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ARTICLE

A Decomposition Model for Risk Equity and Network Accessibility Trade off in Hazardous Material Transportation: An Empirical Study

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ABSTRACT

A major part of goods and substances transported across the world is categorized as hazardous materials (Hazmat) or dangerous goods. Hazmat transportation has potential risks in nature, so it is essential to avoid risk agglomeration in the most frequently selected routes while transport planning in practice. The concern leads authorities and practitioners to prevent risk concentration, so-called risk equity or risk distribution, but it affects a crucial parameter in transport planning known as network accessibility. This study proposes a procedure and develops the corresponding mathematical models for trading off between risk equity and network accessibility. The linearization technique of decomposition transforms the nonlinear format of equations into the linear ones as well as the risk distribution technique of Min(Max) spreads Hazmat transport risk over the network. The inter-relation between risk equity and accessibility has been illustrated to be easily understood and typically studied as a case study in an intercity road network. The proposed procedure has been performed using experimental data, including network specifications and the Origin-Destination matrix of Hazmat planned to be transported. Based on the research results, applying Hazmat risk distribution techniques and network accessibility measures have a reverse relationship. Therefore, authorities should be aware of the effects of risk equity and road network accessibility in Hazmat transport planning.

Keywords: Hazardous Material (Dangerous Goods) Transportation; Risk Equity; Network Accessibility; Mathematical Modeling; Linearization

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1. Introduction

1.1. Hazardous Materials Transportation and Concerns

By definition, hazardous materials or dangerous goods, commonly abbreviated as Hazmat or DG, is attributed to substances or materials that are capable of causing damage to humans, animals, property, and the environment [1]. In the ADR agreement, a continental convention for carrying Hazmat or DG by road in the European countries, the above substances are classified into nine classes of explosives, gases, flammable liquids and solids, oxidizing materials, toxic substances, radioactive materials, corrosive substances, and miscellaneous [2]. They are used in a wide range of industries of manufacturing, cleaning, medicine, research and construction. Other purposes, such as lubricating machinery, cleaning equipment, and medical treatments are also included. In addition, dangerous goods constitute a significant portion of global freight near around 10% of all containerized shipments. The market is also projected to reach $382.9 billion by 2031, with a growth rate of 7% per year [3]. Hazardous material (Dangerous goods) transportation involves the movement of any substances that pose a risk to human health, the environment, or property. Proper handling and transport of Hazmat require specific precautions, including secure packaging, dedicated vehicles, trained personnel, and adherence to regulations. Following the above, hazardous materials transportation is usually on the top priority concerns due to existing possible harms to humans, properties and the environment [4], in particular in the era when reducing fatalities and financial losses, increasing reliability, and promoting transport safety are on the top priority concerns' list in transport industries [5]. Since the consequences of accidents in Hazmat transportation may be catastrophic and may also lead to a domino effect [6], theoretical and practical studies are central and mainly focused on using proper means to manage Hazmat transport accidents and their impacts [7]. They are practically under more attention, followed by risk management regulations in this field [8]. Avoiding route planning in urban areas for transporting high-danger substances [9] and focusing on risk assessment of explosive materials are such recommendations proposed to enhance Hazmat transport safety in this area [10]. In the Middle Eastern country of Iran, many types of hydrocarbon products, such as petrochemicals, their exports, and the demands transported from other countries, make Hazmat transport a more attractive topic to intercity road transport authorities. The location of the country in terms of geography, one of the well-known homes of transit routes for transporting goods, also leads them to deal with Hazmat transportation and their safety issues across the country [11].

1.2. Risk on Hazmat Transport and Modelling

An essential concern in Hazmat transportation is known as "transport risk". This risk is defined as the correlation between hazards and the vulnerability factors associated with one or more components. A component is classified as high-risk based on the likelihood of occurrence and its potential consequences [11]. Transport risk, well-known in Hazmat transportation, comprises four key components: the occurrence rate and intensity of accidents, the affected demographic, environmental factors, and roadway infrastructure [12], later studied and developed by Chen & Bai [13]. In different studies' approaches, they may be also categorized into personnel, vehicle and road factors or considered as parameters including population, traffic safety, volume–capacity ratio, emergency response time, type of hazmat and sensitive and vulnerable places in urban transport planning where safety of vehicles and citizens needs more attention as a major subject [14,15]. Therefore, risk management techniques are typically applied to reduce transportation costs. One of the most well-known techniques to manage Hazmat risk is determining the safest path for Hazmat transportation, which introduces another term, "Hazmat routing problem" [16]. In Hazmat transportation, "Routing" means selecting the best route for carrying dangerous goods, which is not necessarily the shortest path or the least cost path. There are many studies conducted in Hazmat transport modelling regarding routing, such as Hazmat routing, routing-scheduling, and network design problems [17]. While considering the above problem leads experts to develop mathematical models [18], many alternative approaches are also performed in solution procedures [19]. In general, the Hazmat routing is important for researchers from two perspectives. The first one is identifying the optimal solution, which leads to economic savings in practice, and the second is the complexity in the solution procedure [20]. Thus, it is inferred that the routing dilemma in Hazmat transportation does not strictly pertain to finding the shortest route; instead, it strives to identify the safest option, taking into account significant attributes [21].

It is time to discuss mathematical programming. In mathematical modeling, the objective function is usually defined in three forms: two-level, two-stage, and sometimes a utility function. The two-level mathematical model consists of two distinct levels of modeling: the first level involves formulating the objective function, while the second level focuses on defining the constraints. In two-stage models, the initial step is to address the routing problem and identify a set of paths, which is subsequently followed by the second step where experts select the optimal path. n utility objective functions, key concerns such as environmental impacts and transportation expenses are addressed through weighted utilities to create solution models. Historically, research on this issue has concentrated on two main areas: identifying routes that minimize risk and cost, and assessing transport risks to either utilize or circumvent specific routes in the transportation of hazardous materials [21].

In modelling, "Risk" is a primary concern, maybe specifically defined according to the situations, such as in the Hazmat routing problem under emergency conditions or in road-blocking strategies that are employed by governments to mitigate transport risk [22,23]. In these cases, the short travel time is managed for carrying Hazmat in emergencies, where the transport authorities deal with determining the safest path through an affected road network or passing blocked roads. The location-allocation problem is also another topic that typically comes together with the routing problem [24]. For example, for hazardous materials' depots allocation across the region, Alumur and Kara developed a multi-objective model taking into account some limitations to manage hazardous materials of disposal and waste [25]. The approach was to determine the centers of hazardous waste and relevant technology, as well as routes for hazardous waste types in the central region of Anatolia in Turkey. Regarding the risk calculation in this field, Tavakkoli-Moghaddam et al. selected the ideal routes by evaluating candidates in two stages: 1) finding the least risk-associated routes and 2) selecting the best among the high-priority ones [26].

1.3. Hazmat Transport Risk Equity

It is now time to define another concept identified as "Risk Equity" in Hazmat transportation. Transport authorities are dealing with selecting the best approach to share out the Hazmat transport risk called risk equity [24]. When transporting hazardous materials from their origin to various destinations, it is essential to establish routes that ensure the risk associated with such transportation is not concentrated in a limited number of links. Therefore, a fair, logical, and balanced distribution of risk across all routes must be maintained [27]. In terms of utilizing mathematical models, various strategies are available for managing risk in Hazmat transportation, mainly to avoid risk agglomeration in frequently used edges evaluated by statistical approaches [28]. Although the risk arises from the nature of Hazmat transport that may be considered in structure designing [29], the current facilities can also be organized to manage transport risk. Distinct policies may also be formulated regarding the distribution of potential risk within the network and the fairness of risk allocation. For instance, among these policies, one could emphasize safety on the most commonly utilized routes that reduce the overall accumulated risk in the road network. These routes do not signify economic pathways where the objective is to minimize the total distance traveled or the overall travel expenses [25].

1.4. Accessibility

One of the main attributes in transport planning that is defined as the extent to which the land-use and transportation systems enable (groups of) individuals to reach their activities or destinations is "accessibility" [30]. In freight transportation, the regional accessibility is a substantial factor that promotes the region's economic growth [31]. The inconsistency in travel time or distance in the transportation network contributes to unreliability, resulting in higher shipping expenses and ineffective transport operations in different industries. Due to its critical nature, accessibility is assessed in multiple ways by defining and implementing several indicators [32]. In practice, accessibility is assessed through various metrics that gauge the performance of transport networks, especially to demonstrate the vulnerability of network accessibility. Up to now, several methods have been introduced to measure freight accessibility, mainly by calculating the average travel time (or distance or cost) from origins to destinations [33].

A widely recognized equation for measuring accessibility is the gravity model, in which accessibility is influenced by weight or size and is inversely related to distance or cost. The gravity-based models, known as potential accessibility, assess weight opportunities through an impedance factor, defined by a function of distance, travel time, or travel cost [34]. The weight opportunities commonly come from the activities in a certain zone area, origin or destination. The potential accessibility is defined by equation (1) where A_j and W_j are respectively the accessibility and the weight that represents the attractiveness of zone j; t_{ij} $f(_{ij})$ are the measure of separation or impedance factor and impedance function between zones i and j, in that order.

$$A_j = \sum_i w_j . f(t_{ij}) \tag{1}$$

1.5. The Statement of Vision

As mentioned above, the risk equity represents a vital issue in planning of Hazmat transport, where the main issue is to avoid risk agglomeration on the most frequently used links. In practice, transport authorities impose some restrictions on the road network in Hazmat transportation due to applying risk equity or other concerns such as environmental conditions or tunnels restrictions, so transport companies and operators have to select the longer routes to comply with the restrictions. Selecting longer routes causes to increase distance and cost of transportation, known as major impedance factors in transportation (according to equation 1), both result in decreasing the network accessibility. In other words, selecting low-risk paths may lead operators to use longer paths and increase transport costs, which results in reducing network accessibility. Therefore, the trading-off between risk equity performance and network accessibility should be adequately examined. On the other hand, appropriate models need to be developed to explore the relations between risk equity techniques and accessibility. Therefore, the particular aim of this study is to examine the trade-off between risk equity and network accessibility through proposing a procedure, developing mathematical models, and eventually discussing results by using experimental data.

This paper is organized into five sections. After the introduction and scientific background, mathematical modeling is presented by identifying procedure, indices, parameters, variables, and non-linear equations, which are finally transformed to linear equations for simplicity. Section 3 discusses an illustrative example to support readers' easier understanding. Discussions are also made, in detail, followed by more clarifications on the case study and experimental analysis in the fourth section. The concluding section summarizes the summary of research work, findings, and recommendations for further research.

2. Mathematical Modelling

The procedure developed in this study for trading off the risk equity and accessibility comprises two main stages and their corresponding models. The first stage is determining the best routes for all OD pairs by minimizing the total traveled distance. Results are at the highest level of accessibility because the shortest path is set for each OD pair in the first stage. The following stage consists of determining the routes for all origin-destination pairs, with the objective of minimizing the maximum risk associated with the specified links. There is a constraint that restricts accessibility in the second stage, accordingly. Therefore, the modeling is followed in two phases: 1) determining the least lengthy paths for all origin-destination pairs; and 2) determining the minimum associated risk while the network accessibility is restricted. Since the mathematical model developed for the second stage becomes nonlinear, a decomposition technique transforms it into a linear format.

2.1. Indices

G: The intercity road network which is formed by nodes and edges (links)

i: Start node of edge

j: End node of edge

(i, j), (j, i): Set of double-direction edges available in the road network; $(i, j), (j, i) \in G$

OD: Set of Hazmat transport OD pairs

o: Origin node of OD

d: Destination node of OD

2.2. Parameters and Variables

N_{od} : Number of vehicles depart from origin "o" to destination "d";

R_{ij} : Risk rate assigned to edge (i, j); in this research work, it is considered that for each two-way links $R_{ij} = R_{ji}$; More details on risk definition and calculation based on linguistic parameters are available at [35].

L_{ij} : Length of the edge (i, j); for each two-way links, assume $L_{ij} = L_{ji}$;

Variables are also defined as follow:

X_{ij}^{od} ; isa binary variable and is equal to 1, if the edge (i, j) is on the designated route from starting point "o" to endpoint "d"; 0 otherwise;

TS_{od} : The shortest path distance from origin "o" to destination "d".

2.3. Modelling Process

The first objective function to minimize total traveled distance is formulated by equation (2) so called the objective function. It can serve as a substantial indicator of the total cost for route optimization. Thus, the links will be allocated to every origin-destination pair.

$$MinZ_1 = \sum_{(o,d)\in OD} \sum_{(i,j)\in G} N_{od} \times L_{ij} \times X_{ij}^{od} \quad (2)$$

The first constraint is to guarantee a seamless path for each O-D pair. It is a fundamental concept in network modelling to remain on a continuous path. In terms of mathematical modelling, assume that "j" is a node in a road network. The nodes connected to it are defined entrance nodes and noted as En(j), and the others are departure nodes and noted as Ex(j), all graphically depicted in **Figure 1**.

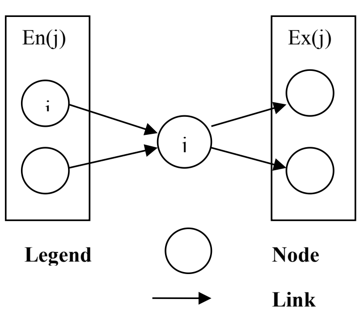

Figure 1. Schematic View for Entrance and Departing Links of Node "*j*".

In general, the difference between the summations of binary variables attributed to the entrance nodes of a specific node "j" and depart from that can meet the continuous path constraint on the network. Looking at **Figure 1**, one can understand that if the summation of departed links minus entrance links is equal to 1, the specified node "j" is an origin node where no link enters and just one link departs from node "j". If the summation is equal to -1, the specified node "j" is a destination node where no link departs and just one link enters node "j". For the other nodes, the result of the summation should be equal to zero whether located in the selected route or not selected. The concept is formulated by the equation (3).

$$\sum_{i\in E_x(j)} X_{ij} - \sum_{i\in E_n(j)} X_{ji} = \begin{cases} 1 & if j=o \\ -1 & if j=d \\ 0 & O.W. \end{cases} \forall j\in G \quad (3)$$

Following the above discussions, equation (4) formulates the constraint that provides seamless paths for all OD pairs, where Ex(j) and En(j) are respectively the sets of departing and entrance links for node "j". This equation guarantees that the path assigned to each OD pair is unbroken through origin and destination nodes. More details on general modeling are also available at and in Hazmat transport routing problems at [22,36].

$$\sum_{i\in E_x(j)} X_{ji}^{od} - \sum_{i\in E_n(j)} X_{ij}^{od} = \begin{cases} 1 & if j=o \\ -1 & if j=d \\ 0 & O.W. \end{cases} \forall j\in G \;\&(o, d)\in OD \quad (4)$$

The aforementioned model identifies the shortest routes for all origin-destination pairs, disregarding the risk equity constraint. Running the previous model will set accessibilities in the ideal values because the shortest paths are established for all OD pairs, even though some links may be designated in many paths, resulting in risk agglomeration across the network.

The secondary objective function aims to identify routes for all origin-destination pairs while simultaneously considering risk equity and accessibility. While there are many approaches in Hazmat transport risk distribution, there is an empirical study shows that the Min(Max) approach is the most effective method in intercity networks [37]. Within this model, the maximum risk related to the network links is minimized through the use of the equation (5).

$$MinZ_2=Max\left\{\sum_{(o,d)\in OD} N_{od}\times L_{ij}\times R_{ij}\times X_{ij}^{od}\,\forall\,(i,j)\in G\right\} \quad (5)$$

Three sets of constraints are required to formulate the objective function as a model. The first is maintaining seamless paths, satisfied by equation (4). It is inserted into the model without any changes. The second set of constraints is to calculate the traveled distance. Equation (6) formulates the shortest distance for all OD pairs, and Equation (7) calculates the accessibility indicator for all destinations.

$$TS_{od}=\sum_{(i,j)\in G} L_{ij}\times X_{ij}^{od}\ \forall(o,d)\in OD \quad (6)$$

$$ACC_d=\sum_{o\in G}\frac{N_{od}}{TS_{od}}\ \forall d\in G \quad (7)$$

The third constraint is to bound significant variations on accessibility indicators compared to the ideal or allowable measures. The limitation or tolerance rate here is considered to be fulfilled by authorities or transport experts, but modeling is enhanced to extend its concept. If the tolerance rate of the shortest distance of OD pairs is respectively defined as "α" and TS'_{od}, equation (8) guarantees that accessibility for each destination remains within the limited bound.

$$\sum_{o\in G}\frac{N_{od}}{TS_{od}}\geq(1-\alpha)*\sum_{o\in G}\frac{N_{od}}{TS'_{od}}\qquad \forall d\in G \quad (8)$$

2.4. Linearization

To satisfy the above constraints, all destination components can be detached origin to another origin. If the accessibility components of a specific destination are satisfied, the whole constraint is ultimately satisfied. Notice that components here are coming from origins where vehicles depart. Therefore, equation (12) can be fragmented into two equations: (13) and (14). It means that equation (12) is satisfied following the satisfaction of equations (13) and (14). Looking carefully at the structures, omitting the number of vehicles as positive scalars, reveals that they can be simplified by equations (15) and (16).

$$\frac{N_1}{Y_1}\geq\frac{(1-\alpha)N_1}{Y'_1} \quad (13)$$

$$\frac{N_2}{Y_2}\geq\frac{(1-\alpha)N_2}{Y'_2} \quad (14)$$

$$\frac{1}{Y_1}\geq\frac{1-\alpha}{Y'_1} \quad (15)$$

$$\frac{1}{Y_2}\geq\frac{1-\alpha}{Y'_2} \quad (16)$$

In this case, by considering "α" as a scalar, the general equation is formulated by equation (17) for all OD pairs to terminate on destination "d" and converted to equation (18) as a linear constraint.

$$\frac{1}{Y_{od}}\geq\frac{1-\alpha}{Y'_{od}} \quad (17)$$

$$Y_{od}\leq\frac{Y'_{od}}{1-\alpha} \quad (18)$$

Following the above procedure, equation (8) can also be replaced by equation (19) in a linear format.

$$\sum_{(i,j)\in G} L_{ij}\times X_{ij}^{od}\leq\frac{TS'_{od}}{(1-\alpha)}\qquad \forall d\in G \quad (19)$$

To summarize what discussed and developed so far, the final model has been re-arranged as follows:

$$MinZ_1=\sum_{(o,d)\in OD}\sum_{(i,j)\in G} N_{od}\times L_{ij}\times X_{ij}^{od} \quad (20)$$

$$\sum_{i\in E_x(j)} X_{ji}^{od}-\sum_{i\in E_n(j)} X_{ij}^{od}=\begin{Bmatrix}1 \text{ if } j=o\\ -1 \text{ if } j=d\\ 0 \quad O.W.\end{Bmatrix}\ \forall j\in G\ \&(o,d)\in OD \quad (21)$$

$$TS'_{od}=\sum_{(i,j)\in G} L_{ij}\times X_{ij}^{od}\quad \forall(o,d)\in OD \quad (22)$$

$$MinZ_2=U \quad (23)$$

$$\sum_{(o,d)\in OD} N_{od}\times L_{ij}\times R_{ij}\times X_{ij}^{od}\leq U\,\forall\,(i,j)\in G \quad (24)$$

$$\sum_{(i,j)\in G} L_{ij}\times X_{ij}^{od}\leq\frac{TS'_{od}}{(1-\alpha)}\qquad \forall d\in G \quad (25)$$

$$\sum_{i\in E_x(j)} X_{ji}^{od} - \sum_{i\in E_n(j)} X_{ij}^{od} = \begin{Bmatrix} 1 \text{ if } j=o \\ -1 \text{ if } j=d \\ 0 \quad O.W. \end{Bmatrix} \forall j\in G \;\&(o,d)\in OD \qquad (26)$$

3. Illustrative Example

In order to clarify how the proposed model works, an illustrative example is provided. Assume a simple network shown in **Figure 2**. It consists of five nodes and six two-way arcs (12 links). The lengths and ranked risks of links are located next to their risks in parentheses. Connections are depicted as single lines, which signifies that for every link, there are two opposing directions of movement accessible. In addition, two OD pairs (1–5) and (2–5), respectively, with 200 and 250 transport units (for example, the number of trucks departed from origin to destination nodes), are tabulated in **Table 1**.

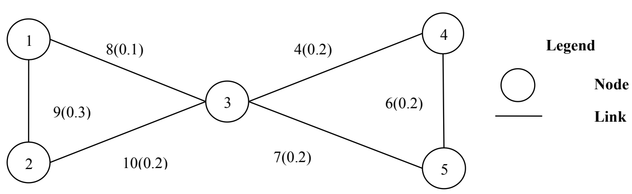

Figure 2. Illustrative Network Structure.

The total travel time is minimized if the risk equity does not apply. In other words, the shortest paths are determined for two OD pairs disregarding risk spreading. The shortest path from node (1) to node (5) is 1–3–5 with a total distance of 15 Km, and the shortest path from node (2) to node (5) is 2–3–5 with a total distance of 17 Km. In this case, three links (1–3), (2–3), and (3–5) are involved in transport planning. The risk loaded on link (1–3) is equal to 8(*Km*) × 0.1(*R*) × 200(*OD*) = 160. The same measure for two links (2–3) and (3–5) is respectively equal to 10 × 0.2 × 250 = 500 and 7 × 0.2 × [200 + 250] = 630. The average risk loaded on the involved links is equal to (160 + 500 + 630)/3 = 430, followed by the variance which is equal to $[(160 - 430)^2 + (500 - 430)^2 + (630 - 430)^2]/3$ = 39267. The accessibility index for the destination (node 5) is calculated as (200/15) + (250/17) = 28.04. Total traveled distance, abbreviated by TTD-Km, is calculated as 15 × 200 + 17 × 250 = 7250 *Km*.

By considering the risk equity as a constraint, the maximum risks associated with all links are minimized, and the results have been tabulated in **Table 2**. The shortest path from node (1) to node (5) is 1–3–4–5 with a total distance of 18 Km, and the shortest path from node (2) to node (5) is 2–3–5 with a total distance of 17 Km. In this case, five links of (1–3), (2–3), (3–4), (3–5), and (4–5) are involved in satisfying demands. The same method has been employed to calculate the associated risk for the links, and risks are summarized in **Table 2**.

Checking the results and comparing them in the two methods revealed that applying risk equity techniques increases the number of involved links, followed by decreasing the average and variance of risk distributed over the network. Put differently, applying risk equity constraint distributes Hazmat transport risk across the network links. The above procedure is applied to the case study by using experimental data in the following sections.

Table 1. Model's Output for Illustrative Example Minimizing Total Traveled Distance.

Origin	Destination	OD demand	Shortest path	Distance	Involved Links (Associated Risk)	Accessibility index (TTD-Km)	Average (Variance)
1	5	100	1 –>3 –>5	15	1–3 (160); 2–3 (500); 3–5 (630)	28.04 (7250)	430 (39,267)
2	5	200	2 –>3 –>5	17			

Table 2. Model's Output for Illustrative Example Minimizing the Maximum of Risk.

Origin	Destination	OD demand	Shortest path	Distance	Involved Links (Associated Risk)	Accessibility measure (TTD-Km)	Average (Variance)
1	5	100	1=>3=>4=>5	18	1–3 (160); 2–3 (500); 3–4 (160), 3–5 (350), 4–5 (240)	25.82 (7850)	282 (16,736)
2	5	200	2=>3=>5	17			

4. Experiments

4.1. Case Study

The intercity road network of Gilan, located in northern Iran, has been selected for the experimental analysis. Comparing to other provinces in Iran, Gilan is a medium-sized province where there are some bigger and smaller ones in the country. The nodes symbolize cities or intersections, whereas the links connect them throughout the network. There are 46 nodes and 126 two-way links in the network. As aforesaid, a two-way link is a link in which two opposite movement directions are available. A student thesis conducted at MehrAstan University and published in the Persian language assessed the risk level in each link [38]. The length and risk in both opposite directions are assumed to be equal for each link. The lengths of edges in the network are known and depicted in **Figure 3**.

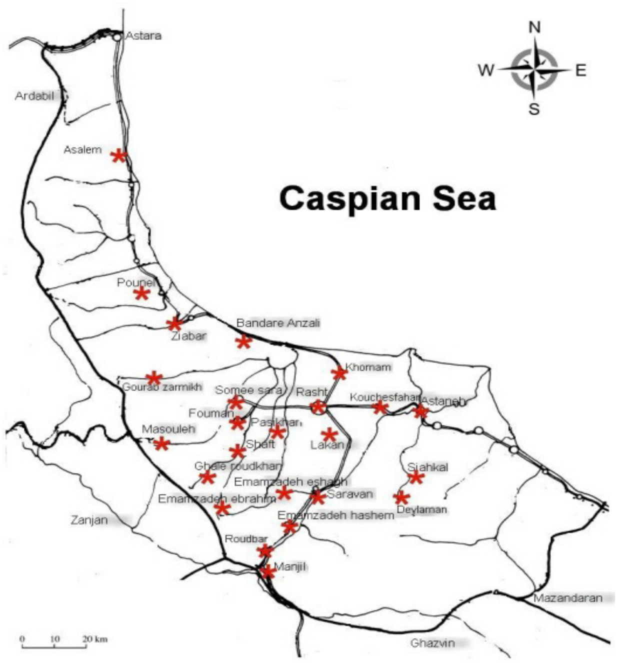

Figure 3. Map of the Gilan Intercity Road Network (Scale: 1 cm = 20 km).

4.2. Analysis and Discussion

Two proposed models run by the well-known software of the General Algebraic Modeling System (GAMS) using the experimental data and results obtained. The accessibility indicators have been calculated for all destinations (16 destinations) utilizing both techniques, with and without considering risk equity constraints. In addition, six tolerance rates were implemented for sensitivity analysis and tabulated in **Table 3**. Notice that the tolerance rate is proposed by transport experts or authorities, depending on the risk priorities and cost regarding Hazmat transport planning and accessibility indicators. The first column is the destination name, followed by the total Hazmat received, scaled by the number of vehicles or trips, in the second column. The third column represents the accessibility indicator if the total traveled distance is minimized (without risk equity constraint). The next five columns represent accessibility measures by considering the risk equity constraint for 5, 10, 15, 25, and 50 percent as tolerance rates. The tolerance rates have been set here for sensitivity analysis, but experts may set them in practice. The column “Free” indicates that no restriction is taken into account for accessibility. For example, the tolerance rate of 10% means that while risk equity is considered for Hazmat transport planning, accessibility is reduced by 10% compared to the ideal value.

More results are tabulated in **Table 3**, including the total traveled distance, number of links involved in transport planning, the average risk on links, and risk variance for selected links. The total traveled distance is the summation of traveled vehicles multiplied by the traveled distance for all OD pairs. The number of involved links is the number of those located in all OD pairs determining paths by the route assignment procedure. The rest represent two statistics of average and variance for the involved links. Eventually, the risk is similarly obtained by multiplying the proportional risk by the number of vehicles and the length of all links.

Looking more sensibly at **Table 3**, more takeaways can be found. The first is regarding the effects of risk equity on accessibility. When the risk equity receives much priority, network accessibility drops. For example, when the risk equity does not constrain the model, the average of the accessibility measure is equal to 27.04, while it drops by 18.80 if the risk equity is fully forced. The risk equity significantly affects the total traveled distance and the number of links involved in Hazmat transport planning. They rise when the risk equity is getting more attention. For instance, without risk equity constraint, the total traveled distance and involved links are 1.75 million-km and

65, respectively, meanwhile they grow up to 2.17 million-km and 90 when the tolerance rate for accessibility is 50%. The above concludes that the mean and the variance of the associated risk to the network links are simultaneously decreased when risk equity importance increases. It is a logical result obtained by the models because the primary role of the risk equity concept is to spread risk across the network, so the more links involved, the total traveled distance increases, and the mean and variance of risks are reduced.

To illustrate outputs more clearly, the above measures are also depicted in **Figures 4** and **5**. **Figure 4** depicts accessibility measures for all destinations utilizing three selected risk equity importance of "Without equity", "25% tolerance", and "Free of constraint". As demonstrated, risk equity significantly influences transport accessibility, as the allocation of risk throughout the network leads to a reduction in accessibility indicators for every destination. **Figure 5** depicts other measures according to the accessibility tolerance rates. Since the measures' dimensions are different, all values have been converted to the closed interval [0, 1] by equation (27).

$$Proportional\ Measure = \frac{Measure - Measure_{Min}}{Measure_{Max} - Measure_{Min}} \quad (27)$$

As shown in **Figure 5**, the mean and variance of transport risk are reduced, but the total traveled distance and the number of involved links are increased when the accessibility restriction is less important.

Table 3. Accessibility Indicators with Risk Equity Constraint.

Destination	Hazmat Received (Trips)	Without equity	Tolerance rate for accessibility					
			0.05	0.10	0.15	0.25	0.50	Free
Amlash	217	3.56	3.56	3.56	3.56	3.29	2.55	2.09
Anzali	2,625	67.31	67.31	67.31	67.31	67.31	67.31	27.34
Astaneh	474	14.79	14.79	14.79	14.78	14.78	11.27	8.44
Astara	2,059	10.01	9.73	9.09	8.52	8.89	9.73	8.52
Fouman	805	25.37	25.37	25.34	25.32	20.21	20.11	12.95
Lahijan	2,479	74.23	74.23	74.23	74.23	64.42	56.64	74.23
Langrood	1,161	22.44	22.44	22.44	22.43	18.18	18.37	7.89
Masal	276	5.15	5.15	5.15	5.15	4.04	3.42	3.42
Rasht	94	1.53	1.53	1.53	1.53	1.49	1.51	1.45
Rezvanshahr	2,669	37.59	37.59	34.66	37.59	29.01	23.41	24.26
Rudbar	3,622	51.65	51.65	51.64	51.65	51.62	41.56	51.57
Rudsar	2,357	34.16	34.16	34.14	34.15	26.69	21.86	18.33
Siahkal	502	15.5	15.5	15.5	15.5	15.5	12.05	6.84
Shaft	356	14.17	14.17	14.17	14.17	14.17	14.16	14.17
Somehsara	1,239	36.37	36.37	36.37	36.37	30.21	30.09	21.32
Talesh	2,384	18.77	17.94	18.77	16.17	18.77	17.94	17.94
Total Traveled Distance		1,748,706	1,775,323	1,808,583	1,872,708	1,969,411	2,165,526	2,594,539
Average Accessibility		27.04	26.97	26.79	26.78	24.29	22.00	18.80
Number of Links Involved		65	69	68	72	81	90	86
Risk Average		157,422	148,617	152,869	150,317	138,730	138,680	173,276
Risk Variance (e10)		87.6	71.3	75.6	69.3	53.2	48.5	49.8

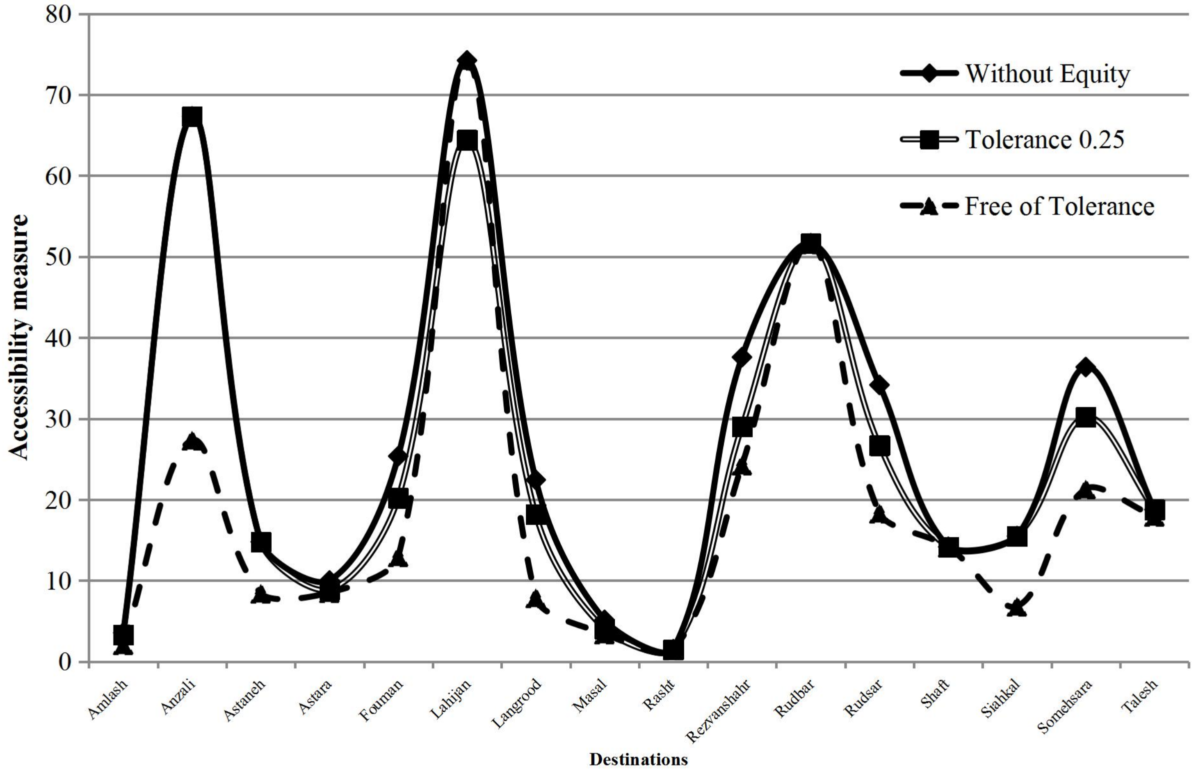

Figure 4. Changes of Accessibilities Over the Network for Destinations.

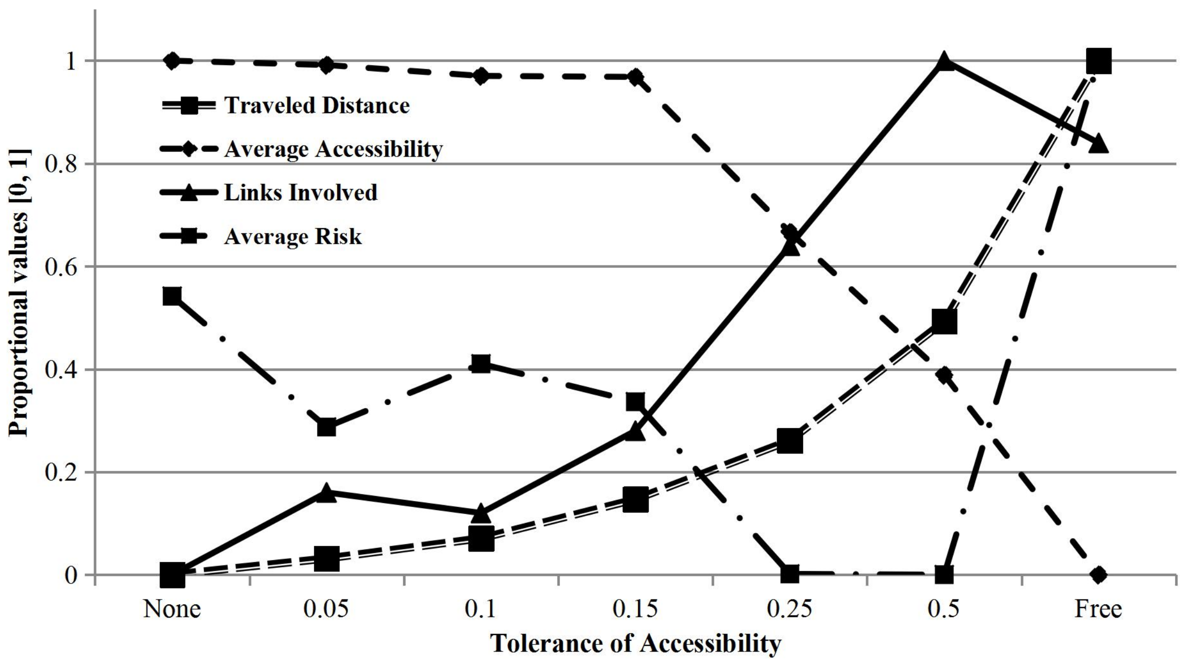

Figure 5. Overall Measures' Behaviors Based on Risk Equity Importance (Tolerance of Accessibility).

5. Summary and Conclusions

In hazardous material transport planning, it is typical for local and/or national authorities to manage the distribution of transport risks across the road network, so they are interested in approaches to avoid risk agglomeration on the most frequently involved links. Therefore, the methods utilized for risk distribution, spread the selected routes over the network, and do not necessarily prefer the shortest paths, resulting in poor network accessibility. Therefore, authorities are looking for methods to simultaneously consider risk equity and network accessibility in transport planning. Following the above concern, a trading-off procedure has been proposed in this research work to explore the relations between risk equity importance and network accessibility measures. During the models' development, a tolerance rate is defined to restrict variations in accessibility. To simplify, a decomposition technique converts a nonlinear model to a linear model. To explore the mutual effects in practice, the Iranian northern province of Gilan was selected as the case study where relevant data were available. Carrying out the proposed procedure with experimental data underscored the contrasting effects of the risk equity constraint and network accessibility, offering a valuable perspective for local and national authorities addressing Hazmat transport planning and decision-making.

Despite the wide scope of Hazmat transportation owing to its critical nature, additional research is suggested to expand the existing study to a larger, national scale, or to distribute risk across particular categories of hazardous materials. Focusing on environmental concerns and involving more links may lead to more undesirable consequences on the population in restricted areas, so it is another topic to study in the future. Other methods of risk distribution are also suggested to be under research by considering practical concerns, such as traffic congestion in urban areas where the safest or shortest routes are not necessarily welcomed by transport companies. New technologies that help authorities reduce the risk of Hazmat transportation can be also under study where telecommunication facilities and devices are used to track the vehicles and enforce transport operators to comply with the risk equity arrangements.

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Informed Consent Statement

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Data Availability Statement

Data is available in Excel format and would be sent through email connection to researchers who are interested in studying more in this field.

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Conflicts of Interest

The author declares no conflict of interest.

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