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INVESTIGATION ON IMPACT LOADS FOR TEST LEVEL 4 CONCRETE BRIDGE BARRIERS

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Abstract: Bridge barriers must be designed for impact loads of different crash test levels proposed in design standards. Crash tests with different load and evaluation criteria are provided in the literature such as National Cooperative Highway Research Program (NCHRP) Report 350 of 1993 which was superseded by the 2009 AASHTO Manual for Assessing Safety Hardware (MASH). Out of these crash test levels, Test Level 4 (TL-4) is considered for vehicles in high-to-moderate traffic highways. The criteria for TL-4 indicated in MASH has changed to higher values of truck weight and speed than the values given in NCHRP Report 350. In MASH, the single-unit vehicle weight increased from 8000 to 10,000 kg and the impact speed increased from 80 to 90 km/h while the impact angle is kept at 15º to the barrier longitudinal direction. However, impact loads used for designing corresponding bridge barriers specified in the 2014 version of the Canadian Highway Bridge Design Code (CHBDC) are not modified for TL-4 based on this new criteria in MASH. This paper presents a literature review of various studies on the determination of equivalent loads to vehicle impact to design TL-4 barriers, including computer modelling and full-scale crash tests with specifications similar to the new criteria of TL-4 in MASH. Based on these studies, it is concluded that the impact loads for TL-4 with new impact conditions are significantly increased. Therefore, new impact loads are suggested for TL-4 barrier for possible inclusion in the 2019 version of the Canadian Highway Bridge Design Code in order to meet the requirements for TL-4 bridge barrier specified in MASH. The proposed changes include the amount of transverse, longitudinal and vertical equivalent impact loading as well as the height of impact point and distributed lengths of such loadings.

1 Introduction

Bridge barriers are designed in order to resist vehicle impacts, and prevent them from overturning by dissipating their impact energy. Consequently, barriers will reduce damage to the vehicle and passengers. In order to design bridge barriers properly for different types of vehicles and crash conditions, test criteria are provided by design standards. Barriers should be designed upon these crash test criteria to be able to safely operate in crashes. Test criteria provided in the National Cooperative Highway Research Program (NCHRP) Report 350 (Ross et al., 1993) were utilized for bridge barrier designs. However, new criteria were recently provided in the AASHTO Manual for Assessing Safety Hardware (MASH, 2009) for test conditions. Therefore, these new criteria should be considered in barrier bridge designs. Test Level 4 (TL-4) is one of the tests provided by MASH that is usually accounted for bridge barriers with roadway with the frequency of passing vehicles similar to the amount of high-to-moderate-traffic highways stated in the Canadian Highway Bridge Design Code (CHBDC, 2014). This test is provided for crash tests of trucks with higher weights than regular cars. The previous conditions for TL-4 provided in NCHRP Report 350 and the new conditions of this test stated in MASH are indicated in Table 1. This table shows that the test vehicle and speed of TL-4 have changed in MASH, from 8,000 (17,600 lb) to 10,000 kg (22,000 lb) and 80 to 90 km/h, respectively; while the impact angle remains at 15º to the barrier longitudinal direction.

Table 1: Criteria for Test Level 4 indicated in NCHRP Report 350 and MASH

Test Level 4 Criteria	Test Vehicle – Designation and Type	Test Conditions	
		Speed – km/h (mph)	Angle – Degrees
NCHRP Report 350	8000S (Single-Unit Van Truck)	80.0 (50)	15
MASH	10000S (Single-Unit Truck)	90.0 (56)	15

Since the amount of weight and speed of the vehicle have increased for Test Level 4 in MASH, the equivalent impact loads will increase as well. Furthermore, the kinetic energy imposed to the system due to the impact that can be evaluated using the Impact Severity parameter (*IS*), is increased about 56% for TL-4 of new conditions in MASH compared to TL-4 with specifications in NCHRP Report 350 (Saez *et al*., 2012). *IS* can be calculated using the following equation:

[1] $IS = 0.5m(V_1 \sin\theta_1)^2$

Where m is vehicle mass (kg), V_1 is impact speed (m/s), and θ_1 is impact angle (degrees).

Hence, the required height of the barrier, which is evaluated using parameters including the impact loads, will be changed. Currently, the transverse impact load in CHBDC 2014 for TL-4 is given as 170 kN (with 1.7 live load factor applied), and the required barrier height is indicated as 800 mm. However, these values need to be revised in the forthcoming CHBDC edition to reflect on MASH changes for TL-4 barrier test criteria.

This paper reviews various studies that investigated, either with software simulation, or by preforming full-scale tests, the TL-4 barrier performance with crash test criteria similar to those for TL-4 indicated in MASH. Recommendation for equivalent impact loads are then drawn for TL-4 barrier.

2 Full-Scale Tests

There have been numerous full-scale tests performed by various researches in different periods. Crash tests are carried out with different conditions. Among these tests, several of them could be considered with similar criteria to the new conditions of TL-4 stated in MASH.

In a research carried out by Jiang *et al.* in 2004, impact loads for different conditions of crash tests were investigated. Although most of the crash tests studied were related to small vehicles, some of the tests for school buses and single-unit trucks were included as well. Crash tests similar to TL-4 criteria include school bus with weight ranging between 9075 kg (20,000 lb) to 9203 kg (20,290 lb) with speed ranging between 93 km/h (58 mph) to 99 km/h (61 mph). The angle of these tests were 15 to 16 degrees, and a concrete median barrier with a height of 810 mm (32 in) was utilized. All of the abovementioned tests resulted in roll over of the vehicles, which shows the barrier height not being adequate for the conditions of the tests. Alternatively, in another test with a 9094 kg (20,050 lb) school bus that was crashed to a vertical concrete barrier with a height of 1070 mm (42 in), speed of 93 km/h (58 mph) and an impact angle of 15 degrees, the barrier sustained the impact and managed to redirect vehicle to the travelling lane. Details of these tests are provided in Table 2:

Table 2: Full-scale Crash Tests Summary from Jiang *et al.* (2004)

Barrier Type	Barrier Height – mm (in)	Vehicle Mass – kg (lb)	Impact Speed – km/h (mph)	Impact Angle – Degrees	Remarks	Test Institute and Year
Vertical Concrete Barrier	1070 (42)	9094 (20050)	93 (58)	15	Redirection	Texas Transportation Institute (TTI) – 1980~1981
Concrete Median Barrier	810 (32)	9203 (20290)	99 (61)	15	Roll over	Dynamic Science Inc. (DSI) – 1984
		9075 (20000)	97 (60)	16	Roll over	
		9080 (20018)	93 (58)	15	Roll over	TTI – 1984

A series of crash tests have been reviewed by Hirsch in 1986. In this study, although it has been carried out more than 30 years ago, several tests can be found with criteria similar to TL-4 of MASH as summarizes in Table 3. The crash tests with values of vehicle weight, speed and angle that match the TL-4 of MASH were performed with school buses. Therefore, the results can be slightly different from a similar test with single-unit trucks. However, the results of the tests show that the vehicle rolls over an 810 mm (32 in) concrete barrier. Moreover, as the impact loads were provided in this study, the minimum and maximum impact loads among the abovementioned tests were equal to 311 kN (70 kips) and 372.3 kN (83.7 kips) for the successful tests. However, CHBDC consider dynamic load allowance of 1.4 to obtain the equivalent static impact loads. This makes the minimum and maximum equivalent loads for the successful tests in Table 3 about 30% and 56.4% greater than the factored equivalent transverse impact force specified in CHBDC 2014 (100 kN x 1.7 live load factor = 170 kN).

Table 3: Full-scale Crash Tests Summary from Hirsch (1986)

Barrier Type	Barrier Height – mm (in)	Vehicle Mass – kg (lb)	Impact Speed – km/h (mph)	Impact Angle – Degrees	Impact Load – kN (kips)	Remarks
Reinforced W-beam bridge rail	686 (27)	9045 (19940)	88.8 (55.2)	15	372.3 (83.7)	Redirection
4-in Aluminium rail on 18-in concrete parapet	810 (32)	9036 (19920)	92.2 (57.3)	14.8	434.1 (97.6)	Redirection , bus rolled over
CMB*	810 (32)	9194 (20270)	99.1 (61.6)	15	533.8 (120)	Bus rolled over
CMB	810 (32)	9067 (19990)	98.0 (60.9)	16	533.8 (120)	Bus rolled over
CMB parapet	810 (32)	9072 (20000)	92.9 (57.7)	15	471.5 (106)	Bus rolled over
Thrie-beam bridge rail	810 (32)	10433 (23000)	91.9 (57.1)	14.7	399.0 (89.7)	Bus rolled over
Concrete wall	1070 (42)	9085 (20030)	92.7 (57.6)	15	365.6 (82.2)	Smooth redirection
Thrie-beam bridge rail	1524 (60)	9072 (20000)	88.8 (55.2)	13.7	355.9 (80.0)	Bus rolled over
Thrie-beam bridge rail	1524 (60)	9072 (20000)	86.7 (53.9)	15.3	311.4 (70.0)	Good redirection

* Concrete Median Barrier

Hirsch concluded that for a safe redirection of school buses with a mass of 9,072 kg (20,000 lb) at speed of 97 km/hr (60 mph), and angle of 15 degrees, a barrier with minimum height of (38 to 42 in) is required. Moreover, the barrier should be designed for an impact load of (100 kips). However, it must be noticed that these conclusions are for school buses, which are more susceptible than other types of vehicles such as trucks with similar masses (Hirsch, 1986). Thus, the minimum height and the impact load for single-unit trucks which are intended in this research, can be less than these amounts.

In another research carried out by Sheikh *et al.* (2012), a full-scale crash test with the criteria of the new TL-4 in MASH has been performed in order to evaluate the impact load of the test. The crash test was executed on a single-sloped concrete barrier of 915 mm (36 in). The test report was provided, results were acceptable as the vehicle did not roll over the barrier. However, the impact load resulting from the crash test was not provided in the report. The authors concluded a barrier with a minimum height of 915 mm (36 in) is required for TL-4 of MASH.

3 Numerical Analysis

The impact load for crash tests can be calculated using equations provided by Olson *et al*. in 1970. The average deceleration and impact load can be calculated based on the principles of dynamics. In Equation (2) the average deceleration is given. Consequently, the average impact load can be determined by multiplying the average deceleration by the mass of the vehicle, as shown in Equation (3).

[2] $$a_{lat.} = \frac{V^2 \sin^2\theta}{2[AL\sin\theta - B(1-\cos\theta) + D]}$$

[3] $$F_{lat.} = Ma_{lat.} = \frac{M \cdot V^2 \sin^2 \theta}{2[AL \sin\theta - B(1-\cos\theta) + D]}$$

Where a_{lat}. is the average deceleration (m/s²), V is the impact speed (m/s), θ is the impact angle (degrees), AL is the distance from vehicle's front to the center of mass (m), B is half of the vehicle's width (m), D is the lateral displacement of the barrier railing (m), F_{lat} is the average lateral impact load (N) and M is the vehicle mass (kg). It must be noted that the amount of D for concrete barriers is zero, which is considered in this study.

Based on Olson's work, Hirsch's equation can be utilized for evaluating the maximum lateral impact load (Max F_{lat}) of small vehicle crashes as follows:

[4] $$Max\ F_{lat} = (\pi / 2) F_{lat}$$

Where F_{lat} is the average impact load of a vehicle crashing into the barrier of the bridge. As stated, this equation can be taken into account for small vehicles, however, it was suggested that the maximum impact load for trucks and buses with a speed of 96 km/h (60 mph) and 15 degrees of impact angle, is about 78% higher than the amount evaluated from Equation (4) (Hirsch, 1986).

Additionally, two approaches of numerical analysis were provided by Saez *et al.* (2012). The first approximation includes a simulated mass-spring model and a mathematical model that is provided in NCHRP Report 86 (Olson et al., 1970). This method considers the influence of changes in vehicle mass, impact speed and angle through a dimensional analysis which is provided in Equations [5] through [7]. Some assumptions are needed for utilizing this method, such as constant acceleration in both lateral and longitudinal directions, vehicle not being snagged by the barrier, neglecting the vehicle rotation, and movement of the center of mass of the vehicle with the entire vehicle (Saez *et al*., 2012).

[5] $$\frac{F_2}{F_1} = \frac{a_2}{a_1} = f\left[\sqrt{\frac{K_2}{K_1}}; \sqrt{\frac{W_2}{W_1}}\right]$$

[6] $$\frac{F_2}{F_1} = \frac{a_2}{a_1} = f\left[\left(\frac{V_2}{V_1}\right)^2; \left(\frac{\sin\theta_2}{\sin\theta_1}\right); \left(\frac{A_1 L_1}{A_2 L_2}\right)\right]$$

[7] $$F_2 = F_1 \times \left[\frac{V_2}{V_1}\right]^2 \left[\frac{\sin\theta_2}{\sin\theta_1}\right] \left[\frac{A_1 L_1}{A_2 L_2}\right] \left[\sqrt{\frac{K_2}{K_1}}\right] \left[\sqrt{\frac{W_2}{W_1}}\right]$$

Where F is impact load, a is lateral acceleration, V is impact speed of the vehicle, θ is impact angle of the vehicle, AL is distance from the front of the vehicle to its center of mass, K is stiffness of the system (vehicle and barrier) and W is mass of the vehicle. In this case, the conditions of NCHRP Report 350 for TL-4 can be considered for sub-index 1, and the conditions of MASH TL-4 can be considered for sub-index 2 in the abovementioned equations.

Other than the parameters of Vi, θi and Wi that are different between NCHRP Report 350 TL-4 and MASH TL-4, the ratio of A_1L_1/A_2L_2 can be considered equal to 1 as there are no changes in the dimensions of the vehicle assumed, and the ratio of K_2/K_1 can be assumed equal to the heights of the barriers in two conditions (h_2/h_1), since the materials are not changed (Saez *et al., 2012*). The results provided by Saez *et al.* show that the impact load of MASH TL-4 is to be 357.5 kN (80.3 kips). In the other approach that was given in the same research, the approximate impact load can be calculated by multiplying the total mass of the vehicle by the lateral acceleration of the vehicle at the center of mass as shown in Equation [8].

[8] $$F_{impact} = m_{total} \times a_{lat}$$

By implementing the values from the successful MASH TL-4 test from Saez *et al.*, the impact load can be evaluated as F_{impact} = 10000 kg × 4.4 m/sec² = 440 kN (99 kips).

4 Software Simulation

In a study carried out by Saez *et al.* (2012), software modelling for TL-4 and TL-5 barriers have been provided using LS-DYNA software and Finite Element (FE) analyses techniques. Ford F800 Series truck which meets the specifications of the 8000S vehicle type in NCHRP Report 350 was used in this study. However, it was modified in order to get the results for the Single-unit truck (10000S) type vehicle indicated in MASH. The analytical study in their research included modelling the vehicle impacting bridge barrier at a speed of 90 km/h and an angle of 15 degrees. The magnitude of impact load of the tests, along with distributions of lateral impact load in vertical and longitudinal directions were evaluated. Different tests were conducted on the software for concrete barriers with different wall heights changing from 915 mm (36 in) to 1070 mm (42 in). The results are shown in Table 4 Where parameters L_t and H_e are the distribution length of the transverse force (F_t), and the height of the same force, respectively.

Table 4: MASH TL-4 Impact Loads from FE Modelling (Saez *et al.*, 2012)

Design forces	Barrier height – mm (in)			
	915 (36)	990 (39)	1070 (42)	Rigid Wall
Transverse force (F_t) – kN (kips)	298.9 (67.2)	321.6 (72.3)	351.9 (79.1)	415.0 (93.3)
Longitudinal force (F_L) – kN (kips)	96.1 (21.6)	105.0 (23.6)	119.2 (26.8)	122.3 (27.5)
Vertical force (F_v) – kN (kips)	168.1 (37.8)	145.5 (32.7)	97.9 (22)	N/A
Longitudinal force distribution (L_L) – m (ft)	1.2 (4)	1.5 (5)	1.5 (5)	4.3 (14)
Vertical height of resultant force (H_e) – mm (in)	637.5 (25.1)	729.0 (28.7)	767.0 (30.2)	1155.7 (45.5)

In the aforementioned study, impact loads for designing concrete bridge barriers for MASH TL-4 were recommended. The transverse impact load, which is the principle design load that is considered for designing bridge barriers, was suggested as 355.9 kN (80 kips). Moreover, it was indicated that a minimum height of 915 mm (36 in) is required for MASH TL-4 considering the impact load provided as a result of the analyses performed. Other recommended load values by Saez *et al.* for MASH TL-4 is given in Table 5 Where L_v is the length of application for the vertical force (F_v).

Table 5: Design Recommendations for MASH TL-4 By Saez *et al.* (2012)

Design Specification	MASH TL-4 Recommendations
Barrier Height – mm (in)	≥ 915 (36)
Transverse force (F_t) – kN (kips)	355.9 (80)
Longitudinal force (F_L) – kN (kips)	120.1 (27)
Vertical force (F_v) – kN (kips)	169.0 (38)
Longitudinal force distribution (L_L) – m (ft)	1.2 (4)
Vertical force distribution (L_v) – m (ft)	5.5 (18)
Vertical height of resultant force (H_e) – mm (in)	762.0 (30)

In a similar research conducted by Sheikh *et al.* (2011), a series of crash tests has been modelled with the criteria of MASH TL-4 as well as those available in NCHRP Report 350, considering concrete single-sloped barriers, for the sake of comparison. MASH TL-4 test was modelled for five different heights of a single-sloped concrete barrier, namely: 915 mm (36 in), 940 mm (37 in), 965 mm (38 in), 990 mm (39 in) and 1070 mm (42 in). The results obtained from LS-DYNA software included three diagrams of roll angle, pitch angle and yaw angle (degrees), with respect of time (sec). Considering the results provided in this study, an impact design load of 329.2 kN (74 kips) was recommended by the authors for MASH TL-4. Furthermore, another FE model was simulated for an 810 mm (32 in) tall barrier with the criteria of NCHRP Report 350 TL-4 in order to compare the impact load with previous tests. Figure 1 presents summary of transverse impact loads for different vehicle masses with similar speed and impact angle obtained from different literature in this paper.

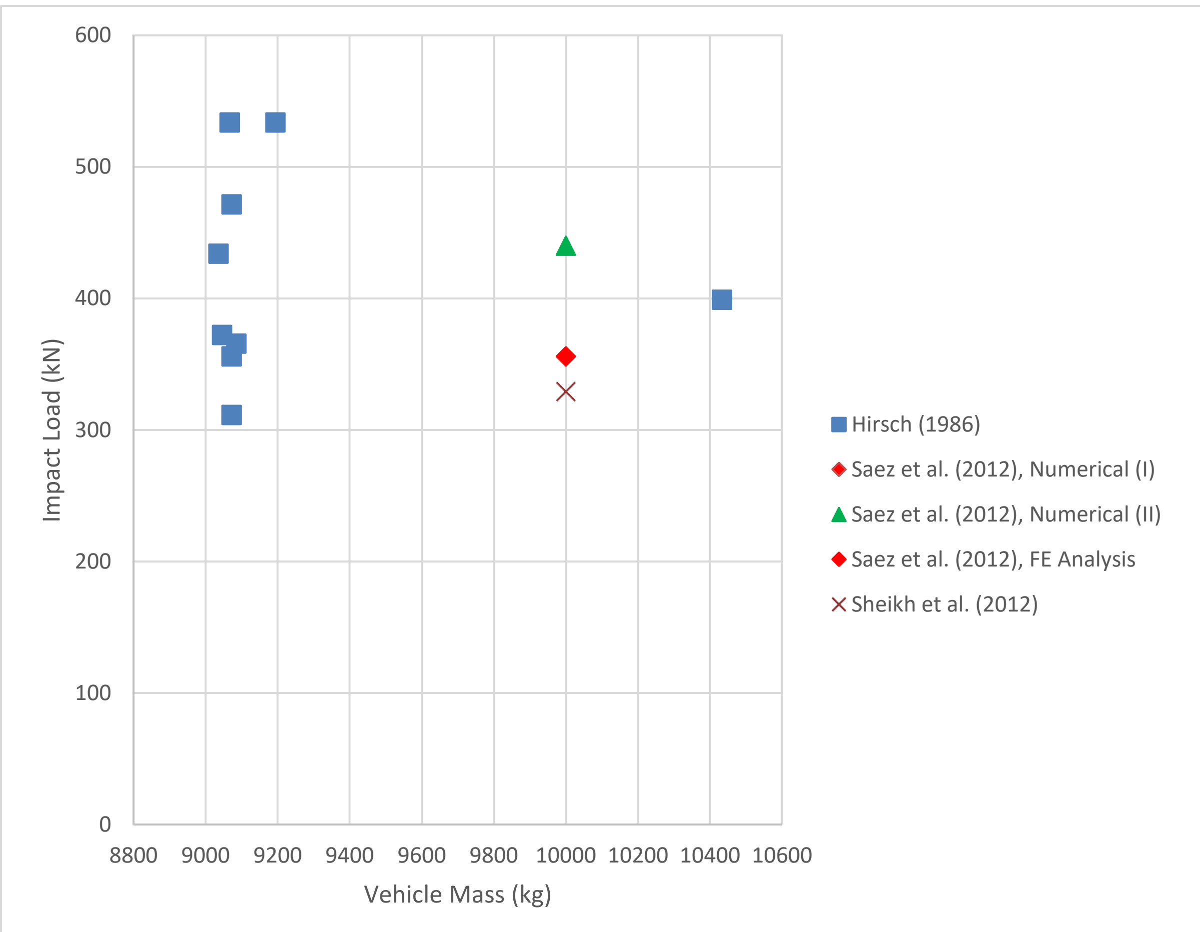

Figure 1: Summary of Impact Loads for Different Vehicle Masses with Similar Speed and Impact Angle

5 Recommendations for CHBDC Revision

Based on the results provided in previous researches mentioned earlier in this paper, it can be concluded that the current barrier design dimensions given in CHBDC for test level 4 is not safe for the impact, and it is likely that the crash of a 10000S single-unit truck with updated criteria in MASH will result in roll-over of the truck. Thus, new dimensions recommended for CHBDC along with the current CHBDC values are given in Table 6. As shown in the table, all variables will increase except L_v (the distribution length of the vertical force), which remains at 5500 mm. The most important variables in Table 6 are the transverse impact load

(F_t) which changes from 100 to 150 kN and the height of the barrier (H_1) which changes from 800 to 915 mm. It should be noted that impact loads given in the table are unfactored and the dynamic effect is not included. For example, the transverse impact load (F_t) which is recommended to be increased to 150 kN should be multiplied by 1.7 as live load factor to obtain the factored transverse force of 255 kN in lieu of 170 kN currently specified in CHBDC. The different height variables listed in Table 6 are shown in Figure 2 for clarity. Figure 3 shows the applied equivalent impact forces at interior and exterior locations of the longitudinal barrier wall.

Table 6: Final Design Recommendations and Comparison with CHBDC 2014

Specifications	Current Design in CHBDC 2014 for TL-4 based on NCHRP Report 350	Recommended Design for MASH TL-4
Height from top of asphalt to top of the barrier (H_1) – mm	800*	915
Height from top of concrete to top of the barrier (H_2) – mm	890	1005
Height from top of asphalt to impact load location (H_3) – mm	700**	760
Height from top of concrete to impact load location (H_4) – mm	790	850
Transverse force (F_t) – kN	100	150
Longitudinal force (F_L) – kN	30	50
Vertical force (F_V) – kN	30	70
Transverse force distribution (L_t) and Longitudinal force distribution (L_L) – mm	1050	1220
Vertical force distribution (L_v) – mm	5500	5500

*Table 12.8, Chapter 12, page 560, CHBDC 2014
**Figure 12.1, Chapter 12, page 562, CHBDC 2014

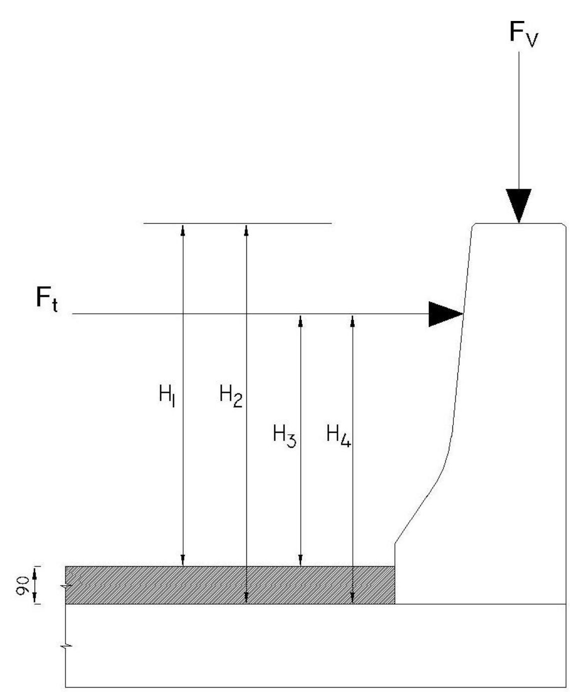

Figure 2: Dimensions of Recommended Barrier for MASH TL-4

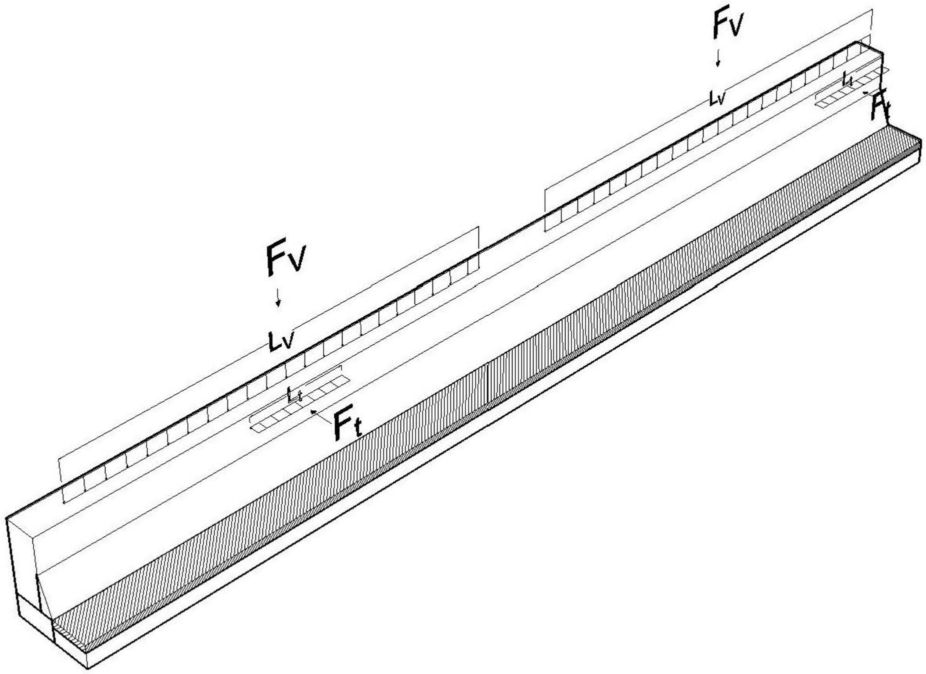

Figure 3: Impact Loads at Interior and Exterior Locations of the Barrier

6 Summary and Conclusions

The 2009 AASHTO Manual for Assessing Safety Hardware (MASH) specifies new crash test requirements for TL-4 barrier with higher values of truck weight and speed than those specified in CHBDC of 2014. In MASH, the single-unit vehicle weight increased from 8000 to 10,000 kg and the impact speed increased from 80 to 90 km/h while the impact angle is kept at 15º to the barrier longitudinal direction. This paper presents a literature review of various studies on the determination of equivalent loads to vehicle impact to design TL-4 barriers, including computer modelling and full-scale crash tests with specifications similar to the new criteria of TL-4 in MASH. Based on these studies, it is concluded that the impact loads for TL-4 with new impact conditions are significantly increased. Therefore, new impact loads are suggested for TL-4 barrier for possible inclusion in the 2019 version of the Canadian Highway Bridge Design Code in order to meet the requirements for TL-4 bridge barrier specified in MASH. The proposed changes include the amount of transverse, longitudinal and vertical equivalent impact loading as well as the height of impact point and distributed lengths of such loadings. In conclusion, this study suggests a factored impact load of 255 kN which is 50% higher than the impact load currently specified in CHBDC of 2014. However, the load distribution length is suggested to increase from 1050 mm to 1220 mm. Also, the barrier minimum height over the asphalt surface is suggested to be 915 mm in lieu of 800 mm specified in CHBDC of 2014. Moreover, the height from top of the asphalt to impact load location is suggested to increase from 700 to 760 mm. A summary of the proposed changes to CHBDC of 2014 is listed in Table 3.

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