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Ministry of Transportation and Infrastructure
South Coast Region
310 – 1500 Woolridge Street
Coquitlam, BC V3K 0B8

Attention: Lina Halwani, Regional Manager, Engineering

Re: Highway 17 & Highway 91 Connector Intersection – Truck Rollover Safety Assessment

Dear Ms. Halwani:

The Ministry of Transportation and Infrastructure (MOTI) has requested R.F. Binnie (Binnie) to investigate the design and the traffic operations of the Highway 17 and Highway 91 Connector intersection with respect to the number of truck rollovers that have occurred since the intersection has been in operation. The SFPR Project was substantially completed and opened for general traffic operation in December 2013, which included the Highway 17 and Highway 91 Connector intersection. Since opening, the intersection has experienced five truck rollover incidents. Binnie is completing a design and traffic operations review to determine if the design and/or traffic operations are contributing factors in the occurrence of truck rollovers at the intersection.

Background

The SFPR is oriented in a west/east configuration and the Highway 91 Connector is oriented in a north/south configuration at the subject intersection. The SFPR has been renamed Highway 17 after the opening of the facility. The table below provides a summary of the truck rollover incidents.

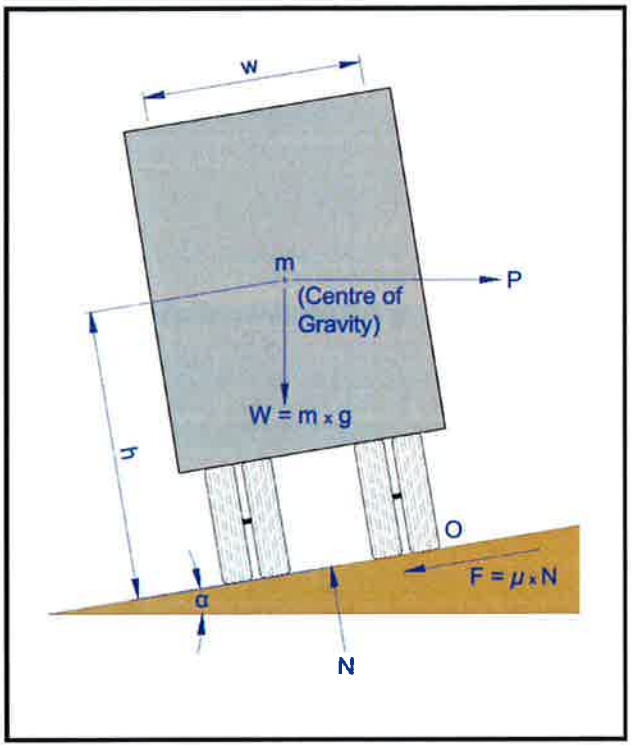
Table 1 Truck Rollover Main Facts

Incident	Type	Date	Intersection Turning Movement
1	Single Truck Rollover	March 6, 2014	Hwy. 17 WB to Hwy. 91 Con. NB
2	Single Truck Rollover	June 24, 2014	Hwy. 91 Con. NB to Hwy. 17 EB
3	Single Truck Rollover	July 9, 2014	Hwy. 17 WB to Hwy. 91 Con. SB
4	Single Truck Rollover	July 23, 2014	Hwy. 17 EB to Hwy. 91 Con. SB
5	Single Truck Rollover	August 6, 2014	Hwy. 17 WB to Hwy. 91 Con. SB

Of the five truck rollover, two have been for the Highway 17 WB to Highway 91 Connector SB movement. Two of the truck rollover incidents were each a single occurrence for a different turning movement, and the turning movement associated with one rollover incident is unknown. Therefore, 50% of the truck rollovers that can be attributed to a particular turning movement are associated with the Highway 17 WB to Highway 91 Connector SB movement.

Scientific Principles for a Truck Rollover

The following figure illustrates the forces that act upon a truck as it travels a circular path.



Forces Acting on a Truck

There are two main forces acting on the truck given by the following equations:

$$\textbf{(1) Centrifugal Force: } P = \frac{m V^2}{R}$$

$$\textbf{(2) Centripetal Force: } F = \mu m g$$

m = mass of the truck
V = velocity of the truck
R = the radius of the curve being travelled by the truck
μ = truck tire friction factor
g = gravity

These forces that act on a truck create an Overturning Moment (OM), which tries to overturn the truck, and a Resisting Moment (RM), which tries to prevent the truck from overturning.

Truck overturning will occur when the Factor of Safety (FOS) preventing overturning is one or less, given by the following equation:

$$(3)\quad FOS = \frac{\cos(\alpha)w/2 + \sin(\alpha)h + \sin(\alpha)h\,V^2/(gR)}{\cos(\alpha)h\,V^2/(gR)}$$

w = the width of the truck wheel base

h = height of the centre of gravity of the truck

α = the angle of the road from a flat plain (ie. the banking of the road/superelevation)

The banking of the road is a small angle (close to zero degrees); consequently, if the angle is set to zero the equation for the FOS preventing overturning simplifies to the following equation:

$$(4)\quad FOS = \frac{w/2}{h\,V^2/(gR)}$$

The main factors that influence truck overturning become readily apparent when examining equation 4. They are:

- The wider the wheel base, the less likely a truck will overturn. Truck wheelbases are generally no wider than 2.6 m since the wheelbase is restricted by the lane width.
- The higher the centre of gravity of the truck, the greater the likelihood that a truck will overturn. The centre gravity of the trailer, including the load that is being carried, is generally the controlling factor. Therefore, the weight, shape and height of the load that a truck is carrying will influence the centre of gravity and the likelihood that a truck may overturn.
- The higher the speed of the truck, the greater the likelihood that a truck may overturn. The speed of the truck is the most significant factor since overturning is dependent on the square of the speed.
- The smaller the radius (ie. the sharper the curve) the greater the likelihood that a truck may overturn.

Equation 3 takes into consideration the superelevation (ie. banking) of the road. Although it is not readily apparent, Equation 3 shows that positive superelevation will help reduce the risk of truck rollover and negative superelevation will increase the risk. However, the superelevation does not have as much of an impact on truck rollover as the other factors described above.

Review of the Detailed Design

Fraser Transportation Group (FTG) completed the design and construction of SFPR, including the Highway 17 and Highway 91 Connector intersection. A review of the intersection design by Binnie confirmed that the intersection design is generally compliant with the following engineering design guidelines:

- Transportation Association of Canada Geometric Design Guide for Canadian Roads (TAC)
- BC Supplement to the TAC Geometric Design Guide 2007 Edition (MOTI TAC Supplement)
- AASHTO A Policy on Geometric Design of Highways and Streets (AASHTO Green Book)

More specifically:

- TAC notes that "grades in excess of 3% are not desirable through an intersection" and the grade through the subject intersection is 4%. Although the grade is slightly above desirable it is still acceptable to have an intersection on a 4 % grade.
- TAC also notes that "superelevation rates in excess of 0.04 m/m through intersection areas adversely affect the smooth operation, particularly for those vehicles turning against the superelevation", and the design superelevation on Highway 17 through the subject intersection is 0.03 m/m. Therefore, the design superelevation is acceptable and in compliance with the design guides.
- The lane widths, including the left turn lane widths, are in compliance with the design guides.
- The design vehicle turning paths shown in the design accommodate the design vehicles. AutoTURN was used to model the turning movements for the WB-20 design vehicle. The modelled turning movements are provided as appendices in Figures 1, 2 and 3, at the back of this letter report. Some of the turning movements are quite sharp and abrupt due to the intersection skew angle, but the intersection skew angle and the design vehicle turning paths are in compliance with the design guides.
- The skew angle of the intersection is 75 degrees, which is within the recommended skew angle provided by the MOTI TAC Supplement for an Arterial Highway Intersection, and the design is acceptable and in compliance with the design guides.

Review of the As-Constructed Intersection

FTG completed a detailed ground survey of the as-constructed intersection, and the field survey confirmed that the intersection has been constructed in conformance with the design.

Intersection Operational Analysis

Although the intersection design is compliant with engineering design guides, there are contributing factors that have resulted in the truck rollovers at the intersection. Furthermore, the analysis shows that the Highway 17 WB to Highway 91 Connector SB intersection turning movement is the most susceptible to truck rollover for the following reasons:

- A major factor in truck roll overs is excessive truck speed, and the turning movement from the high speed facility (Highway 17) onto the lower speed facility (Highway 91 Connector) will be the most susceptible to speeding by truck drivers. Highway 17 is posted at 80 km/h and Highway 91 Connector is posted at 60 km/h. Four of the five recent truck rollovers that noted the turning movement were associated with the turning movement from Highway 17 to Highway 91 Connector.
- The left turns from Highway 17 onto the Highway 91 Connector have an angle in excess of 90 degrees (105 degrees), which results in a sharp turn for this movement. Furthermore, the Highway 17 WB to Highway 91 Connector SB movement is a dual left turning movement, which requires that the vehicle on the outside of the dual left turns make a sharp turn in order to maintain separation between the dual turning vehicles.
- The truck turning radius for the Highway 17 WB to Highway 91 Connector SB movement is approximately 14.5 m measured to the outside turning wheel, which is less than the desirable minimum truck turning radius for a left turn at an intersection from a high speed facility. MOTI TAC Supplement Section 720.03 indicates that a minimum outside front wheel radius of 17.7 m is recommended for left or right turns from a main highway to a secondary road, and that a

17.7 m radius is appropriate for design vehicles speeds up to 25 km/h. MOTI TAC Supplement Section 720.03 indicates that a truck turning radius of 14.5 m is appropriate for design vehicles negotiating turns at lower speeds.

- Both the grade and superelevation of Highway 17 through the intersection contribute to make the cross slope of road worse for the Highway 17 WB to Highway 91 Connector SB movement. The combined effect of the grade and the superelevation result in a cross slope of -0.047 m/m near the mid-point of the left turn. The Highway 17 WB to Highway 91 Connector SB left turn has experienced two of the five recent truck rollovers.

The cross-fall and the turning path minimum radius for the Highway 17 WB to Highway 91 Connector SB movement are shown in Figure 4, as an appendix to this letter report. The minimum turning path radius was found to be 14 m measured to the centre of gravity of the truck trailer, and the steepest cross fall was found to be -0.047 m/m. Using these values, the Factor of Safety (FOS) for truck rollover for the Highway 17 WB to Highway 91C Connector left turn was calculated using Equation 3 for different truck speeds. The results of the analysis are shown in the table below, which indicates trucks are susceptible to rollover when the truck speed exceeds 26 km/h.

Table 1 FOS For Rollover - Hwy. 17 WB to Hwy. 91 Connector Left Turn – Effect of Truck Speed

Truck Speed	Radius	Superelevation	FOS for Rollover
20 km/h	14.0 m	-0.047 m/m	1.87
22 km/h	14.0 m	-0.047 m/m	1.54
24 km/h	14.0 m	-0.047 m/m	1.29
26 km/h	14.0 m	-0.047 m/m	1.10
28 km/h	14.0 m	-0.047 m/m	0.94 Rollover
30 km/h	14.0 m	-0.047 m/m	0.82 Rollover
32 km/h	14.0 m	-0.047 m/m	0.72 Rollover
34 km/h	14.0 m	-0.047 m/m	0.63 Rollover

If the truck path turning radius is revised from 14 m to 16.4 m, the FOS for truck rollover would marginally increase as noted in Table 2 below, but the increase would be minimal. The speed at which trucks would be susceptible to rollover would be almost the same.

Table 2 FOS For Rollover - Hwy. 17 WB to Hwy. 91 Connector Left Turn – Effect of Radius

Truck Speed	Radius	Superelevation	FOS for Rollover
26 km/h	14.0 m	-0.047 m/m	1.10
26 km/h	16.4 m	-0.047 m/m	1.29
28 km/h	16.4m	-0.047 m/m	1.11
30 km/h	16.4 m	-0.047 m/m	0.96 Rollover

If the superelevation on Highway 17 is revised such that that resultant cross-fall is lessened as noted in Table 3 below, the FOS for truck rollover would increase a small amount, but the increase would be small and trucks would still be susceptible to rollover at close to the same speed.

Table 3 FOS For Rollover – Hwy. 17 WB to Hwy. 91 Connector Left Turn – Effect of Superelevation

Truck Speed	Radius	Superelevation	FOS for Rollover
28 km/h	14.0 m	-0.047 m/m	0.94 Rollover
28 km/h	14.0 m	-0.040 m/m	0.96 Rollover
28 km/h	14.0 m	-0.030 m/m	0.99 Rollover

Conclusions

A review of the intersection design completed by the FTG confirmed that the intersection design is compliant with current engineering design guidelines.

Although the intersection design is compliant with engineering design guides, there are contributing factors that have resulted in five truck rollovers at the intersection. An analysis of these contributing factors show that the Highway 17 WB to Highway 91 Connector SB turning movement is the most susceptible to truck rollover if the truck speed exceeds 26 km/h for this turning movement.

Reducing the negative cross-fall along Highway 17 within the intersection would only provide a minimal increase in the FOS for truck rollover and trucks would still be susceptible to rollover at close to the same speed.

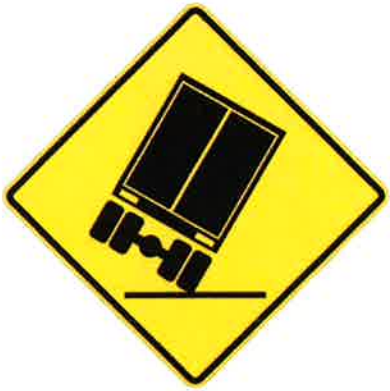
Revising the truck turning path and increasing the minimum truck turning path radius would provide only a marginal increase in the FOS for truck rollover, and the speed at which truck rollovers may occur would increase by only 2 km/h.

The main factor influencing truck rollovers is truck speed and an operating speed of 20 km/h for the truck turning movements would provide a FOS close to 2 for the Highway 17 WB to Highway 91 Connector SB turning movement, which is an appropriate FOS. The FOS for the other intersection truck turning movements would be higher.

Recommendations

Informing truck drivers that they should reduce their speed to 20 km/h or less would reduce the risk of truck rollovers at the intersection. There are various means to achieve this objective; therefore, a staged approach is recommended for implementing speed reduction measures. Short term improvements are recommended for initial implementation that are quick and easy to construct. The short term improvements would be monitored and if issues still exist following implementation, long term improvements could be considered. The following short term intersection improvements are recommended to reduce the risk of truck rollovers:

- Install the W-324 Truck Rollover Warning Sign on all of the approaches with a 20 km/h W-22 Advisory Speed Tab. The signs should be installed at the start of the left or right turn auxiliary lane. Monitor truck turning speed following implementation of the static signs to gauge their effectiveness.



W-324 Truck Rollover Warning Sign

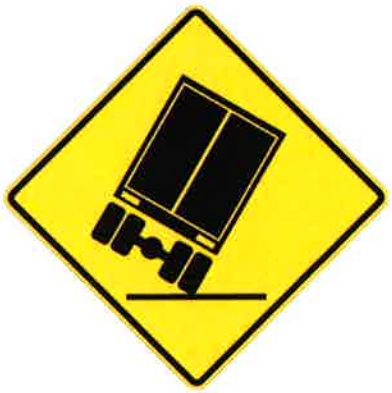
W-22 Advisory Speed Tab

If the short term improvements are effective in resolving the occurrence of truck rollovers then no further action will be required. However, if the short term improvements do not fully resolve the occurrence of truck rollovers, the following long term measures are recommended:

- Provide an Active Warning Sign in addition to the Truck Rollover Warning Sign and the Advisory Speed Tab for the Highway 17 WB to Highway 91 Connector SB movement. The Active Warning Sign could either display the measured speed of the vehicle and advise the drivers that they should slow down if they exceed 20 km/h (option 1), or display a second W-324 Truck Rollover Warning Sign with flashing lights that would be activated if the vehicle speed exceeds 20 km/h (option 2). The Active Warning Sign should be located about 40 to 60 m before the end of the left turn lane. There is limited space for signage adjacent to the left turn lanes; therefore, this sign could be davit mounted over the centre of the left turn lanes, with the base of the davit pole cast-in-place to match the concrete barrier provided adjacent to the left turn lane. A 20 km/h Advisory Speed Tab could also be provided with the Active Warning Sign.

Active Warning Sign

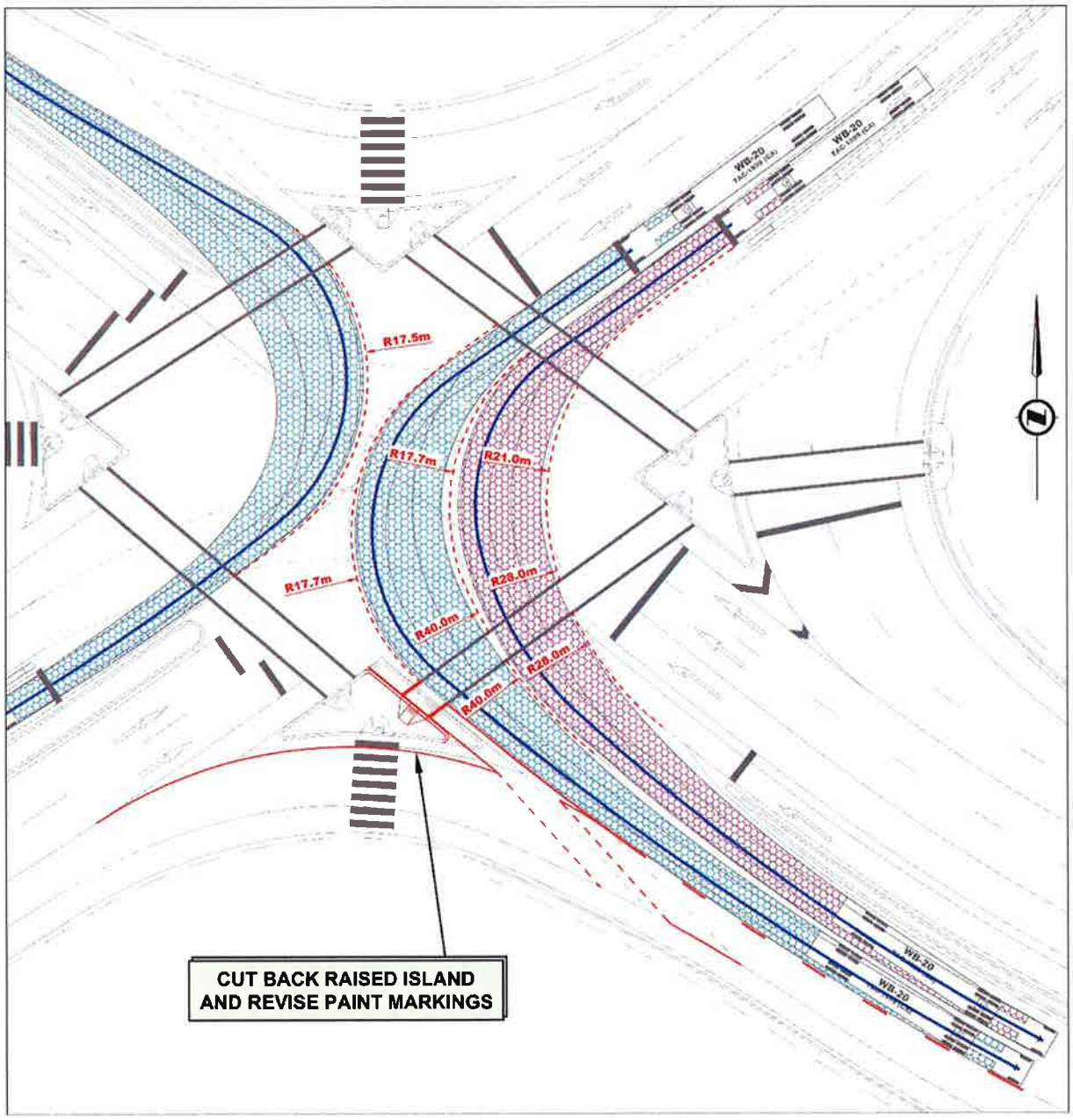
(Option 1)



W-324 with Active Flashing Lights

(Option 2)

- The truck path turning radius for the Highway 17 WB to Highway 91 Connector SB movement could be increased by revising the configuration of the southwest intersection island and revising the intersection continuity lines (dashed lines guiding the left turn movement) as shown in the figure below. If the radius to the centre of the front driving axle is increased from 14.0 m to 16.4 m (17.7 m to the outside front wheel), the factor of safety would increase from 1.10 to 1.29 for a 26 km/h truck speed.



Modified Left Turn Configuration

- The ultimate long term solution would be to replace the intersection with a grade separated facility. This is a very costly solution and construction of an interchange would cause large traffic disruptions. Construction of an interchange would only be considered if the preceding recommendations are not effective in resolving the occurrence of truck rollovers.

Yours truly,
R.F. Binnie & Associates Ltd.

Maurizio Ponzini, P.Eng.
Transportation Division Manager