Optimization of Routes for Hazardous Materials Transportation
A Case Study of Fuel Deliveries in Lisbon

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Abstract: This study aims at contributing to increase road safety by expanding knowledge on how to identify safe urban routes for Hazardous Materials that are commercially doable. A bi-level linear model was implemented in GAMS modelling software considering fuel distribution data and the road network for the city of Lisbon. Its first level consists in road risk minimization whereas the second level aims at maintaining the economic viability of the itineraries. This work expands the research of Rodrigues et al. (2015) by increasing: (1) the comprehensiveness of the road data, and (2) the complexity of the analysis by including, besides resident population, hospital and school users potentially affected by an accident, and by comparing different itineraries and the computational time needed to solve the model. The work analyses much more comprehensive data than those found in previous studies in the literature and was successful in identifying optimal solutions, most of which in short computational time. This suggests that this methodology can be used by the industry to identify routes for fuel distribution in urban environments. In the future, the routes generated by the model will be compared with routes currently used in fuel distribution.

1 INTRODUCTION

Societies nowadays are extremely dependent on Hazardous Materials (HazMats), which fulfil a wide range of purposes, including energy supply to cities, vehicles and industries (Erkut et al., 2007).

This study deals with the transportation of fuels, which are also classified as HazMats (Verter and Kara, 2008). Even though the number of accidents involving HazMats is relatively small – approximately four times less than the probability of being struck by lightning (Transportation and Infrastructure Committee, 2011), when accidents involving HazMats occur, the severity of damages (both personal, environmental and material) can be high (Erkut et al., 2007).

The objective of this research is to contribute to increase road safety through the identification of routes for the transportation of HazMats that minimize the risk of accident without compromising the economic feasibility of the industry. It builds upon and continues the research of Rodrigues (2015) with further challenges of the road network given that here the entire city of Lisbon (Portugal) was analysed as the case study.

2 OPTIMIZATION MODEL

In order to identify safe routes for the transportation of HazMats, the bi-level linear programming model presented by Kara and Verter (2004) was implemented. This model features two problems, which are hierarchically solved. The problems are related and correspond to different entities, in which the choice that one makes is directly influenced by the choice of the other (Bianco et al., 2009). In this particular case, it is acceptable to consider that the regulator, whose objective is to minimize total risk (defined as total population exposure) is in the outer level. Then the transportation companies correspond to the inner level and their objective is to minimize total cost. It is thus clear that the outer level chooses a network where risk is controlled and the inner level then chooses the minimum cost path from those available (Kara and Verter, 2004).

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In Kara and Verter (2004) model, the authors consider that the consequences of an accident involving HazMats occur until a given distance from the place where the accident happened. This means that when a truck is driving through a given arc, only the people within that distance to the arc are exposed to risk. In this model, total risk is the measure used by the regulator and total time spent travelling is used by companies for selecting the routes. However, this can easily be adapted and other risk and economic measures can be used (Rodrigues, 2014).

The outer problem decision regards which arcs should be made available for the transportation of HazMats and has risk as the objective function. Since the inner problem consists in choosing which routes will actually be used for transportation, the binary decision variables from the outer problem constitute parameters for the inner problem. This is essentially the minimum cost flow problem, which minimizes the objective function time (or distance) travelled.

To solve the bi-level model a transformation was applied using the *Karush-Kuhn-Tucker* (KKT) conditions. The resulting model is of the mixed integer linear programming (MILP) type, having as the objective function the one of the outer problem (total risk).

A detailed description of both the bi-level linear programming model as well as the MILP model can be found in Rodrigues (2014) and Rodrigues et al., (2015).

3 CASE STUDY DESCRIPTION

This work follows the methodology that was presented by Rodrigues (2014) but with a different road network for the Lisbon case study, which translates into a larger problem size.

The methodology for data collection and processing as well as the problem simplifications were similar to the one described in Rodrigues *et al.* (2015), and so only the main differences are highlighted in this section.

Data characterising the fuel distribution includes petrol stations and direct clients in Lisbon municipality, supplied by the company. The amount of daily distribution during 2013 was provided and then aggregated to obtain annual amounts.

Rodrigues (2014) used a network for a specific district of Lisbon (Olivais parish). This dataset was a very detailed network, with 654 nodes and 6 origin-destination (O-D) pairs. For the present work, the road network for the entire Lisbon city (mapped in a desktop geographical information system (GIS), namely ArcGIS 10, was analyzed but considering only the higher hierarchy routes. Even though only a part of the roads are featured, this network consists of 2685 arcs and 2285 nodes, which represents a significant increase compared to the networks that have been used previously in the reviewed literature. There is a total of 26 O-D pairs, which also represents a considerable increase in complexity of the problem to be solved.

Figure 1: Road network and census tracts in Lisbon.

Figure 1 represents the road network plus the geographical information referencing basis (census tracts), from which the resident population was determined (Census 2011 data).

The locations of the destinations were given by the petrol company as a list of latitude and longitude GPS coordinates and were georeferenced in the ArcGIS software. Then there was the need to find out which arcs were the closest to each of these locations, which was done using the nearest function available in the software. Figure 2 shows in blue the destinations operating in 2013 (26 in total) and in black those that operated in 2012 but were shut down during 2013 (6 in total).

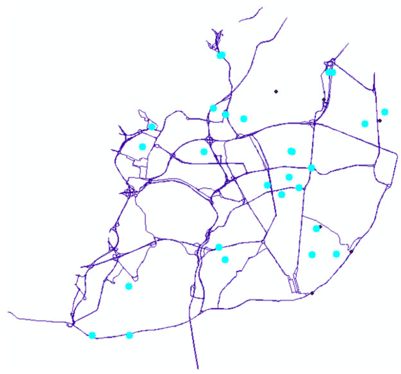

Figure 2: Destinations in the road network.

Besides the resident population, people in schools and hospitals nearby network arcs were also considered (based on facility capacity data provided by Lisbon Municipality). This encompassed 124 public and private schools and 25 public hospitals, depicted in Figures 3 and 4.

Figure 3: Location of schools in the road network.

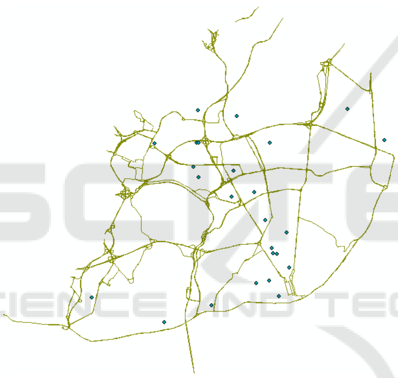

Figure 4: Location of hospitals in the road network.

The incorporation of high-density population centres such as schools or hospitals in models aiming to calculate safe routes for HazMats were not found in the literature review. Authors such as Kara and Verter (2004) had previously discussed the importance of its consideration.

4 COMPUTATIONAL TOOLS

The MILP model was implemented in GAMS modelling system and solved with CPLEX version 12.4.0.0 on a 2.8GHz Intel Core i7 4GB RAM.

The data was extracted from ArcGIS version 10 to an MS Excel spreadsheet, which was then read by GAMS. Functionalities xls2gms and gdx that make the connection between Excel and GAMS regarding model input and output, respectively, were used. After solving the model, an Excel output file is written with a binary table where the arcs used in the route to each destination are expressed.

As a measure of the problem data size, there are over 1200 columns and 6600 rows in the largest table in the Excel input data file.

5 CASE STUDY RESULTS AND DISCUSSION

Results for the case study were obtained based on four different sets of population figures assigned to the network arcs. The MILP model was solved for each of these sets henceforth named “population combination”. For each network arc, two population figures were computed using the GIS software: the population living nearby each arc (the “arc population”) and the fluctuating population due to the schools and public hospitals considered.

Table 1 displays the four different ways these populations figures were combined in a weighted sum to obtain the final value for each arc, which was the one used when solving the MILP model (i.e., the actual model parameter). For solutions A through C a 300 m buffer was applied, while for D the distance of 800 m was used. Thus, comparison of objective function values should consider that the population that was accounted for varies among solutions.

Table 1: Weighted population combinations tested.

Solution	Population combinations
A	1 x arc population + 0 x hosp_school
B	0 x arc population + 1 x hosp_school
C	0.5 x arc population + 0.5 hosp_school
D	0.5 x arc population + 0.5 x hosp_school (800m)

Table 2 shows the numeric characteristics of the model (which depend solely on the road network) and Table 3 shows the results when solving the model to optimality: number of iterations, CPU time and objective function value.

Table 2: Numeric characteristics of the model.

No. of variables	No. of binary variables	No. of constraints
271,842	72,603	1,824,265

Table 3: Summary of results.

Solution	No. of iterations	CPU time (s)	Objective function value
A	76,155	304.6	341,974
B	1,242,987	5,010.1	706,069
C	586,489	706.0	286,199
D	28,681	29.8	316,173

It is worthwhile noticing that the even though the dimension of the model was the same, CPU times ranged from 30 sec observed for solution D to approximately 5 min and 12 minutes in solutions A and C, respectively, and up to 1 hour and 20 minutes in solution B (where only school and hospital population is considered). In solution B, population is concentrated only in a set of points and the impact of not having a more homogeneously distributed population relatively to the network arcs was decisive upon the time required to compute the optimal solution.

Table 4 summarizes, for each solution, the average values of population exposure, travel time and number of arcs per route (chosen to each destination). The average number of trucks per destination is 112.12 per year. This number is constant for each destination as it only depends on the quantity of fuel delivered (information provided by the company). Hence, it is a model parameter, unlike the population exposure, travel time and number of arcs per route that were computed based on the value of the decision variables after solving the model.

It is clear that solution B, the one that accounts for hospitals and schools population only, stands out for presenting higher values for time and number of arcs per route. On the other hand, solution D, with a weight of 0.5 for each type of population and a buffer of 800 meters, is the solution where the population associated with each arc, when solving the MILP model, is more uniform, therefore it is also the one with lowest values for time and number of arcs. Solutions A and C present similar values and intermediate between those of solutions B and D.

Table 4: Summary of results (average values per destination).

Solution	Population exposure (average)	Time (min.) (average)	No. of arcs used (average)
A	13,152	14.76	79.88
B	27,156	26.96	129.23
C	11,007	15.18	74.23
D	12,160	12.29	55.58

Table 5 compares the different solutions for a particular destination (destination 23, for which the number of trucks used is 271). This is located in the the middle of the city, far away from the route origin (A1 highway entrance in Lisbon). While there are only minor changes along the route for solutions A, C and D, there is a major change for solution B. Population exposure is the lowest for solutions C and D, the ones that have a split contribution from each population source. Solution A, the one where all the population from the census tracts is taken into account, is the one with the least amount of people exposed. The one where the most people are exposed is solution B, which is also the longest route (average travel time and number of arcs used).

Table 5: Comparison of model outputs for destination 23.

Solution	Population exposure	Time (min.)	No. of arcs used
A	25,018	19.43	97
B	32,663	50.51	225
C	20,429	18.58	89
D	21,377	15.67	70

Figure 5 illustrates the route for destination 23 and solution A.

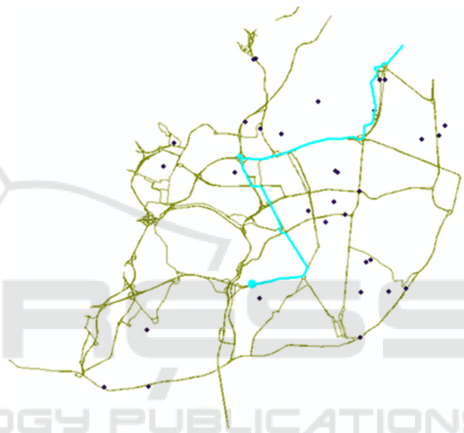

Figure 5: Route for solution A and destination 23.

6 CONCLUSIONS

There is a consensual belief on the importance of minimizing risks associated to HazMats transportation, particularly in urban areas, where increasingly more people live. The growing complexity and density of urban environments is pressing the development of reliable and practical tools to support the industry identifying safe and economically viable HazMats routes. However, the research found in the literature is still limited particularly in the complexity of the analyzed road networks. Aiming at contributing to increase urban road safety and urban economic growth by specifically supporting safe and feasible fuel distribution, this work studied the whole city of Lisbon, capital of Portugal, using up-to-date distribution data provided by one petrol company operating in the city.

A Geographical Information System (GIS) platform was used in which the road network and population were represented for Lisbon. Information extracted from the GIS was subsequently introduced into the mathematical modelling software GAMS. The adopted MILP model successfully identified optimal routes, i.e. those with least population exposure to risk while still keeping economic viability. Results indicate that with an optimized method of representing population exposure along the road network arcs it is possible to compare population exposure for different routes and identify options on best routes for HazMats distribution.

The presented model can be further improved by refining the road network representation, the information on both resident and commuter adjusted daytime population distribution and include traffic data. Once these recommended improvements are built-in and adequate model calibration has been performed there is a real potential for industry adoption of the described methodology for HazMats route planning.

Regarding the impact of this work, the company is very interested in gaining more control upon the fuel distribution routes, which are currently a decision of the subcontracted transportation companies. With the proposed model application, risk and cost are made explicit and both can be considered when deciding the routes.

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