Risk analysis for the road transportation of hazardous chemicals in Singapore — a methodology

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A methodology has been developed for the risk analysis of road transportation of hazardous chemicals in Singapore. The analysis was applied to a case study of liquefied petroleum gas transportation by road tankers. The transportation of liquefied petroleum gas via two existing routes was studied in detail, and the corresponding societal risks were evaluated and compared.

Keywords: liquefied petroleum gas; risk analysis; transportation

The road transportation of hazardous chemicals has always been a concern in Singapore because of the high population density and small size. The industrial estates, particularly those that use and produce hazardous chemicals, are situated in remote areas on the main island or on other offshore islands. However, due to the limited land space, there is simply no way that road transportation of hazardous chemicals to and from major industrial estates can avoid residential areas on the main island. One such example is the Jurong industrial estate. This is served by four main roads, Jln Ahmad Ibrahim, the PIE, Boon Lay Way and Jln Buroh, which all pass through housing estates before reaching any other industrial estates, the port or the causeway (for goods heading overland).

Transportation of hazardous chemicals and petroleum products in Singapore is controlled by the Ministry of the Environment and the Ministry of Home Affairs, respectively. The control is effected through the Poisons (Hazardous Substances) Rule 1986 and the Petroleum Act 1985. These regulations aim to control the transportation of potentially hazardous chemicals, both toxic and flammable, to reduce the consequences that may arise from loss of containment of the hazardous chemical during transit through the road network. In principle, the regulations achieve this by:

(i) imposing sound engineering practice in the design and construction of containers/tankers (in all forms) used for the transportation of hazardous chemicals;
(ii) restricting the routes used, in order to prevent passage through densely populated areas and water catchment areas;
(iii) restricting the movement of hazardous chemicals to within daylight hours, when help is readily available to contain and remedy any accident; and
(iv) requiring the applicant company to prepare an emergency plan to deal with any accidental release of the hazardous chemicals transported.

These requirements are intended to assist the authorities in the control of transportation of hazardous chemicals to ensure the safety of the population. However, there is no comprehensive methodology to assist the industries and the authorities in assessing the societal risk associated with the transportation of hazardous chemicals in Singapore. This project attempts to develop a methodology for risk assessment for land transportation of hazardous chemicals in Singapore, and to apply it to the evaluation of proposed routes. This paper reports on the methodology developed so far, and presents the results of societal risk analysis of two selected routes for the transportation of liquefied petroleum gas (LPG).

Methodology

The methodology developed was based principally on the method used by Health and Safety Executive, UK, for the assessment of societal risk for the road transportation of hazardous chemicals. The method entails:

(i) **Zoning of the route**: making a detailed analysis of the proposed route to segment it into zones of different topography, population density and meteorological conditions;
The two routes analysed in this study were selected to reflect a variation in road usage and off-road population density. Both routes pass through two classes of motorway:

- **Class 1**: Dual carriageway, non-expressway-type road of 8 m width per side
- **Class 2**: Dual carriageway, expressway-type road of 12 m width per side

The different categories of off-road population density were:

- **Industrial estate** (population density = 0.003 per m²)
- **High-density housing estate** (population density = 0.0071 per m²)
- **Low-density housing estate** (population density = 0.0044 per m²)
- **Open areas** (population density = 0)

LPG was assumed to be transported from the respective loading points to the final destination, where the load is discharged. The road tankers return empty to their starting points.

It was assumed that the motorway in front of the road tanker would be clear in the event of an accident, while there would be a pile up of vehicles behind the road tanker. It is expected that motorists on the other side of the road will slow down to observe the accident. Based on these assumptions, the population densities are:

- **behind road tanker** = 0.056 per m²
- **on the other side of the road** = 0.028 per m²

### Identifying the hazards

Accidental release of LPG may lead to the following consequences:

- **torch flame**
- **fireball**
- **flash fire**

- **BLEVE** (boiling liquid expanding vapour expansion)
- **UVCE** (unconfined vapour cloud explosion)

The maximum capacity of LPG tankers in Singapore is 11 tonnes (20 m³) and the regulations restrict the tankers from loading to above 85% of their capacity. From past experience, given the storage condition of the LPG during transportation and the small capacity, it was deemed unlikely that loss of containment of LPG during transportation would lead to a UVCE. Hence, the possibility of a UVCE was not considered in our study. For a thermally induced BLEVE, substantial weakening of tank would take place only after prolonged heating of the tank. Given the small tanker capacity and assuming that the relief valve on the tanker works, it was considered that a BLEVE was unlikely to occur in LPG tankers. Therefore, this report considers only three possible hazards: torch flame (for continuous release only), fireball and flash fire.

### Frequency of incidents

Local data on tanker routes, total loaded LPG tanker distance, total tonnage, accidents that have occurred (frequency and extent of damage) and the storage condition during transportation were collected.

En route release of LPG may arise from puncture or damage to a tanker due to collision or roll-over, and failure or malfunction of the peripheral equipment. Past records show that the failure or malfunction of equipment is unlikely to lead to any large spills (> 1500 kg) or medium spills (150-1500 kg), and that the frequency of occurrence for small spills (< 150 kg) is $3.25 \times 10^{-10}$ per year per tanker km, with a release rate of 2 kg s⁻¹ (Reference 1). The en route puncture frequency per loaded road tanker km for LPG is $4.8 \times 10^{-10}$ per year per tanker km (Reference 1); of this, 90% is assumed to lead to medium spills with a discharge rate of 36 kg s⁻¹, while the other 10% is assumed to lead to catastrophic failure and instantaneous release of the entire tanker contents.

### Estimating hazard zones

Three scenarios were modelled:

- **(i) Instantaneous release of tanker contents.** The possible consequences of such a release are fireball for instantaneous ignition and flash fire for delayed ignition.
- **(ii) Medium spills.** The mass flow rate of such spills is assumed to be 36 kg s⁻¹. The possible consequences of such a spill include a BLEVE if there is flame impingement on the tanker, torch flame for immediate ignition, and flash fire followed by torch flame for delayed ignition.
- **(iii) Small spills.** The small spills considered here are assumed to have a mass flow rate of 2 kg s⁻¹. The possible consequences are torch flame for immediate ignition and flash fire followed by torch flame for delayed ignition.
The lethality limits used in the calculations were:

(i) For those out-of-doors: Those who were caught in the flame (i.e., in the flash fire, fireball or torch flame) were assumed to die.

(ii) For those who were indoors or under shelter:
The lethality criteria for those who were indoors or under shelters were based on the spontaneous ignition of building materials, for an exposure time of 45 s. The exposure time took into account the reaction time of a normal person when exposed to unforeseen circumstances and the time required to run into some form of shelter. The two possible cases are as follows:

- **Torch flame:** there will be no pilot ignition and thus spontaneous ignition only will occur, corresponding to a thermal intensity of 37.5 kW m\(^{-2}\).

- **Flash fire:** pilot ignition is provided by the flash flame, and the corresponding thermal intensity is 12.5 kW m\(^{-2}\).

The PHAST Process Hazard Analysis Software Tools, Version 4.1 (Reference 4), were used to evaluate the various hazard zones. An average wind speed of 2 m s\(^{-1}\) was assumed.

**Route societal risk assessment**

An accident involving the release of a hazardous chemical during transport could take place anywhere en route, so that any individual is unlikely to be at very high risk (except at accident-prone hot spots). However, an accident at any point along the route could involve a large number of people. Thus societal risk is important. This report will therefore concentrate on the assessment of societal risk associated with the transport of LPG through the selected routes. A detailed zoning of the two routes and the associated en route population densities are presented in Appendix 1.

The estimate of the number of fatalities for an event is derived from the following assumptions:

- people outdoors and in contact with the flame are likely to die\(^1\)
- 20% of the indoor population within the flammable cloud will die\(^1\)
- no deaths will occur below 1% lethality (5 kW m\(^{-2}\))\(^1\)
- for non-continuous events, people outside the range of spontaneous ignition (37.5 kW m\(^{-2}\)) and in shelter will survive\(^1\)
- the percentage of the off-road population that are outdoors is 20%, which is a time-average for the working day\(^2\).

The \(F-N\) curves for both routes are given in Figures 1 and 2. The route societal risks for each of the routes are summarized in Tables 1 and 2.

**National societal risk**

The average national societal risk from LPG transportation via a particular route can be estimated by considering the effect of sending the total national tonnage of LPG through that route, and then scaling up to the average national route length of 13.7 km. The resulting average national societal risks based on routes 1 and 2 are shown in Figures 3 and 4, respectively. The total national risk based on each route is summarized in Table 3.

**Discussion**

The national societal risk for both routes showed that the off-road population is at higher risk than the road users, although one would expect the reverse. The risk faced by both road users and the off-road population is a combination of both the extent of the hazard zone and the traffic/population density. High off-road population densities would put a large number of non-road users at risk in the event of a LPG tanker accident.

Sensitivity studies were carried out on the effect of off-road population density and meteorological conditions (by varying the prevailing wind speed). Results showed that the off-road population risk for both routes increased approximately twofold when the prevailing wind speed was increased from 2 to 4 m s\(^{-1}\). Similarly, a 50% reduction in the off-road population density reduces the off-road population risk. The reduction in off-road population risk is most significant.
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Figure 2 Route 2: (a) road user societal risk; (b) off-road population societal risk

Table 1 Route societal risk for route 1

<table>
<thead>
<tr>
<th>N &gt;</th>
<th>1</th>
<th>10</th>
<th>20</th>
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<tr>
<td>F per year ( \times 10^{-6} )</td>
<td></td>
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<tr>
<td>Road users</td>
<td>46.3</td>
<td>45.9</td>
<td>45.4</td>
<td>16.4</td>
<td>1.2</td>
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<tr>
<td>Off-road population</td>
<td>51.6</td>
<td>35.2</td>
<td>14.2</td>
<td>0.3</td>
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Table 2 Route societal risk for route 2

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<tr>
<td>F per year ( \times 10^{-6} )</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Road users</td>
<td>45.4</td>
<td>40.1</td>
<td>33.8</td>
<td>25.1</td>
<td>15.3</td>
<td>1.0</td>
</tr>
<tr>
<td>Off-road population</td>
<td>51.7</td>
<td>47.5</td>
<td>37.5</td>
<td>26.5</td>
<td>14.3</td>
<td>8.2</td>
</tr>
</tbody>
</table>

Figure 3 National societal risk based on route 1

Figure 4 National societal risk based on route 2

Table 3 National societal risk based on routes 1 and 2

<table>
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<th>N &gt;</th>
<th>1</th>
<th>10</th>
<th>20</th>
<th>50</th>
<th>100</th>
<th>200</th>
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</thead>
<tbody>
<tr>
<td>F per year ( \times 10^{-6} )</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Route 1</td>
<td>274.0</td>
<td>227.1</td>
<td>167.0</td>
<td>46.6</td>
<td>3.22</td>
<td>-</td>
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<tr>
<td>Route 2</td>
<td>727.7</td>
<td>657.2</td>
<td>535.4</td>
<td>387.0</td>
<td>221.9</td>
<td>69.3</td>
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</table>

risk for route 2 is significantly higher than that of route 1 (Tables 1 and 2). Closer examination of the routes reveals the reason: 46.0% of route 1 distance passes through unpopulated areas, while unpopulated areas only constitute 12.8% of the total route 2 distance. It is therefore obvious that, from a risk point of view, route 2 is less desirable than route 1.

References


Appendix 1

Route analysis

Population density data:

(i) Population density of back-up traffic

\[\text{Population density of back-up traffic} = 0.056 \text{ per m}^2\]

(ii) Population density on the other side

\[\text{Population density on the other side} = 0.028 \text{ per m}^2\]

(iii) The road used for the transportation of LPG can be classified by the road width as follows:

- class 1: Three-lane two-way motorway = 12 m
- class 2: Two-lane two-way motorway = 8 m

(iv) Off-road population densities are as follows:

- industrial estate = 0.003 per m²
- low-density housing = 0.0044 per m²
- high-density housing = 0.0071 per m²

(v) The off-road population density can be classified into the categories described in Table A1.

Route 1. Route 1 starts from Penjuru Road and ends at Woodlands Causeway. The total route distance is 21.3 km. The total loaded tanker distance travelled for this route is 95891 km per year. The breakdown of the route is as follows:

\[
D(1,A) = 6.7 \quad D(2,A) = 3.1 \\
D(1,B) = 2.3 \quad D(2,B) = 0 \\
D(1,C) = 2.1 \quad D(2,C) = 0.4 \\
D(1,D) = 2.7 \quad D(2,D) = 0 \\
D(1,E) = 0 \quad D(2,E) = 0.3
\]

Route 2. Route 2 starts from Shipyard Road and ends at Bedok South Road. The total route distance is 36.5 km. The total loaded tanker distance travelled for this route is 35800 km per year. The breakdown of the route is as follows:

\[
D(1,A) = 0.7 \quad D(2,A) = 3.8 \\
D(1,B) = 3.0 \quad D(2,B) = 2.6 \\
D(1,C) = 0 \quad D(2,C) = 0.7 \\
D(1,D) = 4.8 \quad D(2,D) = 0.8 \\
D(1,E) = 0 \quad D(2,E) = 0.2 \\
D(1,F) = 0.4 \quad D(2,F) = 8.8 \\
D(1,G) = 0 \quad D(2,G) = 1.9 \\
D(1,H) = 1.1 \quad D(2,H) = 2.2 \\
D(1,I) = 0 \quad D(2,I) = 0 \\
D(1,J) = 0 \quad D(2,J) = 0.7 \\
D(1,K) = 0.6 \quad D(2,K) = 0.5 \\
D(1,L) = 0.6 \quad D(2,L) = 1.1 \\
D(1,M) = 0 \quad D(2,M) = 2.0
\]

D(1,A) refers to the total distance of class 1 road with off-road population density type A, etc. All values are in km.

<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
<th>Off-road population density (per m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Unpopulated both sides</td>
<td>This side</td>
</tr>
<tr>
<td>B</td>
<td>Unpopulated on this side of the road, industrial estate on the other side</td>
<td>0</td>
</tr>
<tr>
<td>C</td>
<td>Industrial estate on this side of the road, unpopulated on the other side</td>
<td>0.003</td>
</tr>
<tr>
<td>D</td>
<td>Industrial estate on both sides of the road</td>
<td>0.003</td>
</tr>
<tr>
<td>E</td>
<td>Industrial estate on this side of the road, industrial estate on the other side</td>
<td>0.0071</td>
</tr>
<tr>
<td>F</td>
<td>Low-density housing on both sides of the road</td>
<td>0.0044</td>
</tr>
<tr>
<td>G</td>
<td>Low-density housing on this side of the road, unpopulated on the other side</td>
<td>0.0044</td>
</tr>
<tr>
<td>H</td>
<td>Unpopulated on this side of the road, low-density housing on the other side</td>
<td>0</td>
</tr>
<tr>
<td>I</td>
<td>Unpopulated on this side of the road, high-density housing on the other side</td>
<td>0</td>
</tr>
<tr>
<td>J</td>
<td>High-density housing on this side of the road, unpopulated on the other side</td>
<td>0.0071</td>
</tr>
<tr>
<td>K</td>
<td>High-density housing on both sides of the road</td>
<td>0.0071</td>
</tr>
<tr>
<td>L</td>
<td>Low-density housing on this side of the road, high density on the other side</td>
<td>0.0044</td>
</tr>
<tr>
<td>M</td>
<td>High-density housing on this side of the road, low-density housing on the other side</td>
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