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GIS-Based Route Planning for Hazardous Material Transportation

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ABSTRACT. As security is of concern today, there is an urgent need to review and improve the way trucks carrying hazardous materials (HAZMATs) are being routed. Routing of such vehicles should not only ensure the safety of travelers in the network, but should also consider the risk of the HAZMAT being used as weapon of mass destruction. This paper seeks to identify evaluation factors used to route these vehicles, taking into consideration safety, costs and most importantly, security. A Geographic Information System (GIS) is used to quantify the factors on each link in the network that contribute to each of the evaluation criteria for a possible route. The Analytic Hierarchy Process (AHP) is used to assign weights to the factors, depending on their perceived relative importance. Each route can then be quantified by a cost function and the suitability of the routes for HAZMAT transportation can be compared. The proposed route evaluation method is demonstrated on a portion of road network in Singapore.

Keywords: AHP, GIS, hazardous materials, routing, security

1. Introduction

Security issues have been receiving increased attention after Sept. 11th, 2001. There is heightened awareness of terrorism and its consequences; and policy makers are taking steps to tighten homeland security. Terrorists may strike anywhere, at anytime. In particular, the use of petrochemical trucks as a possible mode of terrorism has been identified (Field, 2004).

Routing of trucks carrying fuel and other hazardous materials (HAZMATs) has been in practice for decades. Traditionally, the main considerations include costs, safety in terms of vehicle collisions and potential exposure of the public to the HAZMAT substances. Abkowitz and Cheng (1988) proposed a risk/cost framework for HAZMAT routing incorporating cost and risk into a common framework. In assessing the risks involved, they included the effects of human exposure to a dose of chemical. List and Mirchandani (1991) introduced an integrated multi-objective model for routing and siting HAZMAT wastes. In addition to risk and cost, they also considered risk equity, which is measured as the maximum risk per unit population as opposed to total risk, which is the sum of all zonal risks from transportation or treatment.

The use of GIS to aid HAZMAT route planning is not new. Lepofsky and Abkowitz (1993) demonstrated that GIS can be used to integrate plume representation with population data and transport maps to estimate consequences more effectively. They cited a case study of rocket fuel transportation in California. Using combinations of routing criteria (e.g. population exposure, accident likelihood and environmentally sensitive areas) in a single analysis with varying weights on their importance, one can then examine the tradeoffs between various alternatives. The GIS system allowed for computation of the average emergency response time to any segment in the state highway network. The GIS could determine the most efficient method for evacuating and determining the most efficient way to reroute traffic.

Souletrette and Sathisan (1994) applied GIS in the transportation of radioactive materials. Like HAZMAT routing, the key inputs include demographics, environmental features and transportation system characteristic. They identified three methodologies, namely, comparative studies, worst-case assessment and probabilistic risk assessment. Brainard et al. (1996) demonstrated the use of GIS to route aqueous waste cargoes using four methods, namely: 1) routing by shortest time only; 2) routing by motorway and dual carriageway encouragement; 3) outing to avoid population; and 4) routing to avoid acidents. Ground water vulnerability was also a consideration.

The vast collection of literature involving HAZMAT transportation reveals that the main considerations are exposure and accident likelihood. The need to include security considerations has only recently gained greater attention. Abkowitz (2002) points out that transportation risk assessment must accommodate terrorism scenarios that have previously been considered so unlikely to warrant risk management assessment.

In this connection, this paper seeks to identify a set of evaluation criteria that can be used to route the petrochemical trucks, incorporating emphasis on the security aspect in addition to costs, safety and exposure. The identified criteria will then be tested using a GIS coupled with the Analytic Hierarchy Process (AHP) to assess their suitability and alternative routes will be studied and evaluated against the route that complies with the regulations.

AHP is a method which provides the objective mathematics to process the inevitably subjective and personal prefer-

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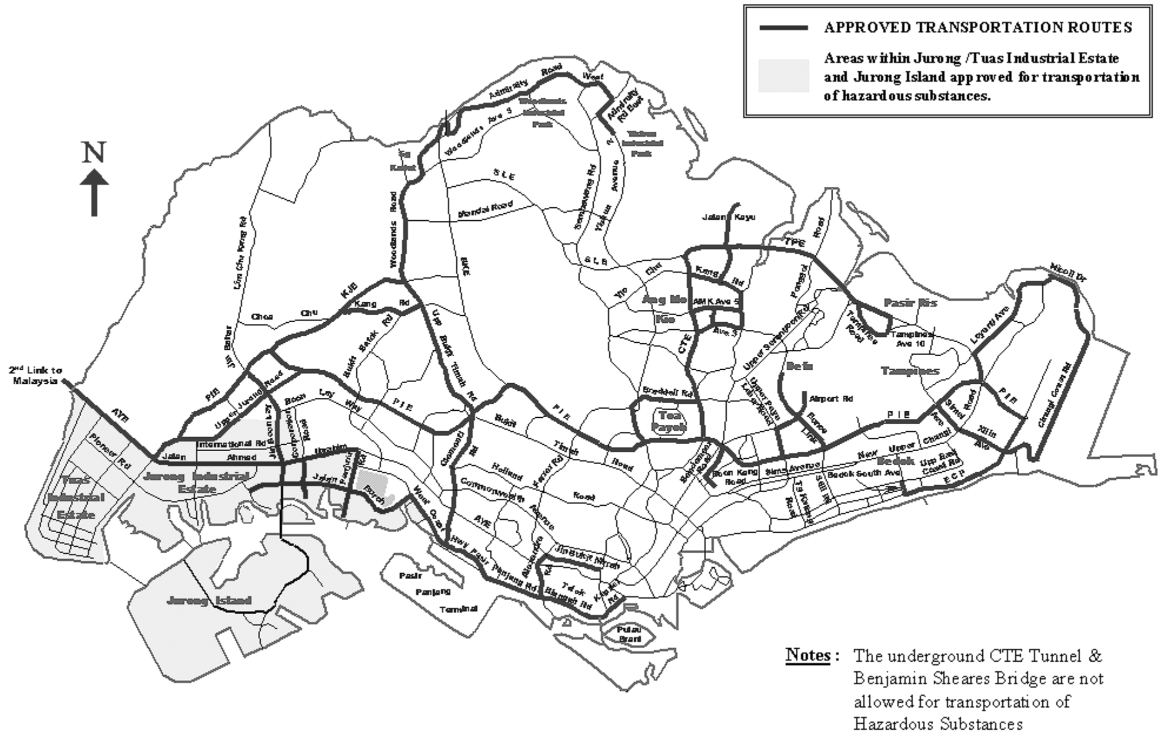

Figure 1. Map of approved HAMAT transportation routes.

ences of an individual or group decision maker (Satty, 1980). While AHP method has been widely used, few studies have been found to incorporate use of GIS with AHP. Their combined use in transportation has so far been observed only for public transportation, where Banai (1998) applied the AHP and GIS to assess the suitability of land use around proposed light rail transit stations. Therefore, combined use of AHP and GIS in HAZMAT route planning has not been attempted before.

The rest of this paper is organized as follows. Next section introduces the practice of HAZMAT routing in Singapore. The proposed methodology on HAZMAT route selection is then described. This is then followed by the GIS analysis and the determination of weights using the AHP. Finally, the paper is concluded with a summary and outlook.

2. HAZMAT Route Planning in Singapore

Singapore is a small nation with a very high population density. Due to land constraints, petrochemical vehicles are bound to pass through highly populated residential areas from Jurong Island, the petrochemical hub, to the rest of the country. Destinations do not only include industrial areas and airports, but also the various petrol stations located island-wide, usually within or in close proximity to populated areas.

Transportation of the petroleum products and other HAZMATs in Singapore is regulated by the National Environment Agency's (NEA) Pollution Control Department and Singapore Civil Defence Force. The control is affected through the Environmental Pollution Control (Hazardous Substances) Regulations under Environmental Pollution Control Act (GoS, 2002) as well as the Fire Safety Act (GoS, 2000). In essence, the requirements for transportation are as follows:

a) The containers and tankers must be designed, manufactured and tested in accordance to internationally-acceptable standards. The tankers must be certified by an approved third party inspection body to have met the stipulated standards.
b) The routes used must be approved, ideally avoiding densely populated areas and water catchment areas. A figure of the recommended routes is shown in Figure 1.
c) Transportation is restricted to within the hours of 7 am to 7 pm, when there is an ample daylight to contain and remedy any accidents.
d) An applicant company is required to put up an adequate emergency response plan describing the specific actions that will be taken by the driver and/or the company's emergency response team in the event of a spill or release.

On top of these, depending on the type of motor vehicle used and its maximum laden weight, the transportation of any goods involving heavy motor vehicles may require prior notification the Land Transport Authority (LTA). This is in accordance with Road Traffic Act (Chapter 276) (GoS, 1997), under Singapore law. This Act requires the owners to indemnify the LTA in respect of any damages that may be caused to any road or bridge by reason of the construction of or the weight

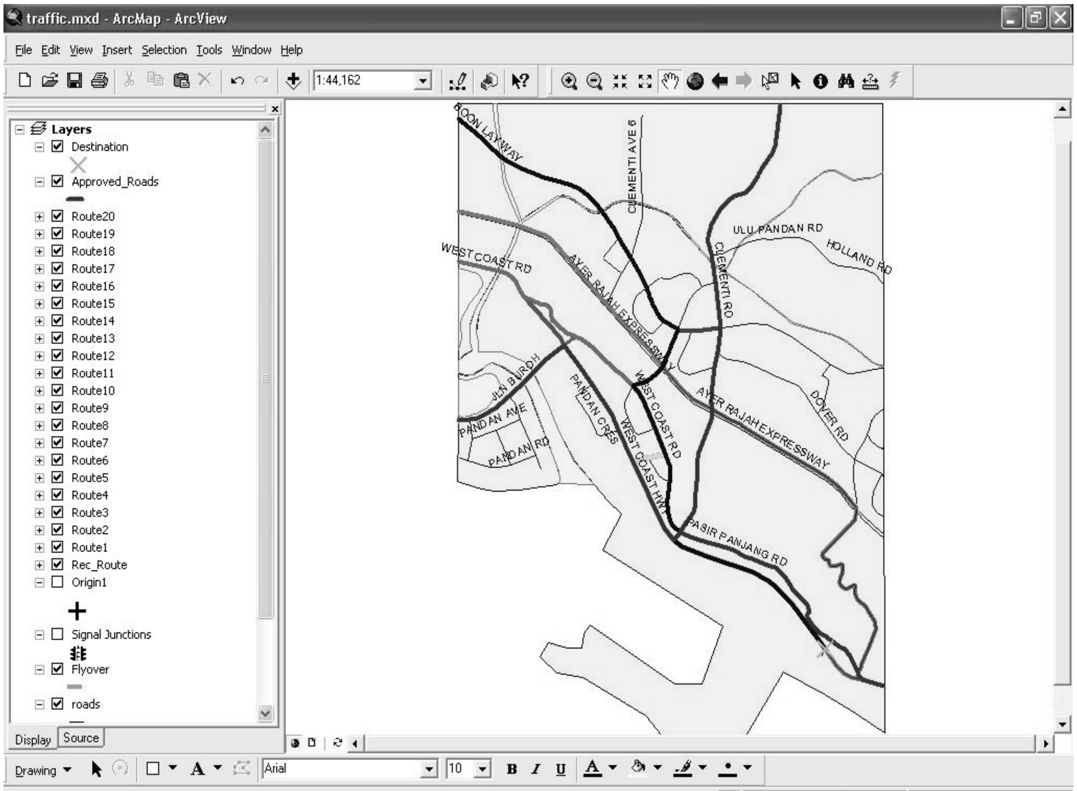

Figure 2. Area of study and the evaluated routes.

transmitted to the road surface by the movement of their vehicles.

In general, the existing regulations specify the allowable links, rather than the approved routes. Given a set of alternate routes between an origin and a destination, quantitative means of evaluating the possible routes remain unknown. The rationale for deeming a link prohibited is also not made known to public. Therefore, this paper attempts to find a way on how to quantitatively evaluate the possible routes.

3. Methodology

A number of the evaluation factors have been modified from those recommended by the U.S. Department of Transportation (FHWA, 1994). Many factors are added or adapted to account for security. A scoring system will be devised by classifying the identified factors. Relevant data are gathered and input into the GIS database. The scores can be considered as substitutes to actual population counts or accident probabilities required in traditional risk analysis. Scores should be a better surrogate to actual accident probabilities, which require accident rate data that are often insufficient or unavailable. Generally, at least three years of truck accident data are preferable to determine accident rates (FHWA, 1994).

The relative importance of the respective criteria and their factors are then determined using AHP. The cumulative weights and scores represent a cost function for each route, which is given by:

$$\text{Cost of route R} = \left(\sum_{c=1}^{n_c} \left(w_c \sum_{cf=1}^{n_{cf}} w_{cf} s_{cf} \right) \right) \qquad (1)$$

where c = criteria; n_c = number of criteria; w_c = weight of criteria c; cf = factor under criteria c; n_{cf} = number of factors under criteria c; w_{cf} = weight of factor f under criteria c; and s_{cf} = score of factor f under criteria c.

The s_{cf} is obtained by evaluating a link against the f^{th} criterion, and w_{cf} by AHP through the comparison of all the pairs of factors. w_c is aggregated from the weights of all the factors (i.e., w_{cf}'s) under the c^{th} criterion. The cost of route R is then aggregated from that of all the links against all the criteria.

Ideally, the actual route used by HAZMAT transporters should incur the least possible costs defined by Equation 1. Therefore, the suitability of the recommended routes will be assessed by comparing them with their alternatives and results should show that they indeed are the routes with the least costs (or among the least).

To test the suitability of the evaluation criteria, an area to

Table 1. Scoring System for Factors and Sub-factors

Exposure Type of Residential A1	1 Sparsely populated	2 Low-rise private housing	3 Mixed Housing	4 Matured Estate	5 New Town
Commercial/ Governmental (No. of bldgs) A2	0 - 5	6 - 10	11 - 15	16 - 20	> 20
Industrial A3	-	-	Flatted factories	Tech Parks	-
Schools (No. of bldgs) A4	0 - 3	4 - 6	7 - 9	10 - 12	> 12
MRT station A5	0 - 2	3 - 4	5 - 6	6 - 8	> 8

the west of Singapore was chosen. This area encompasses the Clementi, the West Coast Road and the National University of Singapore (NUS) campus as shown in Figure 2. Alternative origins were assigned from the Jalan Buroh, West Coast Road, Ayer Rajah Expressway and Boon Lay Way, with a common destination chosen as Port of Singapore Authority (PSA) Gate 6. A total of 20 possible routes were considered in addition to the recommended route.

By taking costs, safety and security into consideration, five main factors have been identified that can be analysed in a GIS environment. They are:

a) Exposure

The population that is exposed in the event of a release or explosion is determined by the population density of the surrounding land use. The exposed population is a key factor in determining the consequences of a release, in estimating risk and in designating routes.

b) Socio-Economic Impact

This factor accounts for the direct and indirect costs incurred from damages accruing to a terror attack.

c) Risks of Hijack

The population density of the surrounding areas determines the ease with which a hijack can take place. Logically, a hijack is likely to occur along a deserted stretch of road.

d) Traffic Conditions

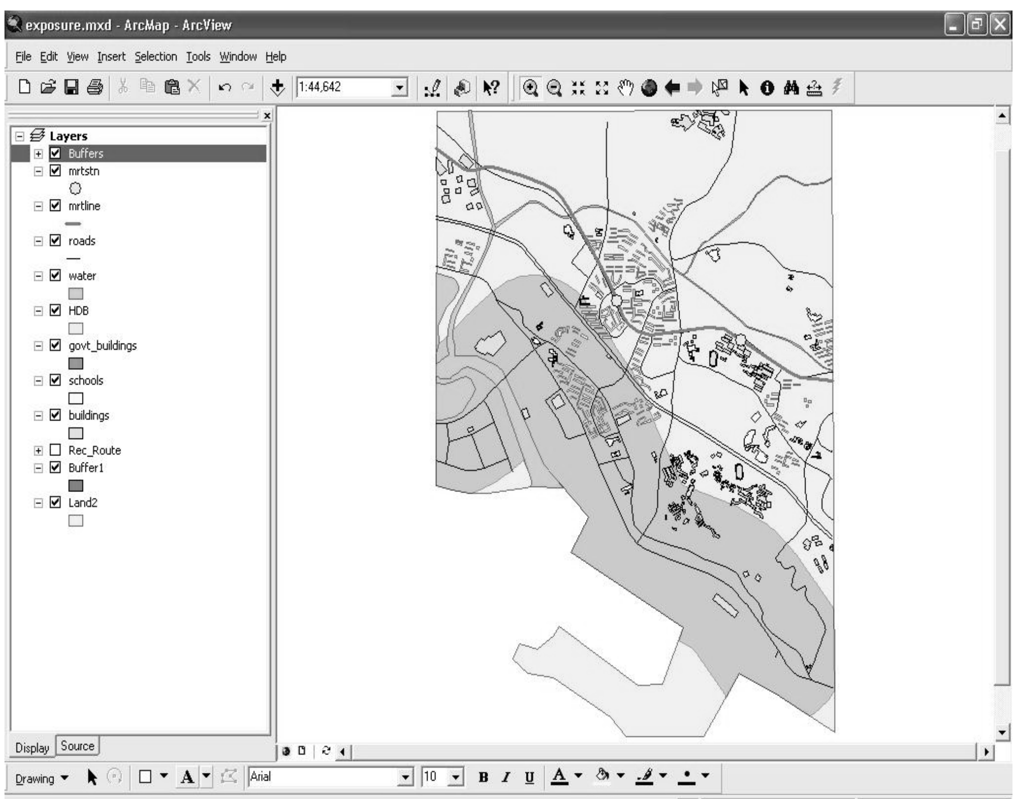

Figure 3. GIS generates buffer zone to simulate impact area.

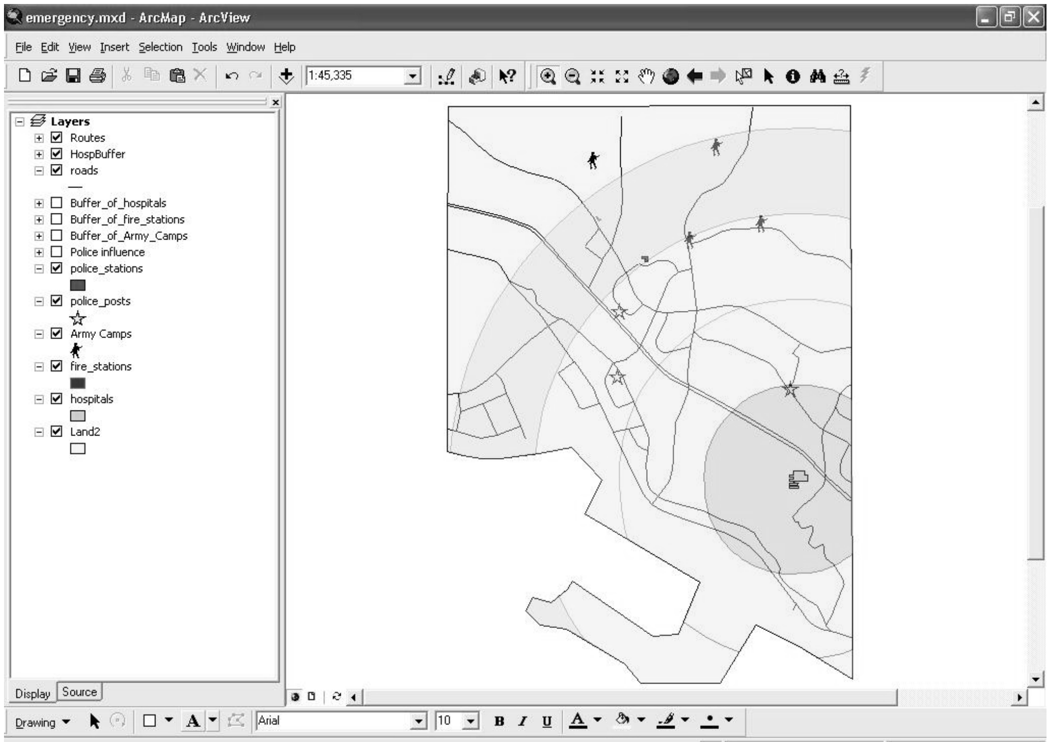

Figure 4. Buffer radiating from a hospital to determine influence.

The conditions of the traffic such as speed and flow will affect travel time, safety and operating costs. Congestions will also lead to higher possibilities of accidents.

e) Emergency Response

Emergency response capabilities can be a critical consideration in evaluating the consequences of an incident leading to a release or explosion. The locations of emergency response teams as well as proximity to hospitals determine the rescue efficiency.

4. Analysis Using GIS and AHP

4.1. Evaluation Using GIS

The use of GIS in the vehicle routing offers a number of advantages over traditional methods. Using maps alone to determine impact area and to find features are tedious and time-consuming. GIS allows the addition of relevant layers that can be used for spatial analysis. GIS offers the database capabilities that can handle attribute data. Attribute queries are easy and accurate. This research uses ArcGIS developed by ESRI.

After identifying the respective criteria, a classification of the factors was done and assigned a score ranging from 1 to 5, depending on the attribute's range of values. Table 1 shows the scoring system for the attributes.

a) Exposure

In GIS, a buffer zone is created to simulate the potential impact area. The potential impact zone for flammable or combustible hazardous materials is taken as 0.8 km in all directions (GoS, 2002). Therefore, a buffer of 0.8 km width was generated for each of the 21 routes (including the recommended route). This is shown in Figure 3.

As the exposed population is the main consideration, the features of concern include the type of residential land use, commercial and/or government buildings in the vicinity, industrial areas, number of schools in the area and also nearby Mass Rapid Transit (MRT) stations. Queries in GIS can find appropriate attributes and the respective scores can be given.

b) Socio-economic Impact

Based on the same buffer zones or impact areas, the damages can be estimated based on the potential physical damage to buildings, or the potential consequences that may result in socio-economic considerations indirectly. This includes potential damage to important infrastructure.

The factors identified that demands consideration include the type of residential housing, the type of commercial buildings, the type of industrial buildings, the size of waterbodies, the location of surrounding petrol stations, bridges and the location of nearby MRT stations.

Routes involving tunnels (the Central Expressway in the case of Singapore) were avoided. This was because tunnels are confined spaces and any release or explosions within a tunnel will lead to great complications. Since tunnels are often critical links, they are best avoided during the routing process

Table 2. Scale of Preference between 2 Elements

Preference weights/ level of importance	Definition	Explanation
1	Equally preferred	Two activities contribute equally to the objective
3	Moderately preferred	Experience and judgment slightly favour one activity over the other
5	Strongly preferred	Experience and judgment strongly or essentially favor one activity over the other
7	Very strongly preferred	An activity is strongly favoured over another and its dominance demonstrated in practice
9	Extremely preferred	The evidence favoring one activity over another is of the highest degree possible of affirmation
2, 4, 6, 8	Intermediate values	Used to represent compromise between the preferences listed above
Reciprocals	Reciprocals for inverse comparison	

Table 3. AHP Calculations to Determine Weights for Main Consideration

Consideration	Exposure	Socio-economic	Risks of terrorism	Traffic conditions	Emer Response	Relative Weights
Exposure	1	2	1/3	1/3	3	0.18
Socio-economic	½	1	1/5	1	3	0.15
Risks of terrorism	3	5	1	1/3	3	0.33
Traffic conditions	3	1	3	1	1/2	0.23
Emergency Response	1/3	1/3	1/3	2	1	0.11
						1.00

(Polzin, 2002).

c) Risks of Hijack

Trucks are in danger of being hijacked in sparsely populated areas. Areas with thick foliage provide good cover and may be used as the terrorists' hiding places to ambush the trucks. Therefore, these two attributes were designated higher scores that deemed them undesirable.

d) Traffic Conditions

Traffic density or traffic flow, average speed, number of signalized junctions and the accident frequency are important considerations for the costs, safety and security. A high traffic density implies that a higher population will be exposed to a release or explosion, but a lower traffic density may increase the likelihood of a hijack taking place along that corridor. A high average speed leads to a shorter transportation time, thus lowering the freight costs. However, it also leads to a higher possibility of accidents and makes it more difficult for the police interdiction, which in itself can be a complex problem (Luedtke and White, 2002).

The number of signal junctions may also aid in police interdiction since the traffic flow may impede a rogue driver at a rate light. On the other hand, a higher number of signalized junctions translates to a longer time taken for the journey and hence, higher costs.

e) Emergency Response

The proximity of the routes to fire stations and hospitals determine the efficiency of rescue operations. Fire stations must be sufficiently nearby to respond quickly to contain the release or put out the fires. At the same time, casualty evacuations must be quick and efficient. Police stations and army camps nearby will also respond to any chaos and extend further assistance. Their presence in the vicinity also serves as deterrence to possible terror attacks. Finally, the number of road lanes can significantly affect rescue operations. In the event that one of the lanes is rendered non-operational, the number of lanes left in operation will either facilitate or delay rescue operations. This is one form of network reduncy. Figure 4 shows the locational influence of a hospital.

4.2. Determination of Weights Using AHP

In order to combine the scores of the above criteria into a meaningful cost function, weights must be assigned to each factor and sub-factor according to their relative importance. Logically, the factors that demand greater emphasis require a higher weightage.

Due to the large number of parameters, i.e. the factors and sub-factors, AHP was used to determine the weights to be used. AHP works by developing priorities, which are derived for the criteria in terms of their importance to achieve the goal (Saaty, 2000). The priorities were derived according to pairwise assessments based on judgement. The relative importances were judged based on a scale of 1 to 9 as shown in Table 2. An inverse comparison resulted in a reciprocal of the above score.

Table 3 shows the pairwise comparison of the five main criteria. Then the cost of each route was obtained. Since the higher scores were given to conditions deemed less desirable, the optimum route was the one with the lowest cost.

4.3. Results and Analysis

The costs of the 20 alternative routes were determined by and compared against the route recommended by the authorities. The overall costs are summarized in Figure 5, which shows clearly that Route 8 has the least cost overall at 2.6709. The least-cost routes originating from Jalan Buroh, the AYE and Boon Lay Way are Routes 1, 15 and 20, with respective costs of 2.7440, 2.7790 and 2.7196. The recommended route is ranked eleventh overall with a cost of 2.7591. Its relatively low rank can be attributed to its high cost in terms of emergency response. Figure 6 summarizes the overall rankings of the 21 routes.

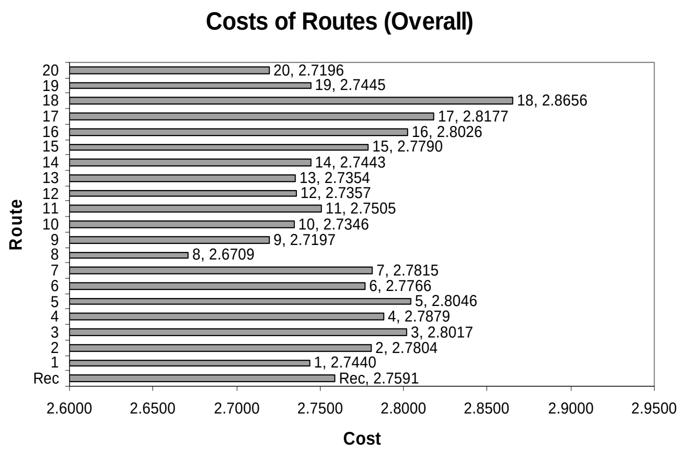

Figure 5. Overall costs of routes considering all the factors.

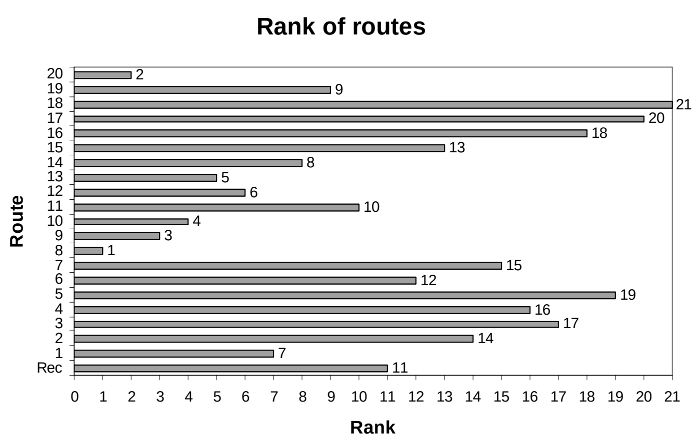

Figure 6. Overall rank of routes.

It is of interest to note that the recommended route remains as having one of the lowest cost. This shows that even without having considered security, the route is already one of the more secured ones. The three routes with the lowest cost were also found to have different origins. However, none of them include the Clementi Road. Thus, the Clementi Road is best avoided during the routing process.

5. Effects of Weights on Main Considerations

Since current routing procedures do not give security and emergency response due consideration, the cost function of the recommended route should be one of the least if their weights are correspondingly lowered. The pair-wise comparison was adjusted as shown in Table 4, giving more emphasis to socio-economic impact and exposure.

Correspondingly, the cost functions should more closely simulate current conditions. As shown in Figure 7, the cost of the recommended route is now the sixth least, with a cost of 2.8062, compared to Route 1, which has the least cost of 2.6624. A comparison of all the overall costs is illustrated in Figure 8, where the recommended route is displayed as Route 21.

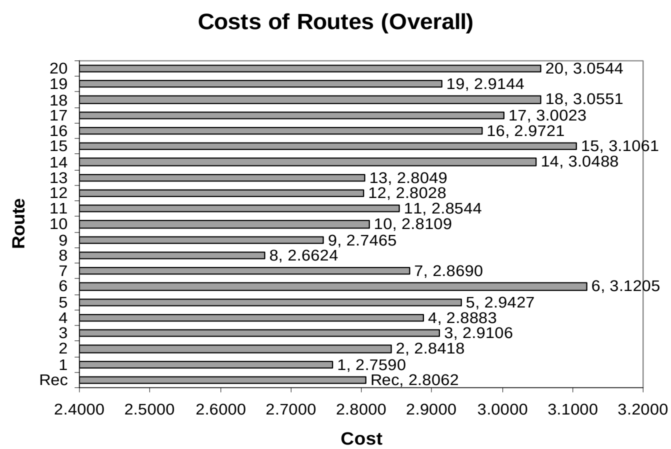

Figure 7. Costs of the routes to simulate current conditions.

6. Conclusions and Future Research

The use of GIS in quantifying and measuring spatial attributes proved to be efficient and more accurate than using tract maps. It allowed for the factors to be quantified so that the right score can be given. However, the drawbacks include the high dependence of the results upon the quality and consistency of the input data. This can be minimized through using the most reliable data sources available and minimizing arbitrary assumptions. Highly accurate traffic data obtained from surveys would be time-consuming and expensive and potentially become out-of-date quickly (Brainard et al., 1996). The data used in this study is deemed representative and suitable for use and the objective is met with agreeable results.

AHP allows the decision makers to decide which criteria calls for greater consideration based on their subjective preferences, especially when the factors in consideration do not have a common scale of measurement, or in some cases, are intangible with no existing scale of measurement. A drawback of the AHP is the extent of subjectivity that is inherent in the process. Preferences differ from person to person and the AHP is best done in a group decision making level (Malczewski, 1999), where a compromise amongst the participants can be

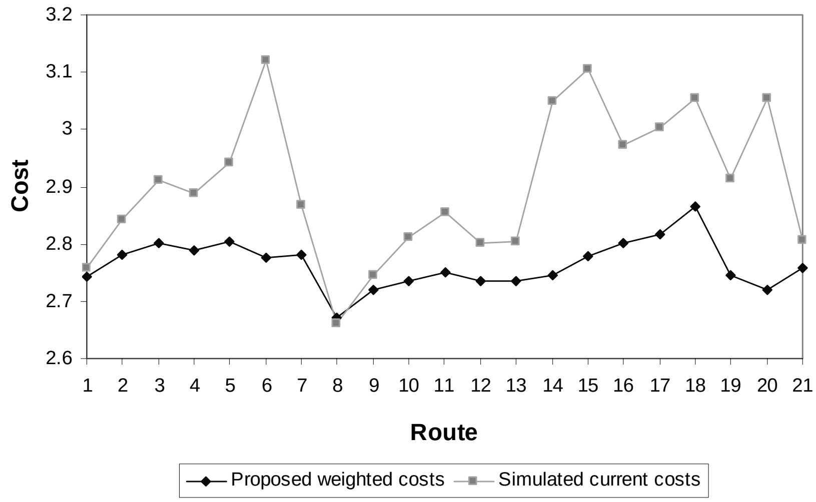

Figure 8. Comparison of costs with the different sets of weights.

Table 4. Pair-wise Comparison of Main Considerations

Consideration	Exposure	Socio-economic	Risks of terrorism	Traffic conditions	Emergency Response	Relative Weights
Exposure	1	½	5	1	4	0.27
Socio-economic	2	1	6	2	5	0.37
Risks of terrorism	1/5	1/6	1	1/4	1/2	0.05
Traffic conditions	1	½	4	1	3	0.22
Emergency Response	¼	1/5	2	1/3	1	0.09
						1.00

reached without subjecting the methodology to unnecessary bias.

The application results show that the current recommended routes are most effective when the main considerations are exposure and socio-economic impact, which is the common practice before September 11th. However, with greater awareness of the need for homeland security, these routes may no longer be the best routes available. Based on the same cost functions and changing the weights to give more emphasis on the security aspects, viz. risk of security and emergency response, the more optimal routes that are relevant today can be determined.

In future, the framework used can be easily extended to cover a much wider extent of the road network in Singapore, requiring more extensive data-collection to ensure the GIS database is accurate and up-to-date. Reclassification of the scoring system is necessary to ensure that the appropriate score will be given corresponding to the extent of study. The methodology, however, remains unchanged, offering flexibility regardless of the extent of study.

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