,037.55	11,080.38	18,223.27	14,878.36	20,015.78
		LI-Pop	36,917.48	43,949.09	36,917.48	43,949.09	36,917.48	38,425.69	36,917.48
		LD-Risk	1,065.32	376.91	1,074.69	376.91	1,028.77	802.69	1,073.63
		LI-Risk	1,877.00	1,947.60	1,877.00	1,947.60	1,877.00	1,920.00	1,877.00
		LD-AP	1.85	1.44	1.83	1.44	1.52	1.35	1.83
		LI-AP	3.76	4.49	3.76	4.49	3.76	4.07	3.76
	Vehicles	3.00	3.00	3.00	3.00	3.00	3.00	3.00	
	AP Matrix	Distance	195.79	215.97	205.06	215.97	205.06	201.37	205.06
		LD-Pop	26,413.86	10,850.36	19,227.88	10,850.36	16,304.41	14,058.87	19,000.72
		LI-Pop	42,444.88	42,907.77	35,233.12	42,907.77	35,233.12	42,608.96	35,233.12
		LD-Risk	1,513.90	390.36	1,142.63	390.36	810.31	850.04	1,134.03
LI-Risk		2,420.00	2,409.70	1,962.35	2,409.70	1,962.35	2,421.84	1,962.35	
LD-AP		2.20	1.40	1.82	1.40	1.82	1.23	1.68	
LI-AP		3.65	3.78	3.56	3.78	3.56	3.70	3.56	
Vehicles	3.00	3.00	3.00	3.00	3.00	3.00	3.00		
N5-i5 20c	Dist. Matrix	Distance	235.05	295.20	322.62	293.31	387.60	289.18	237.33
		LD-Pop	50,813.63	16,884.07	28,033.38	17,053.56	35,690.25	24,010.56	48,525.72
		LI-Pop	94,153.51	89,366.65	64,296.54	89,047.14	66,445.03	98,501.46	90,939.67
		LD-Risk	5,219.74	654.66	1,936.72	650.26	2,163.08	1,803.93	5,251.70
		LI-Risk	9,601.75	7,371.72	4,595.08	7,346.12	4,185.26	8,781.94	9,161.55
		LD-AP	3.27	2.57	2.97	2.53	3.87	2.40	2.94
LI-AP	6.24	7.19	6.64	7.07	7.58	7.17	5.95		

Table B1. (continued)

Inst	Matrix		Objective Min Dist.	Objective Min LD-Pop	Objective Min LI-Pop	Objective Min LD-Risk	Objective Min LI-Risk	Objective Min LD-AP	Objective Min LI-AP
		Vehicles	4.00	4.00	4.00	4.00	4.00	4.00	4.00
	Pop Matrix	Distance	298.55	334.33	302.13	335.21	312.07	359.93	304.35
		LD-Pop	28,802.61	15,166.05	26,039.02	15,188.29	24,119.62	16,014.82	28,410.92
		LI-Pop	52,291.39	55,710.16	50,090.98	55,719.54	50,660.67	58,818.15	50,269.27
		LD-Risk	1,685.78	615.02	1,585.75	612.88	1,228.53	629.81	1,641.65
		LI-Risk	2,798.36	2,783.74	2,617.41	2,776.28	2,571.94	2,866.79	2,612.21
		LD-AP	3.11	2.36	3.00	2.35	2.90	2.33	3.17
		LI-AP	5.99	6.70	5.94	6.66	6.19	7.13	5.89
		Vehicles	4.00	4.00	4.00	4.00	4.00	4.00	4.00
	Risk Matrix	Distance	341.44	375.00	341.44	376.62	360.43	376.62	343.05
		LD-Pop	28,257.59	16,567.75	30,563.97	16,866.20	27,579.99	16,866.20	24,031.24
		LI-Pop	53,692.93	61,282.47	53,692.93	61,720.04	55,622.89	61,720.04	54,130.50
		LD-Risk	1,499.67	597.16	1,601.75	594.89	1,226.39	594.89	869.90
		LI-Risk	2,560.66	2,660.21	2,560.66	2,659.62	2,502.38	2,659.62	2,560.08
		LD-AP	3.11	2.39	3.31	2.37	3.10	2.37	3.11
		LI-AP	6.15	6.79	6.15	6.78	6.37	6.78	6.15
		Vehicles	4.00	4.00	4.00	4.00	4.00	4.00	4.00
	AP Matrix	Distance	255.52	302.39	285.98	309.34	331.10	302.17	269.24
		LD-Pop	31,099.80	15,664.35	19,853.14	16,096.40	27,828.85	16,563.04	27,369.33
		LI-Pop	74,725.15	63,681.04	52,129.70	64,645.01	53,370.29	66,800.61	60,583.59
		LD-Risk	2,519.16	608.77	803.98	608.71	1,266.30	643.44	1,936.29
		LI-Risk	6,234.62	4,415.70	3,017.91	4,419.34	2,543.60	4,656.93	4,491.50
		LD-AP	2.70	2.27	2.65	2.28	3.04	2.26	2.60
		LI-AP	5.88	6.15	5.58	6.18	6.07	6.12	5.48
		Vehicles	4.00	4.00	4.00	4.00	4.00	4.00	4.00

Table B2 – Results found by the CPLEX solver with an unrestricted number of vehicles

Inst	Matrix		Objective Min Dist.	Objective Min LD-Pop	Objective Min LI-Pop	Objective Min LD-Risk	Objective Min LI-Risk	Objective Min LD-AP	Objective Min LI-AP	
N1-i1 13c	Dist. Matrix	Distance	160.02	321.19	226.84	321.19	226.84	404.36	165.72	
		LD-Pop	28,090.08	6,642.52	12,327.04	6,642.52	12,466.03	7,214.53	23,774.14	
		LI-Pop	51,931.07	84,129.13	38,419.86	84,129.13	38,419.86	109,763.58	40,538.42	
		LD-Risk	2,798.63	243.35	724.76	243.35	735.29	447.51	2,165.71	
		LI-Risk	4,565.31	7,341.64	2,066.07	7,341.64	2,066.07	10,415.52	3,262.59	
		LD-AP	1.97	0.88	1.28	0.88	1.27	0.85	1.76	
		LI-AP	3.97	7.02	4.21	7.02	4.21	8.94	3.52	
		Vehicles	2.00	6.00	3.00	6.00	3.00	8.00	2.00	
	Pop	Distance	214.02	513.04	219.62	520.29	220.42	513.04	219.62	
	Matrix	LD-Pop	19,110.69	6,309.24	14,218.09	6,398.38	18,641.99	6,309.24	19,819.27	
		LI-Pop	40,445.92	69,220.78	36,534.55	69,933.85	36,550.07	69,220.78	36,534.55	
		LD-Risk	1,101.10	237.12	615.67	234.91	1,224.05	237.12	1,249.03	
		LI-Risk	2,435.35	2,954.18	2,004.53	2,936.48	1,988.76	2,954.18	2,004.53	
		LD-AP	2.07	0.83	1.84	0.84	1.81	0.83	1.97	
		LI-AP	4.25	8.59	4.08	8.67	4.08	8.59	4.08	
		Vehicles	2.00	9.00	2.00	9.00	2.00	9.00	2.00	
	Risk	Distance	239.02	552.08	239.02	552.08	239.14	564.93	239.14	
	Matrix	LD-Pop	20,246.18	7,034.96	18,136.87	7,034.96	21,299.11	7,090.79	21,413.18	
		LI-Pop	38,671.88	74,360.88	38,671.88	74,360.88	39,034.17	76,518.32	39,034.17	
		LD-Risk	1,060.85	230.32	1,012.47	230.32	1,299.30	261.72	1,315.15	
		LI-Risk	1,968.17	2,823.14	1,968.17	2,823.14	1,967.40	3,024.33	1,967.40	
		LD-AP	2.05	0.84	1.76	0.84	1.98	0.84	2.01	
		LI-AP	4.07	8.38	4.07	8.38	4.05	8.83	4.05	
		Vehicles	2.00	8.00	2.00	8.00	2.00	9.00	2.00	
	AP	Distance	162.57	506.23	224.98	490.75	231.47	680.54	174.34	
	Matrix	LD-Pop	18,357.19	6,548.28	19,842.23	6,644.98	21,706.26	6,860.09	22,047.13	
		LI-Pop	50,009.13	74,062.90	37,714.18	72,427.13	38,446.34	98,505.72	39,613.28	
		LD-Risk	1,270.30	232.45	1,236.46	231.73	1,325.39	373.68	1,737.43	
		LI-Risk	4,355.26	3,972.27	1,976.30	3,917.62	1,971.30	5,662.81	2,811.98	
		LD-AP	1.59	0.83	1.87	0.84	2.09	0.81	1.72	
		LI-AP	3.86	8.49	4.01	8.20	4.02	11.43	3.42	
		Vehicles	2.00	9.00	2.00	8.00	2.00	13.00	2.00	
	N1-i2 13c	Dist. Matrix	Distance	139.82	341.71	161.26	276.86	206.46	368.74	155.15
			LD-Pop	26,355.84	4,052.11	18,968.24	4,304.68	9,858.52	4,073.05	9,127.16
			LI-Pop	43,942.20	62,587.71	30,990.73	54,618.69	33,698.55	66,540.36	31,558.33
			LD-Risk	2,459.12	149.08	1,197.53	148.64	297.77	150.01	354.93
LI-Risk			3,885.00	3,503.42	1,637.56	3,231.45	1,585.62	3,612.50	1,661.95	
LD-AP			1.85	0.56	1.66	0.56	1.36	0.54	0.95	
LI-AP			3.37	6.77	3.20	5.52	3.85	7.20	3.10	
Vehicles			2.00	8.00	2.00	6.00	2.00	9.00	2.00	
Pop		Distance	163.01	505.98	163.01	375.99	165.35	473.20	163.01	
		LD-Pop	7,478.64	3,981.67	7,728.94	4,269.68	17,263.37	3,981.67	17,310.07	
		LI-Pop	27,986.36	66,219.92	27,986.36	50,294.80	28,252.84	63,104.27	27,986.36	
		LD-Risk	273.11	147.13	279.43	143.47	1,022.95	147.13	1,028.97	
		LI-Risk	1,403.85	2,589.00	1,403.85	2,038.59	1,398.58	2,510.45	1,403.85	
		LD-AP	0.91	0.54	0.94	0.58	1.71	0.54	1.73	
		LI-AP	3.06	8.66	3.06	6.31	3.11	8.22	3.06	
Risk		Distance	167.67	414.67	167.67	463.14	170.25	414.67	167.67	
		LD-Pop	17,140.38	4,231.36	16,769.93	4,310.97	8,178.91	4,231.36	8,027.56	
		LI-Pop	29,047.13	54,551.48	29,047.13	59,526.79	29,275.15	54,551.48	29,047.13	
		LD-Risk	994.70	140.23	985.93	137.56	277.85	140.23	280.05	
		LI-Risk	1,388.65	2,003.84	1,388.65	2,122.27	1,384.60	2,003.84	1,388.65	

Table B2. (continued)

Inst	Matrix		Objective Min Dist.	Objective Min LD-Pop	Objective Min LI-Pop	Objective Min LD-Risk	Objective Min LI-Risk	Objective Min LD-AP	Objective Min LI-AP
		LD-AP	1.59	0.52	1.54	0.54	0.97	0.52	0.93
		LI-AP	3.01	6.47	3.01	7.18	3.07	6.47	3.01
		Vehicles	2.00	9.00	2.00	10.00	2.00	9.00	2.00
	AP Matrix	Distance	146.97	518.82	162.95	411.65	184.17	518.82	162.95
		LD-Pop	12,098.51	4,205.48	8,441.47	4,361.78	8,978.76	4,205.48	8,191.17
		LI-Pop	39,231.24	69,519.59	30,607.11	56,893.90	31,553.68	69,519.59	30,607.11
		LD-Risk	1,060.97	140.75	289.16	139.71	297.42	140.75	282.84
		LI-Risk	3,736.74	2,499.65	1,467.80	2,128.22	1,433.79	2,499.65	1,467.80
		LD-AP	1.06	0.52	0.91	0.54	1.05	0.52	0.87
		LI-AP	3.11	8.38	2.91	6.71	3.26	8.38	2.91
Vehicles	2.00	13.00	2.00	10.00	2.00	13.00	2.00		
N1-i3 15c	Dist. Matrix	Distance	140.48	263.48	140.48	265.09	150.63	295.14	140.55
		LD-Pop	18,527.87	5,486.08	18,666.03	5,494.12	19,302.26	5,951.19	19,191.84
		LI-Pop	33,062.43	63,809.55	33,062.43	63,970.32	35,124.73	73,431.82	33,275.81
		LD-Risk	1,497.91	240.45	1,502.23	239.96	1,468.14	423.61	1,511.86
		LI-Risk	2,430.26	4,158.46	2,430.26	4,148.56	2,419.57	5,281.81	2,430.27
		LD-AP	1.58	0.51	1.60	0.51	1.64	0.49	1.65
		LI-AP	2.90	5.34	2.90	5.32	3.07	6.00	2.90
	Vehicles	2.00	6.00	2.00	6.00	2.00	8.00	2.00	
	Pop Matrix	Distance	143.55	436.17	143.55	437.63	143.55	357.04	143.55
		LD-Pop	12,001.29	4,683.99	12,001.29	4,692.02	12,077.17	4,727.68	12,329.96
		LI-Pop	32,680.59	65,002.23	32,680.59	65,194.83	32,680.59	57,312.48	32,680.59
		LD-Risk	836.74	222.81	836.74	222.31	837.14	227.02	844.25
		LI-Risk	2,390.77	3,228.90	2,390.77	3,215.11	2,390.77	3,079.40	2,390.77
		LD-AP	1.05	0.48	1.05	0.48	1.06	0.47	1.10
		LI-AP	2.92	6.91	2.92	6.87	2.92	5.88	2.92
	Vehicles	2.00	10.00	2.00	11.00	2.00	8.00	2.00	
	Risk Matrix	Distance	169.28	391.56	169.53	456.58	174.31	428.48	169.64
		LD-Pop	20,900.70	5,010.26	20,845.90	5,104.57	14,063.57	5,079.00	20,982.75
		LI-Pop	36,263.60	62,035.81	36,080.87	69,752.22	36,695.21	67,771.69	36,443.16
		LD-Risk	1,436.65	208.73	1,437.30	207.65	772.86	208.00	1,435.69
		LI-Risk	2,270.29	2,929.34	2,270.18	3,061.87	2,267.11	3,001.20	2,269.41
		LD-AP	1.80	0.49	1.81	0.48	1.24	0.48	1.79
		LI-AP	3.16	6.12	3.17	6.89	3.18	6.52	3.16
	Vehicles	2.00	7.00	2.00	10.00	2.00	11.00	2.00	
	AP Matrix	Distance	142.44	411.43	142.44	503.55	142.80	449.85	142.80
		LD-Pop	19,661.64	4,891.38	12,713.53	4,953.32	20,891.51	4,953.32	11,769.61
		LI-Pop	34,468.75	65,948.49	34,468.75	78,324.72	34,648.31	70,964.78	34,648.31
		LD-Risk	1,531.48	218.21	862.48	217.91	1,555.30	217.91	840.73
LI-Risk		2,472.13	3,172.11	2,472.13	3,361.16	2,471.25	3,240.92	2,471.25	
LD-AP		1.57	0.47	1.09	0.47	1.70	0.47	0.98	
LI-AP		2.88	6.40	2.88	7.46	2.87	6.79	2.87	
Vehicles	2.00	9.00	2.00	15.00	2.00	13.00	2.00		
N1-i4 15c	Dist. Matrix	Distance	173.74	418.28	194.22	428.51	195.83	458.69	195.83
		LD-Pop	13,072.42	6,676.77	14,901.95	7,282.90	16,166.09	7,335.57	15,293.83
		LI-Pop	38,343.59	92,141.83	32,085.78	90,108.06	32,420.41	105,146.97	32,420.41
		LD-Risk	608.16	246.54	622.99	240.36	639.36	383.64	615.56
		LI-Risk	2,704.19	5,534.60	1,503.35	5,187.51	1,483.05	6,841.54	1,483.05
		LD-AP	1.33	0.79	1.59	0.81	1.68	0.78	1.57
		LI-AP	3.45	8.36	3.40	8.08	3.32	9.25	3.32
	Vehicles	2.00	9.00	2.00	9.00	2.00	9.00	2.00	
	Pop Matrix	Distance	200.19	802.41	201.04	611.56	200.19	718.14	200.19
		LD-Pop	14,072.84	6,161.89	14,085.51	6,330.73	14,072.84	6,339.74	14,211.70
LI-Pop		31,071.37	93,221.27	30,980.65	75,502.12	31,071.37	85,651.02	31,071.37	

Table B2. (continued)

Inst	Matrix		Objective Min Dist.	Objective Min LD-Pop	Objective Min LI-Pop	Objective Min LD-Risk	Objective Min LI-Risk	Objective Min LD-AP	Objective Min LI-AP	
		LD-Risk	592.30	239.94	599.68	230.97	592.30	241.37	594.08	
		LI-Risk	1,455.79	3,482.41	1,470.86	2,995.48	1,455.79	3,301.14	1,455.79	
		LD-AP	1.49	0.80	1.53	0.82	1.49	0.79	1.50	
		LI-AP	3.29	12.21	3.35	9.39	3.29	11.00	3.29	
		Vehicles	2.00	15.00	2.00	11.00	2.00	13.00	2.00	
	Risk Matrix	Distance	205.47	601.04	205.47	795.67	205.47	667.38	205.47	
		LD-Pop	15,171.07	6,365.19	14,442.39	6,644.97	15,309.92	6,740.56	14,438.25	
		LI-Pop	31,963.75	69,608.32	31,963.75	94,829.19	31,963.75	76,831.77	31,963.75	
		LD-Risk	725.17	236.99	593.75	228.08	726.95	239.36	590.74	
		LI-Risk	1,445.41	2,257.13	1,445.41	3,217.57	1,445.41	2,391.96	1,445.41	
		LD-AP	1.58	0.80	1.51	0.81	1.59	0.78	1.50	
		LI-AP	3.29	8.56	3.29	11.43	3.29	9.41	3.29	
		Vehicles	2.00	10.00	2.00	13.00	2.00	10.00	2.00	
	AP Matrix	Distance	184.85	499.25	196.48	657.37	196.48	700.67	196.48	
		LD-Pop	14,079.39	6,598.17	15,064.16	6,911.83	14,750.72	6,773.20	14,750.72	
		LI-Pop	39,612.86	71,573.97	32,602.22	89,909.77	32,602.22	88,907.35	32,602.22	
		LD-Risk	608.17	240.37	725.25	231.22	594.37	240.15	594.37	
		LI-Risk	2,635.34	2,843.23	1,455.06	3,145.01	1,455.06	2,690.96	1,455.06	
		LD-AP	1.33	0.77	1.51	0.77	1.45	0.75	1.45	
		LI-AP	3.31	7.65	3.19	9.72	3.19	10.07	3.19	
		Vehicles	2.00	10.00	2.00	12.00	2.00	13.00	2.00	
	N2-i1 13c	Dist. Matrix	Distance	116.41	215.25	118.25	196.96	123.37	215.25	118.25
			LD-Pop	17,127.03	8,028.39	15,210.42	8,223.11	18,022.82	8,028.39	16,503.09
			LI-Pop	36,939.80	85,203.96	36,570.20	76,781.89	39,491.11	85,203.96	36,570.20
			LD-Risk	923.96	494.36	838.84	410.32	1,071.38	494.36	910.47
LI-Risk			2,338.24	6,110.54	2,355.16	5,158.39	2,242.18	6,110.54	2,355.16	
LD-AP			1.58	0.74	1.45	0.78	1.68	0.74	1.52	
LI-AP			3.41	7.51	3.38	6.77	3.66	7.51	3.38	
Vehicles			2.00	6.00	2.00	5.00	2.00	6.00	2.00	
Pop Matrix		Distance	121.08	396.95	131.07	345.84	158.48	471.33	123.20	
		LD-Pop	15,563.35	7,303.04	14,778.01	7,541.20	19,816.39	7,303.04	15,540.96	
		LI-Pop	35,678.94	95,506.93	34,746.10	81,627.01	37,752.32	109,983.64	34,995.71	
		LD-Risk	944.58	368.16	866.63	342.24	954.78	368.16	968.82	
		LI-Risk	2,099.23	4,820.57	2,107.34	4,035.53	1,943.36	5,484.62	2,109.58	
		LD-AP	1.53	0.72	1.57	0.75	1.93	0.72	1.55	
		LI-AP	3.49	9.37	3.57	8.12	3.83	10.94	3.46	
		Vehicles	2.00	10.00	2.00	9.00	2.00	13.00	2.00	
Risk Matrix		Distance	151.13	396.36	151.13	396.36	164.99	425.58	151.13	
		LD-Pop	18,617.75	7,899.71	15,797.74	7,899.71	19,168.42	7,899.71	19,893.18	
		LI-Pop	38,598.38	88,008.24	38,598.38	88,008.24	39,690.78	93,911.45	38,598.38	
		LD-Risk	816.11	339.12	796.05	339.12	876.47	339.12	872.11	
		LI-Risk	1,810.75	3,853.74	1,810.75	3,853.74	1,769.21	4,138.63	1,810.75	
		LD-AP	1.72	0.73	1.47	0.73	1.76	0.73	1.81	
		LI-AP	3.57	8.19	3.57	8.19	3.68	8.83	3.57	
		Vehicles	2.00	9.00	2.00	9.00	2.00	10.00	2.00	
AP Matrix		Distance	123.88	371.73	128.03	335.74	168.46	456.40	128.03	
		LD-Pop	15,568.24	7,621.08	16,484.19	7,902.48	20,582.64	7,648.96	17,659.83	
		LI-Pop	36,800.33	97,245.50	36,744.12	86,240.07	40,318.30	115,557.13	36,744.12	
		LD-Risk	816.03	373.63	921.44	347.57	924.07	443.89	922.66	
		LI-Risk	2,273.27	5,055.18	1,983.16	4,417.44	1,867.53	6,158.58	1,983.16	
		LD-AP	1.44	0.68	1.52	0.71	1.85	0.68	1.59	
		LI-AP	3.36	8.51	3.34	7.58	3.67	10.31	3.34	
		Vehicles	2.00	9.00	2.00	9.00	2.00	13.00	2.00	

Table B2. (continued)

Inst	Matrix		Objective Min Dist.	Objective Min LD-Pop	Objective Min LI-Pop	Objective Min LD-Risk	Objective Min LI-Risk	Objective Min LD-AP	Objective Min LI-AP	
N2-i2 13c	Dist. Matrix	Distance	124.65	247.17	140.20	247.17	140.20	280.21	140.20	
		LD-Pop	16,942.22	8,069.97	19,213.20	8,069.97	18,339.64	8,184.50	18,941.60	
		LI-Pop	43,013.54	85,312.81	40,314.01	85,312.81	40,314.01	103,617.23	40,314.01	
		LD-Risk	972.03	458.28	986.77	458.28	967.13	489.22	935.61	
		LI-Risk	2,700.67	5,324.09	2,131.88	5,324.09	2,131.88	6,825.75	2,131.88	
		LD-AP	1.57	0.73	1.81	0.73	1.73	0.73	1.72	
		LI-AP	3.90	7.66	3.73	7.66	3.73	9.17	3.73	
		Vehicles	2.00	6.00	2.00	6.00	2.00	8.00	2.00	
	Pop Matrix	Distance	128.33	397.99	142.13	397.99	164.24	416.10	168.87	
		LD-Pop	16,497.86	7,288.93	18,590.66	7,288.93	19,371.38	7,288.93	18,951.41	
		LI-Pop	42,243.98	95,220.17	39,601.53	95,220.17	41,641.15	103,973.26	41,188.72	
		LD-Risk	974.38	390.70	1,023.37	390.70	1,059.85	390.70	1,033.14	
		LI-Risk	2,698.17	5,355.95	2,147.60	5,355.95	2,108.09	5,962.61	2,125.71	
		LD-AP	1.62	0.69	1.74	0.69	1.87	0.69	1.76	
		LI-AP	4.01	9.07	3.80	9.07	4.04	9.82	3.76	
		Vehicles	2.00	8.00	2.00	8.00	2.00	10.00	2.00	
	Risk Matrix	Distance	140.77	427.19	150.31	427.19	179.14	449.87	179.14	
		LD-Pop	26,512.89	8,004.45	19,685.23	8,004.45	19,577.82	8,071.33	20,835.73	
		LI-Pop	46,709.88	102,424.00	42,507.38	102,424.00	44,070.09	103,496.22	44,070.09	
		LD-Risk	1,500.70	362.06	1,012.74	362.06	864.63	372.31	885.70	
		LI-Risk	2,480.67	4,985.23	1,961.42	4,985.23	1,879.36	4,750.24	1,879.36	
		LD-AP	2.40	0.71	1.85	0.71	1.72	0.71	1.75	
		LI-AP	4.21	8.98	3.84	8.98	3.79	9.26	3.79	
		Vehicles	2.00	8.00	2.00	8.00	2.00	11.00	2.00	
	AP Matrix	Distance	125.45	420.52	141.96	295.94	169.41	438.63	169.41	
		LD-Pop	17,402.75	7,616.56	19,045.56	7,776.04	19,818.16	7,616.56	20,141.96	
		LI-Pop	43,428.02	102,191.50	41,346.05	80,129.89	42,530.21	110,944.58	42,530.21	
		LD-Risk	945.63	421.97	835.06	399.01	836.54	421.97	936.92	
		LI-Risk	2,420.50	5,729.32	2,024.49	4,500.81	1,986.34	6,335.97	1,986.34	
		LD-AP	1.48	0.65	1.59	0.67	1.58	0.65	1.76	
		LI-AP	3.84	8.82	3.62	6.89	3.56	9.57	3.56	
		Vehicles	2.00	8.00	2.00	6.00	2.00	10.00	2.00	
	N2-i3 15c	Dist. Matrix	Distance	83.48	146.32	91.87	169.57	103.89	182.79	91.87
			LD-Pop	13,669.08	3,989.04	10,644.92	4,007.28	13,856.19	4,019.62	10,644.92
			LI-Pop	26,338.71	49,137.73	25,540.00	56,710.34	26,594.79	58,859.24	25,540.00
			LD-Risk	1,069.42	198.33	569.64	187.89	592.98	195.26	569.64
			LI-Risk	1,817.43	3,231.13	1,380.90	3,792.83	1,233.95	4,008.44	1,380.90
			LD-AP	1.22	0.40	1.05	0.40	1.36	0.40	1.05
			LI-AP	2.48	4.47	2.45	5.15	2.56	5.40	2.45
			Vehicles	2.00	4.00	2.00	5.00	2.00	5.00	2.00
		Pop Matrix	Distance	87.32	304.20	92.42	253.71	124.74	253.71	92.42
			LD-Pop	12,560.16	3,729.66	10,319.25	3,729.66	12,281.95	3,729.66	10,822.88
LI-Pop			29,453.90	64,420.29	24,441.46	54,470.66	26,580.31	54,470.66	24,441.46	
LD-Risk			718.73	185.85	563.24	185.85	586.30	185.85	663.97	
LI-Risk			1,862.20	3,110.32	1,431.11	2,624.68	1,252.64	2,624.68	1,431.11	
LD-AP			1.27	0.39	1.09	0.39	1.28	0.39	1.09	
LI-AP			2.88	6.79	2.51	5.67	2.80	5.67	2.51	
Vehicles			2.00	10.00	2.00	8.00	2.00	8.00	2.00	
Risk Matrix		Distance	108.38	322.38	113.41	262.87	136.19	293.16	110.23	
		LD-Pop	13,145.51	3,948.88	10,243.87	4,119.40	12,409.67	3,948.88	14,216.61	
		LI-Pop	29,981.30	68,777.28	26,894.02	57,326.84	29,047.88	62,874.07	27,116.04	
		LD-Risk	642.53	178.68	512.88	176.72	572.03	178.68	574.97	
		LI-Risk	1,479.58	3,018.94	1,181.06	2,536.81	1,171.86	2,734.04	1,213.21	
		LD-AP	1.25	0.38	0.97	0.41	1.14	0.38	1.29	
		LI-AP	2.83	6.62	2.59	5.54	2.72	5.97	2.59	

Table B2. (continued)

Inst	Matrix		Objective Min Dist.	Objective Min LD-Pop	Objective Min LI-Pop	Objective Min LD-Risk	Objective Min LI-Risk	Objective Min LD-AP	Objective Min LI-AP	
	AP Matrix	Vehicles	2.00	10.00	2.00	7.00	2.00	9.00	2.00	
		Distance	83.60	219.06	92.12	241.51	128.98	256.55	92.12	
		LD-Pop	11,476.83	3,889.72	11,451.30	4,103.12	13,492.26	3,903.36	10,618.04	
		LI-Pop	26,384.51	50,175.26	25,342.69	56,897.09	28,344.54	58,449.34	25,342.69	
		LD-Risk	635.70	180.82	593.70	177.70	560.37	179.74	555.98	
		LI-Risk	1,755.43	2,276.47	1,309.19	2,964.94	1,181.15	2,603.39	1,309.19	
		LD-AP	1.04	0.39	1.02	0.41	1.23	0.37	1.05	
		LI-AP	2.48	4.64	2.43	5.31	2.63	5.28	2.43	
		Vehicles	2.00	6.00	2.00	7.00	2.00	8.00	2.00	
N2-i4 15c	Dist. Matrix	Distance	131.29	274.76	144.08	218.20	176.51	312.93	143.06	
		LD-Pop	23,614.22	9,261.72	24,179.81	9,906.34	27,882.20	9,429.34	15,165.00	
		LI-Pop	43,645.20	84,616.40	41,216.38	62,244.14	45,534.29	92,759.75	41,308.97	
		LD-Risk	1,592.80	494.89	1,442.75	476.40	1,395.21	524.95	813.73	
		LI-Risk	2,790.88	5,288.31	2,419.76	3,797.42	2,272.07	5,777.07	2,419.12	
		LD-AP	2.08	0.89	2.29	0.95	2.58	0.88	1.40	
		LI-AP	3.95	7.72	3.92	5.82	4.22	8.51	3.89	
			Vehicles	2.00	7.00	2.00	5.00	2.00	9.00	2.00
	Pop Matrix	Distance	137.69	479.29	144.46	465.61	153.99	450.14	144.43	
		LD-Pop	13,701.67	8,471.98	21,136.70	8,540.97	24,803.77	8,979.24	19,273.78	
		LI-Pop	40,386.02	92,519.57	38,636.89	86,383.72	39,998.33	93,723.20	38,711.45	
		LD-Risk	678.57	408.78	1,285.64	396.36	1,290.82	470.21	1,170.32	
		LI-Risk	2,339.75	4,315.31	2,174.56	3,749.09	2,000.96	4,408.27	2,165.86	
		LD-AP	1.36	0.88	2.08	0.89	2.39	0.87	1.88	
		LI-AP	3.89	9.52	3.82	8.89	3.90	9.45	3.79	
			Vehicles	2.00	10.00	2.00	10.00	2.00	10.00	2.00
	Risk Matrix	Distance	155.99	504.16	168.91	530.71	168.91	504.16	168.91	
		LD-Pop	24,090.49	9,232.69	25,987.66	9,355.20	20,294.56	9,232.69	25,090.41	
		LI-Pop	43,721.49	101,765.21	42,839.54	104,553.97	42,839.54	101,765.21	42,839.54	
		LD-Risk	1,264.42	356.26	1,201.01	353.90	909.40	356.26	1,133.37	
		LI-Risk	2,054.16	3,775.29	1,877.43	3,838.59	1,877.43	3,775.29	1,877.43	
		LD-AP	2.25	0.82	2.39	0.83	1.86	0.82	2.29	
		LI-AP	4.03	9.14	3.95	9.40	3.95	9.14	3.95	
			Vehicles	2.00	10.00	2.00	11.00	2.00	10.00	2.00
	AP Matrix	Distance	136.34	448.45	150.50	416.05	156.60	448.45	145.45	
		LD-Pop	17,541.91	9,100.34	21,731.06	9,338.92	17,489.73	9,100.34	15,154.50	
		LI-Pop	42,520.21	98,851.02	40,080.90	87,446.28	41,145.26	98,851.02	40,972.39	
		LD-Risk	1,020.60	378.77	1,281.13	358.78	818.18	378.77	843.76	
LI-Risk		2,569.44	4,151.95	2,165.55	3,373.38	1,942.71	4,151.95	2,266.81		
LD-AP		1.60	0.81	2.05	0.82	1.63	0.81	1.36		
LI-AP		3.94	8.84	3.75	7.86	3.78	8.84	3.69		
		Vehicles	2.00	10.00	2.00	9.00	2.00	10.00	2.00	
N3-i1 13c	Dist. Matrix	Distance	127.75	278.65	130.69	233.19	134.96	332.26	133.19	
		LD-Pop	27,149.41	13,591.29	21,015.56	14,012.47	18,453.23	13,738.47	19,638.88	
		LI-Pop	51,459.49	107,424.02	49,116.69	89,440.55	50,220.34	129,532.35	50,687.52	
		LD-Risk	1,725.95	706.35	1,092.54	669.92	954.98	753.18	1,041.75	
		LI-Risk	2,911.43	6,035.19	2,620.62	4,851.06	2,476.86	7,211.10	2,593.47	
		LD-AP	2.56	1.37	2.12	1.41	1.93	1.35	1.91	
		LI-AP	4.98	10.76	5.03	8.90	5.06	12.62	4.92	
			Vehicles	3.00	8.00	3.00	6.00	4.00	10.00	4.00
	Pop Matrix	Distance	136.09	452.55	144.80	448.53	172.26	427.20	142.92	
		LD-Pop	20,281.64	11,540.72	19,013.99	11,996.76	15,316.58	11,717.02	18,582.58	
		LI-Pop	46,620.62	112,818.51	43,345.11	113,251.64	45,228.02	112,006.67	44,672.53	
		LD-Risk	1,018.82	526.88	985.78	520.58	728.21	540.36	882.54	
		LI-Risk	2,481.39	5,091.17	2,154.72	5,123.64	2,019.34	5,378.13	2,246.97	

Table B2. (continued)

Inst	Matrix		Objective Min Dist.	Objective Min LD-Pop	Objective Min LI-Pop	Objective Min LD-Risk	Objective Min LI-Risk	Objective Min LD-AP	Objective Min LI-AP	
		LD-AP	2.18	1.23	2.08	1.27	1.79	1.22	2.07	
		LI-AP	4.93	12.14	4.80	12.21	5.04	11.99	4.68	
		Vehicles	3.00	11.00	4.00	10.00	4.00	11.00	3.00	
	Risk Matrix	Distance	149.49	443.50	169.25	457.98	169.25	405.55	169.25	
		LD-Pop	18,689.19	11,926.10	18,627.57	11,977.41	19,782.62	11,955.99	19,399.01	
		LI-Pop	48,815.82	112,948.31	45,663.66	116,810.16	45,663.66	98,939.35	45,663.66	
		LD-Risk	949.80	504.63	783.69	500.47	840.47	509.06	824.49	
		LI-Risk	2,425.55	4,814.45	1,935.41	4,910.03	1,935.41	4,233.26	1,935.41	
		LD-AP	1.86	1.24	1.91	1.25	2.07	1.23	2.02	
		LI-AP	5.16	12.04	4.91	12.43	4.91	10.62	4.91	
		Vehicles	3.00	10.00	4.00	11.00	4.00	9.00	4.00	
		AP Matrix	Distance	131.17	359.28	141.20	354.24	154.74	457.39	139.40
	LD-Pop		21,054.04	11,966.20	16,924.23	11,987.38	18,585.47	12,305.97	16,569.31	
	LI-Pop		49,213.39	108,568.55	45,049.36	98,515.79	45,109.09	135,167.96	46,321.49	
	LD-Risk		1,272.42	539.49	874.91	513.02	853.45	588.02	830.46	
	LI-Risk		2,751.16	5,341.81	2,152.92	4,571.82	2,030.19	6,645.98	2,276.84	
	LD-AP		1.97	1.20	1.71	1.21	1.91	1.19	1.66	
	LI-AP		4.78	10.54	4.61	9.78	4.61	13.08	4.50	
	Vehicles	3.00	10.00	4.00	9.00	4.00	13.00	4.00		
	N3-i2 13c	Dist. Matrix	Distance	131.61	416.75	131.61	328.75	154.51	442.67	131.61
			LD-Pop	18,776.27	12,944.81	18,776.27	13,148.56	20,369.02	12,975.56	19,776.67
LI-Pop			46,158.97	137,511.03	46,158.97	110,673.44	48,209.56	145,418.94	46,158.97	
LD-Risk			1,069.76	699.61	1,069.76	663.85	1,158.94	684.66	1,076.77	
LI-Risk			2,516.52	7,628.43	2,516.52	6,022.54	2,440.82	7,892.54	2,516.52	
LD-AP			1.80	1.24	1.80	1.27	1.93	1.23	1.85	
LI-AP			4.33	12.97	4.33	10.48	4.57	13.68	4.33	
Vehicles		2.00	9.00	2.00	6.00	3.00	10.00	2.00		
Pop Matrix		Distance	146.99	555.42	149.25	496.98	186.22	529.84	148.25	
		LD-Pop	20,081.30	10,876.76	19,156.53	11,119.93	19,604.62	10,971.96	19,538.91	
		LI-Pop	44,905.75	120,443.16	41,991.18	113,264.42	44,927.57	111,165.66	42,181.81	
		LD-Risk	1,184.22	519.84	1,083.64	502.14	923.49	557.22	1,151.26	
		LI-Risk	2,526.06	5,742.95	2,227.70	5,508.23	2,019.55	5,184.14	2,274.40	
		LD-AP	2.10	1.16	1.88	1.18	2.07	1.12	2.00	
		LI-AP	4.82	12.82	4.38	12.29	4.76	11.72	4.31	
Vehicles		2.00	9.00	2.00	8.00	2.00	9.00	2.00		
Risk Matrix		Distance	153.42	614.45	153.42	703.26	185.88	472.75	153.42	
		LD-Pop	19,690.27	11,067.23	20,345.67	11,445.37	24,597.78	11,258.47	20,820.91	
		LI-Pop	43,901.25	125,401.11	43,901.25	145,220.17	45,875.68	97,953.24	43,901.25	
		LD-Risk	896.02	493.88	917.53	482.95	979.59	527.50	1,078.21	
		LI-Risk	2,088.60	5,267.15	2,088.60	6,020.94	1,905.87	4,034.18	2,088.60	
		LD-AP	2.04	1.20	2.07	1.22	2.46	1.17	2.03	
		LI-AP	4.38	13.40	4.38	15.61	4.74	10.24	4.38	
Vehicles		2.00	9.00	2.00	10.00	2.00	7.00	2.00		
AP Matrix		Distance	137.24	539.95	144.86	469.24	183.55	611.04	139.58	
		LD-Pop	20,040.87	11,068.08	19,028.86	12,235.41	20,646.89	11,083.51	19,146.15	
		LI-Pop	45,821.48	122,402.13	44,272.97	113,930.77	47,441.12	143,951.57	44,405.70	
		LD-Risk	1,125.24	556.71	1,089.71	532.54	997.91	564.05	1,097.18	
		LI-Risk	2,500.45	6,187.22	2,400.51	5,704.15	2,148.00	7,406.61	2,420.24	
		LD-AP	1.88	1.09	1.78	1.24	1.99	1.07	1.80	
	LI-AP	4.28	11.93	4.14	11.16	4.60	13.77	4.13		
Vehicles	2.00	9.00	2.00	8.00	2.00	12.00	2.00			
N3-i3 15c	Dist. Matrix	Distance	174.14	283.92	186.70	267.54	192.94	329.20	186.70	
		LD-Pop	24,116.07	13,860.58	25,823.30	14,242.44	23,312.35	14,381.86	24,471.88	
		LI-Pop	56,855.51	85,313.26	51,796.20	78,271.90	52,756.12	93,917.51	51,796.20	

Table B2. (continued)

Inst	Matrix		Objective Min Dist.	Objective Min LD-Pop	Objective Min LI-Pop	Objective Min LD-Risk	Objective Min LI-Risk	Objective Min LD-AP	Objective Min LI-AP	
		LD-Risk	1,073.04	648.45	1,151.91	594.55	996.29	676.36	1,193.47	
		LI-Risk	2,904.19	4,313.48	2,465.13	3,863.81	2,365.74	4,618.16	2,465.13	
		LD-AP	2.28	1.43	2.58	1.50	2.43	1.41	2.38	
		LI-AP	5.26	8.40	5.10	7.77	5.33	9.39	5.10	
		Vehicles	3.00	8.00	3.00	7.00	3.00	9.00	3.00	
	Pop Matrix	Distance	192.06	444.51	205.57	355.16	211.64	385.79	205.57	
		LD-Pop	23,692.12	12,566.39	22,978.62	13,195.24	24,261.99	12,616.38	22,978.62	
		LI-Pop	49,057.86	97,790.79	47,252.25	77,618.90	48,397.95	84,626.45	47,252.25	
		LD-Risk	1,087.87	556.97	1,103.18	531.37	927.53	576.68	1,103.18	
		LI-Risk	2,178.50	4,307.11	2,166.76	3,311.46	2,028.61	3,763.78	2,166.76	
		LD-AP	2.42	1.35	2.41	1.44	2.67	1.32	2.41	
		LI-AP	5.04	10.66	5.01	8.41	5.18	9.15	5.01	
		Vehicles	3.00	12.00	3.00	9.00	3.00	10.00	3.00	
	Risk Matrix	Distance	200.97	460.07	200.97	460.07	220.04	455.20	200.97	
		LD-Pop	23,786.46	13,304.48	21,388.21	13,304.48	23,246.18	13,514.05	21,388.21	
		LI-Pop	49,066.89	92,864.79	49,066.89	92,864.79	50,641.40	96,528.42	49,066.89	
		LD-Risk	1,025.41	512.21	870.57	512.21	929.22	548.75	870.57	
		LI-Risk	2,020.33	3,498.78	2,020.33	3,498.78	1,953.98	3,701.85	2,020.33	
		LD-AP	2.60	1.47	2.28	1.47	2.50	1.44	2.28	
		LI-AP	5.35	10.36	5.35	10.36	5.50	10.65	5.35	
		Vehicles	3.00	11.00	3.00	11.00	3.00	10.00	3.00	
	AP Matrix	Distance	179.07	354.59	195.27	358.52	203.90	441.14	195.27	
		LD-Pop	21,524.46	12,881.34	22,839.15	13,359.60	24,451.32	13,328.38	21,975.44	
		LI-Pop	52,201.23	84,794.64	47,529.50	85,788.32	48,357.82	102,258.67	47,529.50	
		LD-Risk	915.79	609.11	1,039.67	546.22	1,106.49	599.82	1,040.33	
		LI-Risk	2,603.82	3,786.88	2,207.98	3,722.92	2,113.41	4,443.00	2,207.98	
		LD-AP	2.09	1.34	2.29	1.42	2.43	1.31	2.21	
		LI-AP	4.86	8.55	4.74	8.69	4.95	10.37	4.74	
		Vehicles	3.00	9.00	3.00	9.00	3.00	12.00	3.00	
	N3-i4 15c	Dist. Matrix	Distance	187.29	315.66	191.47	306.49	204.79	325.08	190.02
			LD-Pop	35,342.02	18,972.22	28,805.68	19,536.23	35,686.32	19,758.57	31,644.84
			LI-Pop	67,692.17	112,076.63	65,198.57	108,302.81	66,502.02	121,211.76	67,216.29
LD-Risk			1,936.16	933.15	1,578.12	914.83	1,747.31	1,019.60	1,776.35	
LI-Risk			3,737.74	6,216.03	3,384.11	5,947.61	3,334.61	6,973.55	3,676.02	
LD-AP			3.31	2.00	3.04	2.07	3.54	1.96	3.01	
LI-AP			6.59	11.15	6.67	10.79	6.88	11.89	6.58	
Vehicles			3.00	7.00	3.00	7.00	3.00	8.00	3.00	
Pop Matrix		Distance	211.36	427.64	217.20	482.93	229.21	515.08	218.01	
		LD-Pop	28,468.72	17,563.05	25,406.07	17,920.03	28,505.95	17,619.96	26,086.75	
		LI-Pop	58,563.04	102,659.34	55,765.75	130,621.58	56,914.46	124,156.94	55,830.52	
		LD-Risk	1,479.27	798.71	1,305.10	764.20	1,524.04	774.45	1,298.15	
		LI-Risk	3,094.10	4,768.80	2,844.91	6,140.91	2,816.74	5,678.87	2,844.14	
		LD-AP	3.06	1.91	2.77	1.93	3.12	1.91	2.86	
		LI-AP	6.24	11.15	6.01	13.94	6.16	13.56	5.99	
		Vehicles	3.00	9.00	3.00	10.00	3.00	11.00	3.00	
Risk Matrix		Distance	230.65	759.08	231.68	492.08	230.77	759.08	231.68	
		LD-Pop	30,748.91	18,540.30	28,388.97	18,540.30	27,635.63	18,540.30	27,842.10	
		LI-Pop	63,235.06	194,527.35	59,419.41	119,877.21	59,901.84	194,527.35	59,419.41	
		LD-Risk	1,383.21	714.32	1,214.93	714.32	1,171.44	714.32	1,238.28	
		LI-Risk	2,742.94	7,581.35	2,620.21	4,682.78	2,551.45	7,581.35	2,620.21	
		LD-AP	3.14	1.94	2.95	1.94	2.76	1.94	2.81	
		LI-AP	6.63	20.12	6.10	12.41	6.26	20.12	6.10	
		Vehicles	3.00	15.00	3.00	10.00	3.00	15.00	3.00	
AP Matrix		Distance	210.15	413.57	217.05	429.46	238.18	715.00	216.75	
		LD-Pop	32,645.69	18,349.48	26,549.02	19,908.37	29,174.81	18,695.40	30,663.98	

Table B2. (continued)

Inst	Matrix		Objective Min Dist.	Objective Min LD-Pop	Objective Min LI-Pop	Objective Min LD-Risk	Objective Min LI-Risk	Objective Min LD-AP	Objective Min LI-AP	
		LI-Pop	62,140.31	104,111.64	58,973.13	107,257.30	61,204.48	176,418.51	59,284.72	
		LD-Risk	1,681.04	812.94	1,189.70	778.62	1,359.06	861.53	1,437.65	
		LI-Risk	3,156.85	4,876.91	2,754.00	4,915.26	2,715.51	8,489.19	2,822.53	
		LD-AP	3.10	1.88	2.65	1.98	3.04	1.83	2.84	
		LI-AP	6.01	10.21	5.81	10.52	6.19	17.24	5.78	
		Vehicles	3.00	8.00	3.00	8.00	3.00	14.00	3.00	
N3-i5 16c	Dist. Matrix	Distance	168.54	281.75	170.01	267.56	171.81	305.30	170.01	
		LD-Pop	23,512.30	11,327.66	22,965.10	12,874.89	21,533.84	11,530.60	20,182.45	
		LI-Pop	49,683.11	91,049.22	44,382.61	86,223.14	44,818.13	95,969.24	44,382.61	
		LD-Risk	1,233.75	512.50	1,112.59	501.46	1,067.78	522.62	891.35	
		LI-Risk	2,479.31	4,527.13	2,080.71	4,398.88	2,079.58	4,801.87	2,080.71	
		LD-AP	2.36	1.18	2.36	1.37	2.23	1.15	2.12	
		LI-AP	4.93	8.86	4.62	8.39	4.71	9.43	4.62	
		Vehicles	3.00	8.00	3.00	7.00	3.00	10.00	3.00	
	Pop Matrix	Distance	179.79	367.21	179.79	382.19	191.43	437.37	185.22	
		LD-Pop	20,998.20	10,105.19	20,998.20	10,741.08	22,254.19	10,127.06	21,557.07	
		LI-Pop	41,603.46	81,443.01	41,603.46	84,217.95	43,204.03	86,706.89	43,061.48	
		LD-Risk	1,116.86	407.90	1,116.86	395.01	1,084.78	442.35	1,111.92	
		LI-Risk	2,070.65	3,400.13	2,070.65	3,470.26	2,050.87	3,540.19	2,150.97	
		LD-AP	2.22	1.09	2.22	1.17	2.43	1.06	2.17	
		LI-AP	4.50	8.64	4.50	8.90	4.74	9.39	4.43	
		Vehicles	3.00	10.00	3.00	10.00	3.00	11.00	3.00	
	Risk Matrix	Distance	197.77	395.44	197.77	418.78	198.19	398.77	198.19	
		LD-Pop	22,210.24	10,642.96	22,948.93	10,667.11	22,826.25	10,954.63	21,892.09	
		LI-Pop	44,537.02	84,449.93	44,537.02	88,426.03	44,949.87	86,295.57	44,949.87	
		LD-Risk	1,003.80	393.76	999.64	379.35	1,016.37	390.07	989.80	
		LI-Risk	1,854.52	3,197.37	1,854.52	3,257.51	1,853.62	3,267.06	1,853.62	
		LD-AP	2.35	1.18	2.45	1.18	2.39	1.17	2.31	
		LI-AP	4.83	9.11	4.83	9.57	4.82	9.39	4.82	
		Vehicles	3.00	10.00	3.00	10.00	3.00	10.00	3.00	
	AP Matrix	Distance	180.04	436.59	182.07	363.42	205.51	428.28	189.00	
		LD-Pop	25,319.21	10,105.43	17,594.93	10,623.80	20,114.31	10,127.30	21,331.82	
		LI-Pop	47,506.84	94,938.10	42,188.71	81,955.02	47,390.07	96,035.70	45,115.58	
		LD-Risk	1,278.48	407.52	799.75	396.65	876.03	441.97	959.95	
		LI-Risk	2,338.95	4,097.00	2,031.26	3,570.74	2,011.08	4,397.31	2,130.67	
		LD-AP	2.45	1.09	1.84	1.17	2.07	1.06	2.06	
		LI-AP	4.72	9.83	4.38	8.46	4.85	9.84	4.38	
		Vehicles	3.00	10.00	3.00	10.00	3.00	10.00	3.00	
	N4-i1 13c	Dist. Matrix	Distance	138.72	444.53	157.59	292.20	168.24	418.80	142.10
			LD-Pop	24,383.98	9,962.13	25,615.83	10,422.94	22,469.05	9,993.49	20,634.98
			LI-Pop	52,246.89	116,066.21	44,513.75	79,364.13	48,302.75	123,542.11	46,497.26
LD-Risk			1,684.90	539.83	1,535.66	417.80	998.26	529.79	1,185.54	
LI-Risk			3,191.26	6,469.05	2,502.76	4,183.14	2,272.87	7,150.64	2,570.83	
LD-AP			2.15	0.96	2.50	1.08	2.28	0.95	1.94	
LI-AP			4.76	11.20	4.44	7.68	4.71	11.33	4.31	
Vehicles			2.00	8.00	2.00	5.00	2.00	8.00	2.00	
Pop Matrix		Distance	154.13	509.94	167.96	325.04	194.78	477.47	168.22	
		LD-Pop	20,894.58	9,325.72	18,523.87	10,933.98	21,329.11	9,326.04	24,734.30	
		LI-Pop	44,135.74	108,660.47	42,655.15	71,056.74	43,939.93	103,033.36	42,728.87	
		LD-Risk	1,246.63	498.79	916.30	415.18	1,025.24	500.62	1,459.88	
		LI-Risk	2,500.71	5,768.03	2,350.95	3,568.97	2,177.93	5,439.33	2,347.46	
		LD-AP	2.12	1.02	2.01	1.22	2.35	1.01	2.52	
		LI-AP	4.53	11.82	4.46	7.71	4.68	11.14	4.46	
		Vehicles	2.00	10.00	2.00	6.00	2.00	9.00	2.00	

Table B2. (continued)

Inst	Matrix		Objective Min Dist.	Objective Min LD-Pop	Objective Min LI-Pop	Objective Min LD-Risk	Objective Min LI-Risk	Objective Min LD-AP	Objective Min LI-AP
	Risk Matrix	Distance	166.44	544.91	192.16	904.11	214.15	585.70	176.78
		LD-Pop	26,477.33	10,848.79	25,969.07	11,962.62	30,391.12	10,920.36	28,799.37
		LI-Pop	50,604.75	109,855.85	48,149.97	170,701.87	50,590.38	116,565.25	48,543.48
		LD-Risk	1,247.19	396.64	1,132.12	367.20	1,196.82	377.26	1,324.17
		LI-Risk	2,195.55	3,542.19	2,011.03	5,118.70	1,987.04	3,707.77	2,083.54
		LD-AP	2.44	1.06	2.50	1.17	3.00	1.05	2.67
		LI-AP	4.72	10.87	4.67	16.94	4.98	11.46	4.56
		Vehicles	2.00	7.00	2.00	13.00	2.00	8.00	2.00
	AP Matrix	Distance	146.90	340.58	168.88	421.80	177.41	557.97	148.52
		LD-Pop	27,144.63	10,509.10	26,121.81	12,331.48	23,333.83	10,631.37	17,979.86
		LI-Pop	49,846.09	98,604.97	45,837.05	99,562.63	48,661.23	141,575.19	46,045.12
		LD-Risk	1,579.66	506.52	1,477.48	395.27	1,136.98	522.87	787.75
		LI-Risk	2,812.73	5,361.98	2,365.73	4,302.53	2,157.10	6,742.02	2,459.16
		LD-AP	2.46	0.94	2.40	1.15	2.16	0.92	1.65
LI-AP		4.52	8.57	4.19	8.95	4.46	12.22	4.15	
	Vehicles	2.00	6.00	2.00	7.00	2.00	11.00	2.00	
N4-i2 13c	Dist. Matrix	Distance	130.56	217.95	135.50	207.56	135.50	226.51	135.50
		LD-Pop	19,698.51	6,628.76	17,779.04	6,768.42	17,779.04	6,760.85	17,779.04
		LI-Pop	42,547.47	62,124.75	33,789.01	57,631.84	33,789.01	68,942.39	33,789.01
		LD-Risk	1,239.66	243.09	829.91	223.16	829.91	238.95	829.91
		LI-Risk	2,578.14	2,964.46	1,558.91	2,688.56	1,558.91	3,694.88	1,558.91
		LD-AP	1.86	0.67	1.74	0.66	1.74	0.66	1.74
		LI-AP	3.97	5.74	3.34	5.31	3.34	6.50	3.34
		Vehicles	2.00	6.00	2.00	5.00	2.00	5.00	2.00
	Pop Matrix	Distance	134.71	410.63	135.26	246.45	187.27	431.04	135.89
		LD-Pop	15,031.77	6,037.32	12,051.98	6,172.11	19,261.09	6,118.86	15,091.35
		LI-Pop	32,960.61	72,864.88	32,842.58	48,579.88	38,593.80	77,765.65	33,025.63
		LD-Risk	714.65	206.86	471.37	203.39	791.87	220.71	722.43
		LI-Risk	1,533.21	2,462.63	1,538.59	1,781.55	1,472.96	2,836.73	1,539.35
		LD-AP	1.51	0.65	1.24	0.65	2.00	0.63	1.50
		LI-AP	3.35	7.85	3.29	5.08	3.93	8.53	3.28
		Vehicles	2.00	9.00	2.00	5.00	2.00	8.00	2.00
	Risk Matrix	Distance	160.07	298.30	160.07	602.22	196.42	602.22	161.12
		LD-Pop	22,293.33	6,815.45	14,154.94	6,878.64	17,328.75	6,878.64	19,656.69
		LI-Pop	38,897.42	60,341.37	38,897.42	112,141.65	41,730.15	112,141.65	39,133.10
		LD-Risk	873.36	187.67	406.78	187.53	647.20	187.53	821.50
		LI-Risk	1,350.65	1,684.58	1,350.65	2,737.99	1,311.83	2,737.99	1,348.55
		LD-AP	2.09	0.61	1.28	0.62	1.64	0.62	1.88
		LI-AP	3.57	5.45	3.57	10.12	3.84	10.12	3.56
		Vehicles	2.00	6.00	2.00	13.00	2.00	13.00	2.00
	AP Matrix	Distance	138.09	334.71	138.09	414.34	199.32	436.03	138.09
		LD-Pop	13,379.40	6,954.53	13,379.40	7,062.18	21,417.81	6,954.53	16,963.67
		LI-Pop	34,706.16	76,955.88	34,706.16	86,111.05	43,340.25	94,028.96	34,706.16
		LD-Risk	470.07	229.93	470.07	203.90	789.28	229.93	712.25
LI-Risk		1,540.15	3,014.35	1,540.15	2,815.52	1,491.31	3,388.06	1,540.15	
LD-AP		1.12	0.57	1.12	0.58	1.80	0.57	1.49	
LI-AP		3.10	6.31	3.10	6.98	3.67	7.74	3.10	
	Vehicles	2.00	7.00	2.00	9.00	2.00	10.00	2.00	
N4-i3 15c	Dist. Matrix	Distance	196.43	349.52	203.90	287.33	199.76	400.36	196.80
		LD-Pop	34,550.32	16,046.93	30,219.75	18,624.48	28,172.50	16,340.48	27,195.21
		LI-Pop	56,177.87	103,546.28	55,383.48	86,400.26	57,449.77	124,128.57	55,873.02
		LD-Risk	1,920.35	1,039.35	1,864.56	740.88	1,375.36	1,076.75	1,461.90
		LI-Risk	3,088.73	6,132.05	3,239.14	4,453.13	3,049.86	7,936.46	3,061.90
	LD-AP	3.18	1.58	2.86	1.81	2.76	1.55	2.57	

Table B2. (continued)

Inst	Matrix		Objective Min Dist.	Objective Min LD-Pop	Objective Min LI-Pop	Objective Min LD-Risk	Objective Min LI-Risk	Objective Min LD-AP	Objective Min LI-AP	
		LI-AP	5.33	9.49	5.36	7.99	5.51	11.42	5.29	
		Vehicles	3.00	7.00	3.00	6.00	3.00	9.00	3.00	
	Pop Matrix	Distance	205.86	658.84	209.78	623.16	209.78	693.13	209.78	
		LD-Pop	26,948.79	13,865.43	23,744.57	14,429.98	19,891.52	13,942.12	24,042.13	
		LI-Pop	50,155.39	125,897.35	47,717.48	122,673.58	47,717.48	132,250.64	47,717.48	
		LD-Risk	1,681.03	662.44	939.13	532.02	802.30	689.51	1,157.77	
		LI-Risk	2,684.09	5,640.19	2,085.39	5,211.10	2,085.39	5,500.89	2,085.39	
		LD-AP	2.64	1.41	2.49	1.52	2.03	1.39	2.36	
		LI-AP	5.00	13.01	4.83	12.62	4.83	13.59	4.83	
		Vehicles	3.00	12.00	3.00	10.00	3.00	12.00	3.00	
	Risk Matrix	Distance	219.73	663.19	219.73	870.13	219.73	669.86	219.73	
		LD-Pop	22,185.81	15,850.59	25,380.68	15,850.59	22,185.81	15,871.04	24,069.59	
		LI-Pop	52,769.68	132,262.84	52,769.68	170,689.42	52,769.68	132,287.97	52,769.68	
		LD-Risk	782.25	484.20	1,071.15	484.20	782.25	514.26	1,064.79	
		LI-Risk	1,969.83	4,093.47	1,969.83	5,114.82	1,969.83	4,030.52	1,969.83	
		LD-AP	2.03	1.50	2.33	1.50	2.03	1.48	2.19	
		LI-AP	4.81	12.35	4.81	16.04	4.81	12.28	4.81	
		Vehicles	3.00	11.00	3.00	15.00	3.00	11.00	3.00	
	AP Matrix	Distance	214.51	634.92	225.54	588.70	225.54	810.43	225.54	
		LD-Pop	23,914.25	15,775.93	27,987.27	16,807.87	24,673.69	15,775.93	29,591.77	
		LI-Pop	55,203.26	133,101.25	54,295.88	123,809.74	54,295.88	170,791.82	54,295.88	
		LD-Risk	903.08	741.30	948.12	549.16	878.18	741.30	1,220.43	
		LI-Risk	2,771.75	5,414.26	2,091.57	4,815.13	2,091.57	7,197.60	2,091.57	
		LD-AP	2.02	1.30	2.37	1.42	2.08	1.30	2.56	
		LI-AP	4.73	11.06	4.62	10.39	4.62	14.18	4.62	
		Vehicles	3.00	11.00	3.00	9.00	3.00	15.00	3.00	
	N4-i4 16c	Dist. Matrix	Distance	172.60	235.05	204.43	267.80	232.98	287.10	203.22
			LD-Pop	21,268.83	15,688.96	25,199.33	18,584.08	25,203.35	15,880.00	26,688.73
			LI-Pop	58,273.45	72,149.10	51,797.57	74,326.98	53,383.13	98,390.97	51,936.17
			LD-Risk	1,138.00	732.88	1,124.39	714.14	1,171.07	778.77	1,457.14
			LI-Risk	3,642.38	4,038.37	2,521.67	4,099.45	2,284.47	6,040.20	2,590.12
			LD-AP	1.99	1.54	2.50	1.95	2.50	1.51	2.50
LI-AP			5.38	6.63	5.05	7.08	5.45	8.83	4.99	
Vehicles			4.00	5.00	4.00	5.00	4.00	7.00	3.00	
Pop Matrix		Distance	190.79	597.38	204.12	431.14	301.19	422.58	203.33	
		LD-Pop	22,281.29	15,072.61	22,630.46	19,394.04	24,120.63	15,169.26	21,516.96	
		LI-Pop	53,008.70	116,439.81	46,170.29	84,716.45	54,461.29	96,446.95	46,193.33	
		LD-Risk	1,143.33	726.30	897.87	681.84	944.81	710.21	1,043.35	
		LI-Risk	2,757.88	4,854.93	2,004.47	3,469.96	1,952.26	4,401.56	2,005.69	
		LD-AP	2.22	1.61	2.54	2.19	2.59	1.58	2.12	
		LI-AP	5.23	12.83	4.87	9.23	6.03	10.02	4.86	
		Vehicles	4.00	11.00	4.00	8.00	4.00	7.00	3.00	
Risk Matrix		Distance	219.93	486.90	220.72	659.07	220.72	456.93	219.93	
		LD-Pop	24,215.47	16,295.33	24,010.10	17,078.55	24,929.89	16,312.04	25,119.40	
		LI-Pop	49,756.65	94,365.65	49,733.60	129,099.58	49,733.60	89,152.80	49,756.65	
		LD-Risk	1,020.65	671.29	829.81	636.21	1,048.83	672.18	998.88	
		LI-Risk	1,851.46	3,011.66	1,850.24	4,240.48	1,850.24	2,868.28	1,851.46	
		LD-AP	2.42	1.62	2.37	1.72	2.52	1.49	2.55	
		LI-AP	4.97	9.28	4.98	12.72	4.98	8.81	4.97	
		Vehicles	3.00	9.00	3.00	11.00	3.00	13.00	3.00	
AP Matrix		Distance	186.93	408.94	205.53	375.14	257.44	696.33	207.50	
		LD-Pop	22,347.06	15,740.57	26,716.78	18,428.12	22,577.21	16,256.85	23,987.25	
		LI-Pop	54,191.61	95,976.56	48,463.08	78,489.50	54,004.68	150,901.23	49,814.10	
		LD-Risk	1,249.88	716.37	943.72	674.13	1,047.03	725.90	1,124.22	
		LI-Risk	2,993.57	3,957.58	2,003.61	2,850.19	1,978.86	5,717.00	2,016.01	

Table B2. (continued)

Inst	Matrix		Objective Min Dist.	Objective Min LD-Pop	Objective Min LI-Pop	Objective Min LD-Risk	Objective Min LI-Risk	Objective Min LD-AP	Objective Min LI-AP	
		LD-AP	2.01	1.49	2.64	1.81	2.13	1.44	2.16	
		LI-AP	4.94	8.71	4.64	7.38	5.13	13.56	4.64	
		Vehicles	4.00	7.00	3.00	8.00	3.00	10.00	4.00	
N5-i1 15c	Dist. Matrix	Distance	144.08	250.97	170.52	226.55	176.89	364.39	149.92	
		LD-Pop	22,575.98	8,284.89	21,075.21	9,220.22	16,606.91	9,165.11	22,788.87	
		LI-Pop	43,239.53	61,797.02	37,835.40	56,587.18	39,057.76	86,767.37	43,943.75	
		LD-Risk	1,950.80	454.22	1,794.89	380.19	790.27	525.15	1,677.00	
		LI-Risk	3,373.99	3,831.99	2,580.11	3,252.47	2,090.86	5,336.46	3,380.65	
		LD-AP	1.68	0.96	1.62	1.05	1.66	0.89	1.63	
		LI-AP	3.29	5.31	3.34	4.79	3.44	7.36	3.24	
			Vehicles	3.00	7.00	3.00	7.00	3.00	11.00	3.00
	Pop Matrix	Distance	152.66	329.33	158.22	370.89	158.88	405.53	154.60	
		LD-Pop	17,474.91	6,462.69	15,084.95	6,488.10	17,629.17	6,488.10	11,953.70	
		LI-Pop	32,229.73	48,211.15	31,823.95	51,739.33	31,966.31	56,450.68	32,500.38	
		LD-Risk	1,328.94	290.76	1,036.15	289.96	1,117.07	289.96	594.00	
		LI-Risk	2,003.15	2,168.27	1,782.86	2,252.41	1,773.09	2,422.84	1,994.02	
		LD-AP	1.45	0.81	1.38	0.80	1.55	0.80	1.16	
		LI-AP	2.95	5.86	3.02	6.23	3.01	6.99	2.94	
			Vehicles	3.00	9.00	3.00	10.00	3.00	11.00	3.00
	Risk Matrix	Distance	165.62	338.85	165.62	535.57	166.21	535.57	166.21	
		LD-Pop	11,575.04	7,028.77	19,749.62	7,028.77	10,692.91	7,028.77	19,157.81	
		LI-Pop	34,402.06	53,020.10	34,402.06	71,899.60	34,471.56	71,899.60	34,471.56	
		LD-Risk	463.49	271.96	1,066.98	271.96	440.72	271.96	1,054.32	
		LI-Risk	1,708.09	2,029.61	1,708.09	2,565.79	1,707.21	2,565.79	1,707.21	
		LD-AP	1.16	0.79	1.59	0.79	1.06	0.79	1.56	
		LI-AP	3.02	5.67	3.02	8.57	3.01	8.57	3.01	
			Vehicles	3.00	10.00	3.00	15.00	3.00	15.00	3.00
	AP Matrix	Distance	154.09	334.04	162.58	338.61	163.18	533.63	158.65	
		LD-Pop	14,660.10	7,028.77	18,940.49	7,028.77	19,229.37	7,193.96	21,343.73	
		LI-Pop	37,041.93	52,912.21	34,452.90	53,320.43	34,522.41	74,302.26	35,318.81	
		LD-Risk	853.56	271.96	1,059.15	271.96	1,064.73	272.44	1,311.56	
		LI-Risk	2,575.79	2,024.29	1,714.81	2,030.49	1,713.93	2,572.79	1,961.95	
		LD-AP	1.28	0.79	1.48	0.79	1.52	0.79	1.55	
		LI-AP	3.00	5.59	2.99	5.67	2.98	8.56	2.89	
			Vehicles	4.00	9.00	5.00	10.00	4.00	15.00	3.00
	N5-i2 16c	Dist. Matrix	Distance	189.02	448.15	209.61	345.46	239.92	408.89	199.52
			LD-Pop	40,194.08	9,353.96	23,165.71	9,648.82	15,809.40	9,582.63	18,204.90
			LI-Pop	61,869.61	90,806.24	41,024.78	77,705.70	45,321.01	86,894.35	46,786.77
LD-Risk			3,293.11	436.97	1,576.43	422.54	954.21	430.12	1,043.27	
LI-Risk			4,620.81	4,900.62	2,534.76	4,454.41	2,488.32	4,783.23	3,330.44	
LD-AP			2.55	1.08	2.19	1.07	1.67	1.06	1.51	
LI-AP			4.28	8.71	4.02	7.18	4.48	8.20	3.86	
			Vehicles	3.00	11.00	3.00	7.00	4.00	8.00	3.00
Pop Matrix		Distance	202.18	581.29	214.19	553.58	219.90	473.66	205.56	
		LD-Pop	17,631.23	8,548.22	14,623.46	8,680.41	14,865.63	9,009.63	16,149.32	
		LI-Pop	36,748.99	85,280.74	36,564.60	83,165.81	38,371.90	62,550.51	36,839.00	
		LD-Risk	1,099.71	368.25	777.19	366.20	750.34	389.31	801.44	
		LI-Risk	2,037.34	3,733.27	2,039.65	3,701.95	1,912.55	2,658.74	2,028.78	
		LD-AP	1.97	1.08	1.58	1.07	1.73	1.07	1.49	
		LI-AP	3.84	10.39	4.03	10.09	4.09	8.03	3.83	
			Vehicles	3.00	12.00	3.00	12.00	3.00	10.00	3.00
Risk Matrix		Distance	225.72	770.87	225.72	770.87	229.21	673.23	225.72	
		LD-Pop	14,754.80	9,116.93	14,814.58	9,116.93	15,460.90	9,127.29	18,088.23	
		LI-Pop	39,631.54	104,858.73	39,631.54	104,858.73	39,684.59	95,896.83	39,631.54	

Table B2. (continued)

Inst	Matrix		Objective Min Dist.	Objective Min LD-Pop	Objective Min LI-Pop	Objective Min LD-Risk	Objective Min LI-Risk	Objective Min LD-AP	Objective Min LI-AP
		LD-Risk	697.33	345.09	677.71	345.09	758.50	347.06	736.15
		LI-Risk	1,864.37	3,887.26	1,864.37	3,887.26	1,862.74	3,688.56	1,864.37
		LD-AP	1.58	1.07	1.59	1.07	1.71	1.06	1.72
		LI-AP	4.00	12.14	4.00	12.14	4.02	10.88	4.00
		Vehicles	3.00	16.00	3.00	16.00	3.00	14.00	3.00
	AP Matrix	Distance	202.54	523.72	206.04	523.14	221.59	745.48	206.04
		LD-Pop	24,196.97	9,283.61	18,206.92	9,292.24	15,708.76	9,473.10	18,608.08
		LI-Pop	42,881.13	86,903.69	38,286.98	86,355.45	40,098.20	109,953.00	38,286.98
		LD-Risk	1,777.92	357.05	1,071.88	356.58	735.89	357.41	1,079.80
		LI-Risk	2,806.43	3,466.01	2,008.53	3,468.67	1,884.70	4,014.96	2,008.53
		LD-AP	1.98	1.04	1.75	1.03	1.63	1.02	1.86
		LI-AP	3.78	8.84	3.66	8.87	3.88	11.69	3.66
		Vehicles	3.00	11.00	3.00	10.00	3.00	16.00	3.00
N5-i3 16c	Dist. Matrix	Distance	189.02	448.15	209.61	345.46	239.92	408.89	199.52
		LD-Pop	40,194.08	9,353.96	23,165.71	9,648.82	15,809.40	9,582.63	18,204.90
		LI-Pop	61,869.61	90,806.24	41,024.78	77,705.70	45,321.01	86,894.35	46,786.77
		LD-Risk	3,293.11	436.97	1,576.43	422.54	954.21	430.12	1,043.27
		LI-Risk	4,620.81	4,900.62	2,534.76	4,454.41	2,488.32	4,783.23	3,330.44
		LD-AP	2.55	1.08	2.19	1.07	1.67	1.06	1.51
		LI-AP	4.28	8.71	4.02	7.18	4.48	8.20	3.86
	Pop Matrix	Vehicles	3.00	11.00	3.00	7.00	4.00	8.00	3.00
		Distance	202.18	581.29	214.19	553.58	219.90	473.66	205.56
		LD-Pop	17,631.23	8,548.22	14,623.46	8,680.41	14,865.63	9,009.63	16,149.32
		LI-Pop	36,748.99	85,280.74	36,564.60	83,165.81	38,371.90	62,550.51	36,839.00
		LD-Risk	1,099.71	368.25	777.19	366.20	750.34	389.31	801.44
		LI-Risk	2,037.34	3,733.27	2,039.65	3,701.95	1,912.55	2,658.74	2,028.78
		LD-AP	1.97	1.08	1.58	1.07	1.73	1.07	1.49
	Risk Matrix	LI-AP	3.84	10.39	4.03	10.09	4.09	8.03	3.83
		Vehicles	3.00	12.00	3.00	12.00	3.00	10.00	3.00
		Distance	225.72	770.87	225.72	770.87	229.21	673.23	225.72
		LD-Pop	14,754.80	9,116.93	14,814.58	9,116.93	15,460.90	9,127.29	18,088.23
		LI-Pop	39,631.54	104,858.73	39,631.54	104,858.73	39,684.59	95,896.83	39,631.54
		LD-Risk	697.33	345.09	677.71	345.09	758.50	347.06	736.15
		LI-Risk	1,864.37	3,887.26	1,864.37	3,887.26	1,862.74	3,688.56	1,864.37
	AP Matrix	LD-AP	1.58	1.07	1.59	1.07	1.71	1.06	1.72
		LI-AP	4.00	12.14	4.00	12.14	4.02	10.88	4.00
		Vehicles	3.00	16.00	3.00	16.00	3.00	14.00	3.00
		Distance	202.54	523.72	206.04	523.14	221.59	745.48	206.04
		LD-Pop	24,196.97	9,283.61	18,206.92	9,292.24	15,708.76	9,473.10	18,608.08
		LI-Pop	42,881.13	86,903.69	38,286.98	86,355.45	40,098.20	109,953.00	38,286.98
		LD-Risk	1,777.92	357.05	1,071.88	356.58	735.89	357.41	1,079.80
LI-Risk		2,806.43	3,466.01	2,008.53	3,468.67	1,884.70	4,014.96	2,008.53	
LD-AP	1.98	1.04	1.75	1.03	1.63	1.02	1.86		
LI-AP	3.78	8.84	3.66	8.87	3.88	11.69	3.66		
Vehicles	3.00	11.00	3.00	10.00	3.00	16.00	3.00		

Table B3 – Influence of the fleet size/ number of vehicles on the LD objective function values

Value	Instance	Matrix	Fleet Size (number of vehicles)										
			3	4	5	6	7	8	9	10	11	12	13
LD-pop	N3-i5	Dist	14,471	12,378	11,782	11,484	11,367	11,328	11,328	11,328	11,328	11,328	11,328
		Pop	13,740	11,512	10,766	10,481	10,255	10,179	10,140	10,105	10,105	10,105	10,105
		Risk	15,078	12,636	11,605	11,133	10,876	10,733	10,682	10,643	10,643	10,643	10,643
		AP	13,776	11,549	10,780	10,496	10,256	10,185	10,145	10,105	10,105	10,105	10,105
	N4-i4	Dist	18,463	16,031	15,689	15,689	15,689	15,689	15,689	15,689	15,689	15,689	15,689
		Pop	18,433	15,875	15,390	15,235	15,144	15,108	15,077	15,074	15,073	15,073	15,073
		Risk	19,216	17,069	16,661	16,417	16,321	16,297	16,295	16,295	16,295	16,295	16,295
		AP	18,579	16,310	15,968	15,793	15,741	15,741	15,741	15,741	15,741	15,741	15,741
LD-risk	N3-i5	Dist	659.16	565.04	524.24	506.10	501.46	501.46	501.46	501.46	501.46	501.46	501.46
		Pop	578.50	481.19	443.72	421.62	408.41	402.83	398.75	395.01	395.01	395.01	395.01
		Risk	538.19	457.26	417.47	399.60	389.17	382.87	379.81	379.35	379.35	379.35	379.35
		AP	577.06	486.68	450.45	426.85	412.08	404.41	399.28	396.65	396.65	396.65	396.65
	N4-i4	Dist	772.96	715.63	714.14	714.14	714.14	714.14	714.14	714.14	714.14	714.14	714.14
		Pop	739.61	691.20	684.52	682.93	681.94	681.84	681.84	681.84	681.84	681.84	681.84
		Risk	707.39	659.17	644.70	639.03	637.12	636.34	636.24	636.21	636.21	636.21	636.21
		AP	751.85	682.48	677.83	674.90	674.39	674.13	674.13	674.13	674.13	674.13	674.13
LD-AP	N3-i5	Dist	1.5331	1.3232	1.2316	1.1945	1.1693	1.1542	1.1528	1.1528	1.1528	1.1528	1.1528
		Pop	1.4857	1.2502	1.1548	1.1084	1.0832	1.0681	1.0609	1.0609	1.0602	1.0602	1.0602
		Risk	1.6477	1.3691	1.2666	1.2180	1.1946	1.1787	1.1716	1.1692	1.1692	1.1692	1.1692
		AP	1.4817	1.2440	1.1548	1.1084	1.0832	1.0681	1.0602	1.0572	1.0572	1.0572	1.0572
	N4-i6	Dist	1.7855	1.5784	1.5427	1.5128	1.5063	1.5063	1.5063	1.5063	1.5063	1.5063	1.5063
		Pop	1.8014	1.6388	1.5901	1.5790	1.5757	1.5757	1.5757	1.5757	1.5757	1.5757	1.5757
		Risk	1.8939	1.6679	1.6416	1.6232	1.6159	1.6133	1.6133	1.6133	1.6133	1.6133	1.4877
		AP	1.7736	1.5510	1.4992	1.4693	1.4497	1.4425	1.4420	1.4415	1.4415	1.4415	1.4415