Dynamic Load Allowance Provisions for Box Culverts with Low Fill Depth

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ABSTRACT

It is well established that vehicular traffic traveling over bridge-like structures can impart a dynamic load effect that is greater than vehicles' static weight alone. In order to account for this increased load, bridge design codes use a factor known as the dynamic load allowance (*IM*) to amplify static vehicular live loads. In the current version of the American Association of State Highway and Transportation Officials (AASHTO) Manual for Bridge Evaluation (MBE), reductions in *IM* are allowed for bridges having span lengths greater than 12.2 m with road surfaces in good condition. In addition, the current AASHTO LRFD Bridge Design Specifications allow for a reduced *IM* for culverts with higher fill depth. However, many culverts have neither span lengths greater than 12.2 m nor higher fill depths and thus are not eligible for such *IM* reductions. This paper investigated whether similar *IM* reductions can be considered for culverts with smaller span lengths and fill depths. The Field experiments conducted suggest that culverts having span lengths less than 12.2 m and fill depths less than 0.5 m could be considered for similar *IM* reductions allowed by the MBE.

Keywords: dynamic load allowance, load amplification, buried culverts, load rating, fill depth.

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INTRODUCTION

Load rating is the process by which bridge type structures are evaluated for their ability to service traffic. Unlike in design, load ratings use information gathered during field inspections to inform the structural analysis and thus are based on existing conditions, rather than potential future conditions. The result of a load rating is a rating factor (*RF*), which is the ratio of a structure's available load capacity to the live load demand. The American Association of State Highway and Transportation Officials (AASHTO) Manual for Bridge Evaluation (AASHTO 2011) defines *RF* as:

$$RF = \frac{C - \gamma_{DC}(DC) - \gamma_{DW}(DW) \pm \gamma_P(P)}{\gamma_{LL}(LL + IM)} \quad (1)$$

Where:

C = Capacity

DC = Dead load due to components

DW = Dead load due to the wearing surface and utilities

LL = Live load

P = Permanent load

γ_{DC} = Dead load components factor

γ_{DW} = Dead load wearing surface and utilities factor

γ_{LL} = Live load factor

γ_p = Permanent load factor

IM = Dynamic load allowance

If the calculated value of *RF* is found to be less than one, the structure’s capacity is less than the demand and the weight of vehicles allowed to cross the structure must be restricted.

All loads used in (1) are considered static; however, it is known that moving vehicles drive a load pulse through the structure that can induce force effects greater than the static live load alone. As a result, *IM* is used to amplify the static live load to account for these affects. Experimentally, *IM* for a structure can be determined as the ratio between the dynamic increment (i.e., Dynamic response (R_{Dyn}) minus the static response (R_{stat})) and the static response:

$$IM = \frac{R_{Dyn} - R_{stat}}{R_{stat}} \quad (2)$$

Over the past 150 years, much research has been conducted examining the dynamic behavior of bridges (McLean and Marsh 1998). Bridges are defined as longitudinal structures that have a span length greater than 12.2 m (FHWA 1995). For bridges, *IM* has primarily been seen as a function of road surface roughness and the ratio between a bridge's natural frequency and the natural frequency of the vehicle loading the structure (AASHO 1962; Billing 1984; Tilly 1986; Hwang and Nowak 1991; Paultre et al. 1992; Nowak 1999; Wekezer et al. 2010). In addition, it has been recognized that trucks typically oscillate at two dominant frequencies: one between 2 and 5 hertz; and another between 10 and 15 Hz (Csagoly et al. 1972; Cantieni 1984; Tilly 1986).

Surface roughness and future wearing of surface conditions are difficult to estimate during design. The AASHTO LRFD Bridge Design Specifications (AASHTO 2012) define *IM* as 0.33. Additionally, during the load rating of longitudinal members over 12.2 m in length, AASHTO (2011) allows for a reduction in *IM* to 0.20 and 0.10 for bridges with only minor surface deviations and smooth riding surfaces, respectively. The difficulty of estimating surface conditions could also make it difficult to accurately determine a bridge's natural period, particularly over time where joint conditions can vary.

Reinforced concrete box culverts (RCBC) are similar to bridges in many ways and fall under AASHTO (2011, 2012) specifications for load rating. The two primary differences between culverts and conventional bridges are that culverts are designed to function at full hydraulic capacity and are typically—but not always—covered by soil (FHWA 1995). While plenty of data exists on the dynamic behavior of bridges, only a handful of studies have examined culverts due to the relatively low hazard and risk of culvert failure as well as the relatively small cost of construction. During the inspection and load rating process, performed in the state of Delaware, some RCBC that appeared to be in good condition upon inspection received load ratings that are less than one. When load ratings fall below one, the customary measure is to post the RCBCs with vehicle weight restrictions.

In 1926, Spangler et al. (1926) experimentally examined the effects of live load on small, circular culverts (exact dimensions not given) under static and dynamic conditions. For the dynamic tests, trucks were driven at speeds between 0 and 4.5 m/s and fill depths ranged between 0.6 and 3.7 m. During these tests, significant rutting was present due to the lack of pavement on roads at that time. Consequently, an *IM* of 0.5 to 1.0 was recommended to account for rough road surfaces.

More recently, (Manko and Beben 2008) dynamically tested a corrugated steel bridge in Sweden, examining the influence of vehicle speed, road surface roughness, and vehicle braking. The logarithmic decrement of damping was also recorded. The bridge had an effective span length of 12.3 m and the combined depth of fill and pavement was 1.0 m. *IM* calculated in the longitudinal direction of the bridge ranged between 0.05 and 0.31. The largest and smallest *IM* were calculated for vehicle speeds of 10 km/h and 50 km/h, respectively. *IM* values calculated for braking ranged between 0.18 and 0.20. To test the effects of road surface roughness, a plank (or threshold) was placed in the roadway to simulate a large surface deformation or discontinuity. *IM* values calculated for threshold tests ranged between 0.15 and 0.20. Values of the logarithmic decrement of damping ranged from 0.028 to 0.427, with an average of 0.14. Based on these results, damping can be calculated to range between 0.004 and 0.068, with an average of 0.023.

In 2012, Beben (2013) also conducted a series of experimental dynamic load tests on four corrugated steel culverts—two pipe culverts and two box (or arch) culverts. Culverts had varying span lengths and fill depths. During these tests, culverts were instrumented at quarter points with both strain gauges and inductive gauges to measure vertical displacement. Static displacements were determined both by stopping a loaded truck at critical points along the culvert and by filtering the dynamic test data. Dynamic tests were conducted at vehicle speeds of 10 km/h to 70 km/h in increments of 10 km/h. Results showed good agreement between methods for determining the culverts' static response.

Generally, the dynamic filtration method produced higher static loads (and thus lower *IM* values). However, differences were not greater than four percent. Vehicle speeds of 60 km/h produced the highest *IM* in each test, ranging from 0.12 to 0.26 for displacements and 0.11 to 0.29 for strains. It was also determined that *IM* increased as span length increased. Additionally, *IM* decreased as fill depth increased. Of the two parameters, fill depth was more influential on *IM*. Beben (2013) also observed that the relationship between *IM* and the ratio of fill depth to span length is approximately linear.

Chen and Harik (2012) used finite element modeling to examine the dynamic amplification of a buried concrete arch culvert due to truckloads. Parameters considered were vehicle speed, road surface roughness, concrete damping ratio, pavement type, and the ratio between truck suspension frequency and culvert frequency. All materials were considered linear elastic and damping was only applied to the concrete culvert. Results showed that dynamic amplification as a function of truck velocity fluctuates considerably between velocities of 5 and 55 m/s. In some instances, *IM* fluctuates over 100 percent. A change in damping coefficient from 4 to 1 percent caused the maximum *IM* to increase from 0.10 to 0.34. Good agreement was observed between concrete and asphalt pavement models. Road surface roughness had a considerable effect on *IM* (Wells 2016). For roads in "perfect" condition, an *IM* of 0.05 was observed for a truck traveling 20 m/s, while a road in extremely poor condition yielded an *IM* of 1.00. The influence of a truck's suspension was also tied to road surface conditions. For roads in "perfect" condition, the ratio between the truck and culvert's natural frequencies had virtually no effect on *IM*. However, poor road conditions caused *IM* to vary from approximately 0.18 to 1.20 for ratios close to 1.0.

Wells (2016) also performed a parametric finite element analysis examining dynamic loads on culverts. In total, he considered 324 different two-dimensional culvert models. The average natural frequency observed was 35.7 Hz with a standard deviation of 14.7 Hz. Consequently, it is not anticipated that most culverts will experience resonance with trucks.

Despite the small amount of research on this topic that has produced varying results, it has been generally accepted for several decades that *IM* decreases as fill depth increases. According to AASHTO (2012) *IM* decreases according to the equation:

$$IM = 33(1.0 - 0.125D_E) \geq 0\% \qquad (3)$$

Where D_E is the fill depth measured in feet.

This paper examines the suitability of the current specifications for load rating culverts with short span lengths and small fill depths. Experimental work, that involved a selection and field testing of five culverts in the state of Delaware, was designed and executed to investigate whether *IM* reductions can be considered for culverts with smaller span lengths and fill depths.

DESCRIPTION OF CULVERTS

The five culverts tested in this study are located in northern Delaware. Table 1 gives the geometric properties of each culvert. Fill depths range from 0 to 0.5 m, span lengths range from 3 m to 7.7 m, slab thicknesses range from 0.3 m to 0.76 m and pavement thicknesses range from 0.07 m to 0.44 m. Table 2 gives the construction type, number of marked lanes, pavement type, roadway condition and roadway approach angle of the five culverts tested. As can be seen, several different construction types were chosen. This was done in order incorporate the behavior of a variety of RCBC foundation and construction types. In all culvert locations, the pavement type was asphalt and the roadway was observed to be in good, smooth conditions. The inside of a typical four sided box culvert is shown in Figure 1.

Table 1 Culvert Geometric Properties

Culvert No.	Fill Depth (m)	Span Length (m)	Slab Thickness (m)	Pavement Thickness (m)
1	0.38	3.00	0.30	0.23
2	0.50	4.30	0.30	0.15
3	0.41	5.50	0.51	0.20
4	0.00	7.70	0.38	0.44
5	0.00	6.40	0.76	0.07

Table 2 Culvert Construction Types and Roadway Conditions

Culvert No.	Construction Type	Total Marked Lanes	Roadway Approach Angle
1	Cast-in-place, four-sided box	2	10^0
2	Precast, four-sided box	2	0^0, curved
3	Cast-in-place, three-sided box	4	9^0
4	Precast, three-sided box	2	0^0
5	Precast, three-sided box	2	0^0

Fig. 1 Typical Box Culvert

It is important to note that all culverts tested have roadway surfaces in good condition. As a result, they would be eligible for a reduced *IM* of 0.1 if their span lengths were over 12.2 m according to AASHTO (2011). Additionally, fill depths are less than 0.5 m. Thus, they are eligible for little reduction in the *IM* prescribed by AASHTO (2012).

TEST PROCEDURES

When testing each culvert, the roadway was broken into what is referred to as three "tested" lanes—one in each marked lane and one directly over the marked centerline. Because *IM* is a ratio of the dynamic increment to the static response, fully loaded dump trucks were driven across the culverts at typical (or "dynamic") vehicle speeds of 8.9, 13.4 and 17.9 m/s and a quasi-static speed of 2.2 m/s. Table 3 shows the number of passes planned at each vehicle speed and lane. Fewer dynamic passes were conducted for Culvert 1 than for Culverts 2 through 5. This is because Culvert 1 was tested first, after which it was determined that more dynamic passes were necessary.

In each pass, two trucks are driven across the culvert. Trucks are spaced far enough apart so that their loads do not interfere with one another. Table 4 shows the weight of the trucks used.

Table 3 Planned Organization of Tests

Culvert No.	Speed (m/s)	Number of Truck Passes		
		Lane 1	Lane 2	Lane 3
1	2.2	2	2	2
	8.9	-	1	-
	13.4	1	1	1
	17.9	-	1	-
2-5	2.2	2	2	2
	8.9	2	2	2
	13.4	2	2	2
	17.9	2	2	2

Table 4 Truck Weight

Culvert	Truck 1 (kN)	Truck 2 (kN)
1	283	282
2	304	295
3	252	274
4	258	251
5	235	242

INSTRUMENTATION

The five culverts tested in this study were instrumented with a Bridge Diagnostics Inc. (BDI), Structural Testing System (STS), which includes quick mount strain transducers, data acquisition system and software. A typical instrumented setup is shown in Figure 2. The BDI strain transducers have a 76 mm (3 in.) gauge length. The data acquisition was performed at 100 Hertz data sampling rate. This rate was found adequate to capture the peak strain responses. In many instances 229 mm (9 in.) steel extensions were placed on the sensors to increase the gauge length to 305 mm (12 in.). This is recommended when testing concrete. The transducer/extension apparatus had steel feet at both ends that were used to mount the sensor to the culvert. Transducers were affixed to the culvert using high viscosity, rubber toughened cyanoacrylate glue applied with an accelerant. Prior to mounting the sensors, the surface was prepared using a wire brush or grinder when necessary.

In several tests, it was attempted to use string potentiometers to measure displacement; however deflections were so small that results could not be distinguished from ambient noise. For that reason, only strain measurements are reported and discussed in this paper.

Fig. 2 Typical instrumented culvert

For each test, two marked lanes were instrumented and tested. The marked lanes were then broken down into the three tested lanes mentioned previously. Strain gauges were placed at the center and edges of the three tested lanes. Thus, at least five sensors are placed on each culvert. For culverts constructed of precast sections (Culverts 2, 4 and 5), strain gauges were also placed at the center of box sections when one of the original five sensors was located near a joint between sections. Figures 3 – 7 show the sensor layout for the five culverts tested. Culvert 1 was instrumented with five sensors, Culvert 2 was instrumented with eight sensors, Culvert 3 was instrumented with five sensors, Culvert 4 was instrumented with eight sensors and Culvert 5 was instrumented with seven sensors. The center of each tested lane is shown as x_1, x_2 and x_3, respectively.

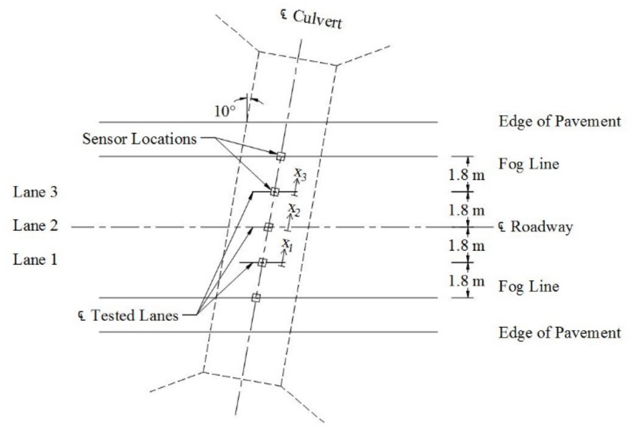

Fig. 3 Culvert 1 Sensor Locations

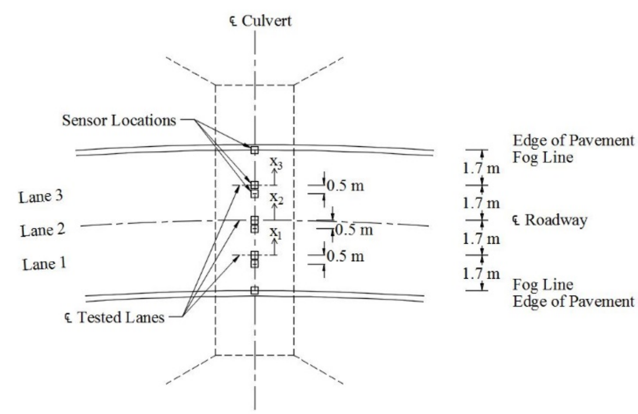

Fig. 4 Culvert 2 Sensor Locations

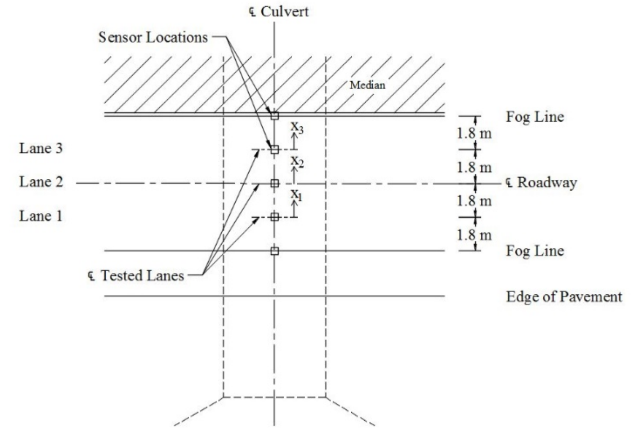

Fig. 5 Culvert 3 Sensor Locations

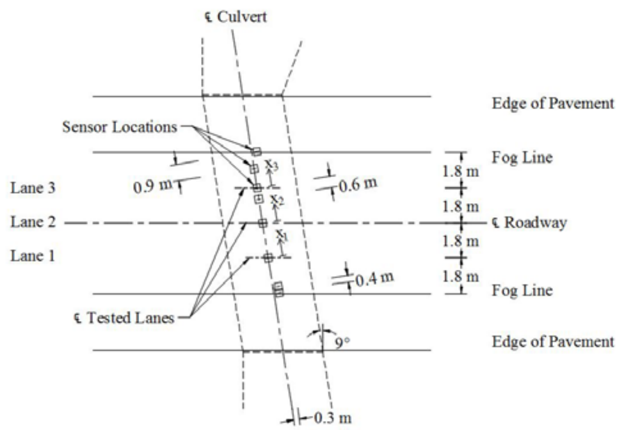

Fig. 6 Culvert 4 Sensor Locations

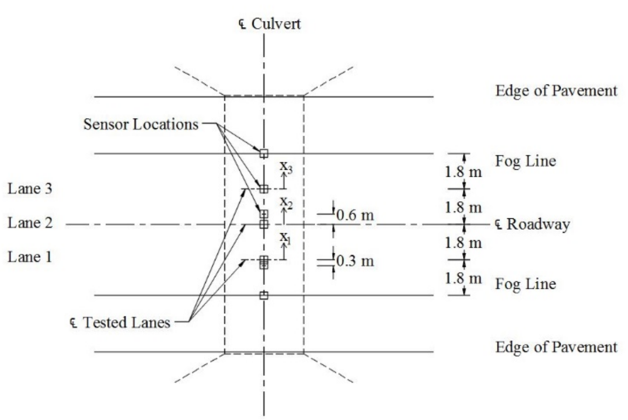

Fig. 7 Culvert 5 Sensor Locations

DETERMINATION OF *IM*

The goal for each load test is to determine an *IM* for each culvert. Since only strain data was found to be useful during testing, *IM* is calculated at every sensor location according to the equation:

$$IM = \frac{\varepsilon_{Dyn} - \varepsilon_{stat}}{\varepsilon_{stat}} \quad (4)$$

Where:

ε_{Dyn} = Dynamic strain

ε_{stat} = Quasi-static strain

Figure 8 shows an example of strain due to Truck 1 in Lane 2 collected during the testing of Culvert 2 at x_2 = 0 m. Figure 9 shows a typical test truck that was used in this study. The two quasi-static passes and one dynamic pass are shown. In all passes a smaller load—the front axle—can be identified as crossing the culvert first and a larger load—a combination of the two rear axles— can be identified crossing second.

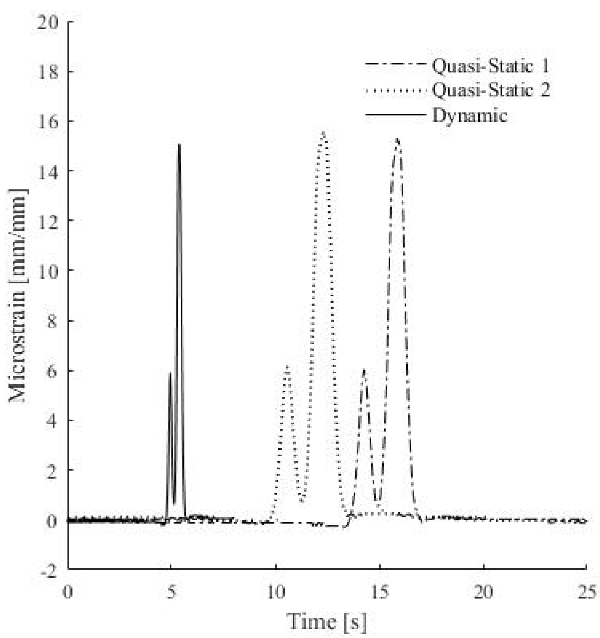

Fig. 8 Time History Analysis of Strain in Lane 2 of Culvert 2 due to Truck 1

Fig. 9 Typical Truck Used for Field-Testing

As indicated in Table 2, two quasi-static passes are made by both trucks in each lane during all tests. The quasi-static strain used in (4) is the average of the maximum quasi-static strains recorded in each pass. This is done to minimize the influence of a potential outlier on the entire data set. The dynamic strain used in (4) is taken as the maximum strain recorded in a dynamic pass.

It should be noted that static strains recorded for truck 1 are only compared to dynamic strains recorded for truck 1, and vice versa, when calculating *IM*. The *IM* for each pass is taken at the location of maximum static strain. This is because the location experiencing the largest load is most critical when load rating a structure.

RESULTS

Culvert 1

When testing Culvert 1, one dynamic pass was made by each truck in lane 2 at 8.9 m/s, one pass was made by each truck at 17.9 m/s and one pass was made in each tested lane at 13.4 m/s. Ten total passes were completed. The maximum, average and standard deviation of *IM* values recorded were 0.0959, -0.0167 and 0.0909, respectively. Figure 10 shows the results observed during the testing of Culvert 1. The origin is taken at the center of the roadway. Thus, x_2 is at x=0 in Figure 3. The center of lane 1 is -1.8 m, the center of lane 2 is 0 m and the center of lane 3 is 1.8 m.

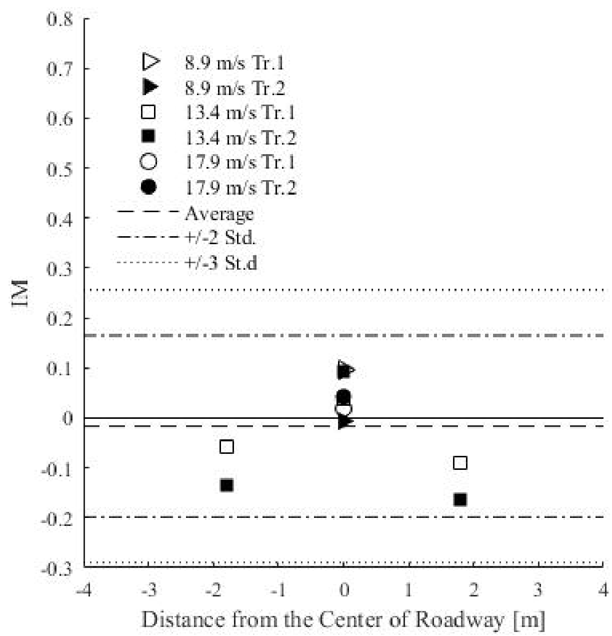

Fig. 10 Culvert 1 Results

Culvert 2

Two dynamic passes were planned for each truck in the three tested lanes during the testing of Culvert 2. However, truck 2 broke down during testing. Consequently, it did not complete one pass in lane 3 at 17.9 m/s and did not complete any passes at 8.9 m/s. As a result, only 29 of the planned 36 total passes were completed. The maximum, average and standard deviation of *IM* values recorded during the 29 passes were 0.0322, -0.0797 and 0.0605, respectively. Only two instances were observed when the *IM* at the location of maximum static strain was greater than zero. Figure 11 shows the results observed during the testing of Culvert 2. It should be noted that the maximum static and dynamic strains observed in lane 2 were recorded at -0.5 m from the center of the roadway.

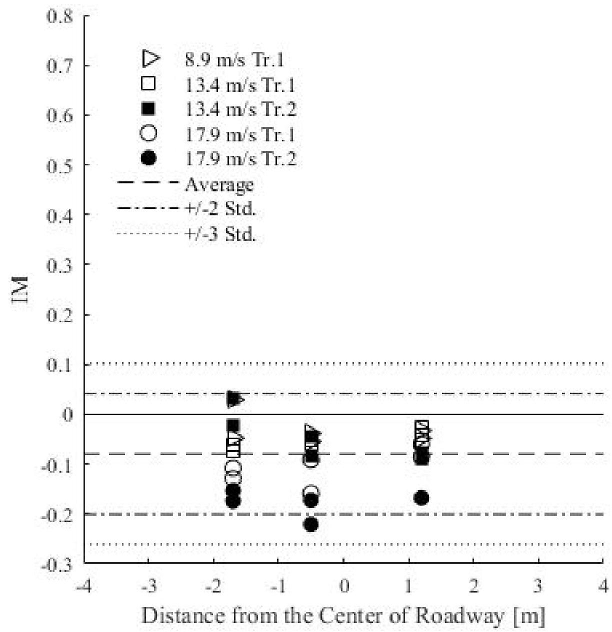

Fig. 11 Culvert 2 Results

Culvert 3

Two dynamic passes were planned for each truck in the three tested lanes during the testing of Culvert 3. Thirty-six total passes were completed. The maximum, average and standard deviation of *IM* values recorded during the 36 passes were 0.1266, -0.0345 and 0.0737, respectively. Figure 12 shows the results observed during the testing of Culvert 3. It should be noted that the maximum static and dynamic strains observed in lane 3 were recorded 3.6 m from the center of the roadway.

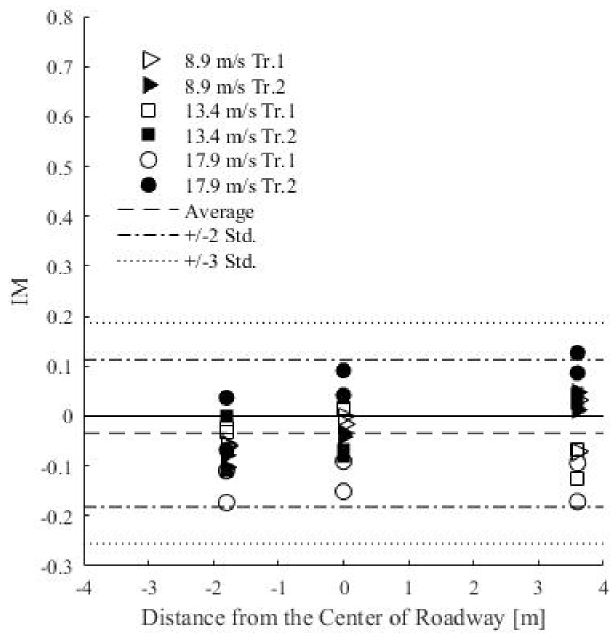

Fig. 12 Culvert 3 Results

Culvert 4

Two dynamic passes were planned for each truck in the three tested lanes during the testing of Culvert 4. As a result, 36 total passes were completed. The maximum, average and standard deviation of *IM* values recorded during the 36 passes were 0.0543, -0.0446 and 0.0474, respectively. Figure 13 shows the results observed during the testing of Culvert 4. It should be noted that the maximum static and dynamic strains for both lane 1 and lane 2 were recorded at 0 m from the center of the roadway.

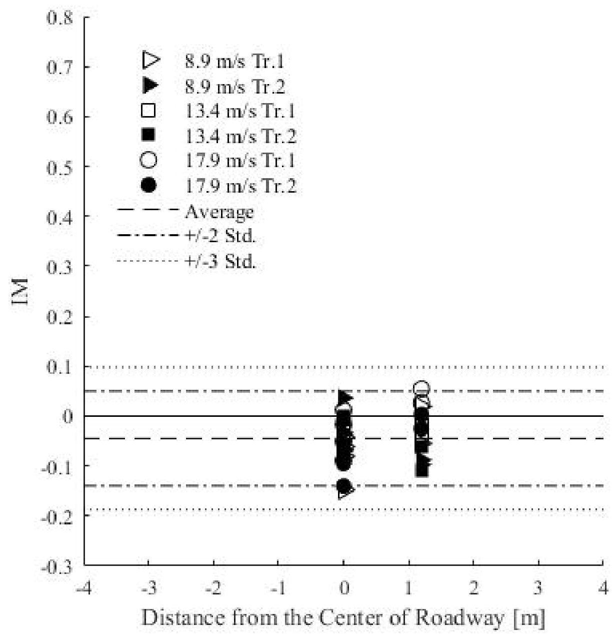

Fig. 13 Culvert 4 Results

Culvert 5

Two dynamic passes were planned for each truck in the three tested lanes during the testing of Culvert 5. However, an error occurred during one of the tests in lane 1 at 8.9 m/s. As a result, data is only available for 34 of the 36 passes completed. The maximum, average and standard deviation of *IM* values recorded during the 34 passes were 0.1978, 0.0136 and 0.0704, respectively. Figure 14 shows the results observed during the testing of Culvert 5. It should be noted that the maximum static and dynamic strains for both lane 1 and lane 2 were recorded at -1.8 m from the center of the roadway and the maximum static and dynamic strains for lane 3 were recorded at 3.6 m from the center of the roadway.

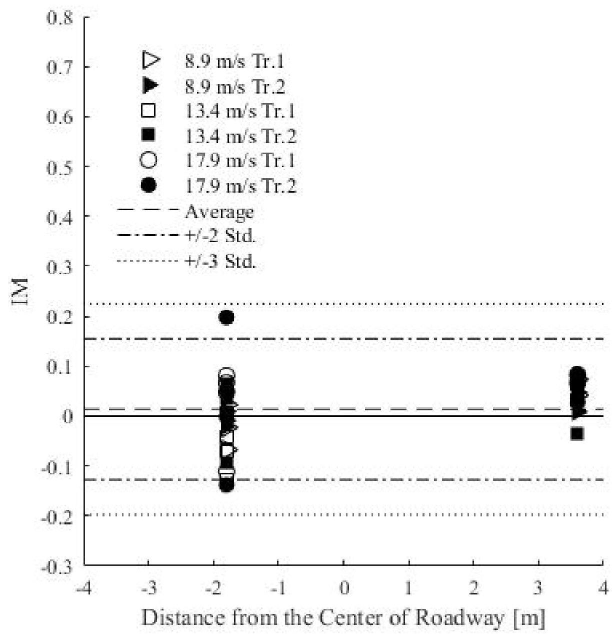

Fig. 14 Culvert 5 Results

Combined Results

Table 5 shows the maximum *IM*, average *IM*, standard deviation of *IM*, average *IM* plus two standard deviations, the average *IM* plus three standard deviations and the total number passes completed for the five culverts tested as well as the combined results. The maximum *IM* of 0.1978 was recorded during the testing of Culvert 5 and the average *IM* value of all passes was -0.0335. Assuming results are normally distributed, the average plus two standard deviations has a 2.5 percent probability of exceedance and the average plus three standard deviations has a 0.15 percent probability of exceedance. Thus, the average *IM* plus three standard deviations represents the statistical maximum *IM*. Accept for Culvert 5, the average plus two standard deviations better approximates the maximum observed *IM*. The average plus two standard deviations of all test results is 0.1111 and the average plus three standard deviations of all test results is 0.1835.

Table 5 Combined *IM* Results

	Fill Depth	Maximum *IM*	Average *IM*	Std. Deviation *IM*	Avg. +2 Std. Deviation *IM*	Avg. +3 Std. Deviation *IM*	Total Passes
Culvert 1	0.38	0.0959	-0.0167	0.0909	0.1651	0.2560	10
Culvert 2	0.50	0.0322	-0.0797	0.0605	0.0413	0.1017	29
Culvert 3	0.41	0.1266	-0.0345	0.0737	0.1128	0.1865	36
Culvert 4	0.00	0.0543	-0.0446	0.0474	0.0501	0.0975	36
Culvert 5	0.00	0.1978	0.0136	0.0704	0.1544	0.2248	34
Combined	--	0.1978	-0.0335	0.0649	0.1111	0.1835	145

The relationship between the results of this study and fill depth in comparison to that prescribed by AASHTO (2012) are shown in Figure 15. All *IM* values observed during testing as well as their associated average *IM* plus three standard deviations are below those prescribed by AASHTO. AASHTO (2012) allows for a reduction in *IM* of 0.1353 *IM*/m. In comparison, the slope of the maximum, average plus two standard deviation, and average plus three standard deviation trendlines are -0.1145, -0.0239 and 0.0045 *IM*/m, respectively. While the slope of the maximum *IM* trendline is similar to that of the AASHTO reduction, the average plus two standard deviations and the average plus three standard deviations are nearly zero.

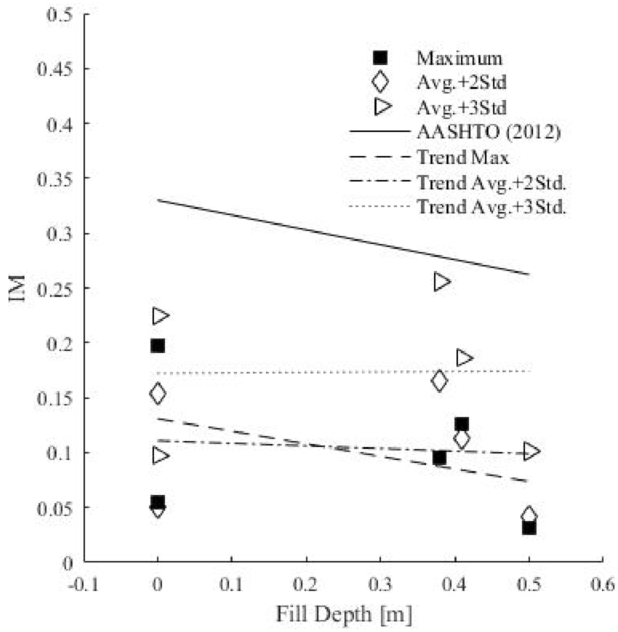

Fig. 15 *IM* as a Function of Fill Depth

DISCUSSION OF RESULTS

Given that the trendlines of the average plus two standard deviations and average plus three standard deviations both have a slope of approximately zero, it does not appear that depth of soil cover significantly influences *IM* for box culverts with cover less than 0.5 m. Additionally, the average *IM* plus two standard deviations is 0.1111 and the average *IM* plus three standard deviations is 0.1835. These values are 30 to 66 percent less than the range of *IM* values allowed by AASHTO (2012)—0.33 to 0.2624—and are more in line with the reductions allowed by AASHTO (2011) for bridges with road surfaces in good condition. The literature indicates that the two largest factors influencing the dynamic behavior of non-buried bridges are resonance and road surface roughness. Wells (2016) demonstrated that most culverts will not experience resonance with truck traffic due to their high natural frequencies. All culverts tested in this study also had road surfaces in good condition. Consequently, the observed results should be expected.

CONCLUSIONS AND RECOMMENDATIONS

This study examined the dynamic load allowance (*IM*) of culverts with span lengths between three and 7.7 m and fill depths between zero and 0.5 m. All road surfaces were in good condition. The *IM* for each truck pass was determined by taking the ratio of dynamic strain to static strain at the location of maximum static strain. The maximum *IM* observed during testing was 0.1978. The *IM* was -0.0335 on average, indicating that the typical dynamic loading condition will impart a lesser load to the culvert than will a static load. Additionally, an *IM* greater than 0.10 was not observed for three of the five culverts.

Based on a statistical analysis of results, *IM* changes little with respect to soil cover for box culverts with less than 0.5 m of fill present. This is a deviation from AASHTO (2012), which suggests that *IM* decreases as a result of increasing fill depth. Based on the limited results of this study and assuming results are normally distributed, 97.5 percent of *IM* values for culverts with little to no cover are expected to be less than 0.1111 and 99.85 percent of *IM* values are expected to be less than 0.1835. These results show good agreement with the reductions allowed by AASHTO (2011) of 0.2 and 0.1 for bridges with only minor surface deviations and smooth riding surfaces, respectively. Accordingly, it is recommended that a similar reduction be allowed for culverts with span lengths less than 12.2 m.

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