

A SMOOTHNESS PROVISION FOR BRIDGE DECKS

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ABSTRACT

This paper describes a contemporary survey of bridge ride quality and discusses its use to support the development of a modern smoothness provision for bridge decks. The survey found that bridges have an average of 60 percent more roughness than most mainline highway pavements (as measured through the International Roughness Index [IRI]). However, a secondary analysis revealed that beam and girder camber could easily contribute more than 1000 mm/km of IRI roughness, which suggests that IRI may not be an equitable tool for measuring construction quality of bridges. This finding led to an additional analysis that focused on a simulated rolling straightedge for use as a tool to control smoothness. Ultimately, the study demonstrated how inertial (and high-speed) profiling equipment can be applied to control bridge deck roughness through the use of a simulation that mimics the traditional 3-m straightedge.

INTRODUCTION

The results of a recent national highway user survey indicated that pavement condition was the top priority of the traveling public (1). Further interpretation of the survey suggested that anything that could be done to promote smoothness of the highway riding surface would provide the highest dividends in terms of overall user satisfaction. More generally, it can be said that the traveling public expects three important things from the highway surface: a smooth ride, adequate resistance to skidding, and sufficient strength to transfer the traffic loading to the next component of the roadway structure. These three requirements remain, regardless of whether the roadway surface is the top 50 mm of conventional asphalt concrete pavement or an integrally cast concrete deck for a 2000-m segmental-box bridge.

To the typical highway user, the designation of a riding surface as roadway pavement or bridge deck is not important. Ideally, only visual cues would allow a distinction. In reality, however, bridges often distinguish themselves by providing abrupt and acute examples of poor ride quality. During construction of a bridge deck, ride quality is rarely a primary consideration and often suffers as designers and constructors concentrate on addressing dead-load deflections, proper steel placement, and adequate cover depths. Beyond the deck, an inability to achieve adequate compaction near the abutments results in roadway approach embankments and approach slabs that are subject to excessive levels of settlement. The manifestation of this settlement dispenses an uncomplimentary “introduction” to many bridges and simply exacerbates what is too often an otherwise inferior riding experience.

Virginia’s *Road and Bridge Specifications* rely on the 3-m straightedge to control smoothness of newly constructed and/or overlaid bridge decks (2). This provision for smoothness reflects an assumption that the construction inspector is present and actively participating in the placement of the surface. Unfortunately, more often now than ever, state-force inspectors are simply not available to exercise this sort of “real-time” control. Add to this the inability of a 3-m device to perceive many significant features that contribute to roughness and it becomes clear that there is ample room for improvement in the way bridge smoothness is approached.

PURPOSE AND SCOPE

This paper describes a contemporary survey of the ride quality of Virginia’s bridges. It also discusses an analysis of the potential impact of beam/girder camber on bridge ride quality. Last, a modern adaptation of the conventional straightedge provision is combined with the results of the survey to provide the rudiments of a new construction specification for bridge decks.

METHODS

Survey of Bridge Ride Quality

The survey of bridge riding quality included structures of varying age, structural type, and service condition. To simplify the data collection while maintaining an adequate variety of bridges, the survey was designed to cover major highway corridors throughout the state.

Roughness Testing

Once the candidate highway corridors were identified, the field testing component involved simply collecting a measure of roughness for each bridge. A roughness test entailed a single pass over the bridge (at highway speed) with an inertial road profiler. During that pass, an elevation profile was recorded for both the left and right wheel paths. To allow the analyst to

distinguish the roughness contributed by various components of a bridge (e.g., deck, approach slabs, joints), the operator of the profiler inserted “flags” in the data as he crossed over the beginning and end of the deck slab. To ensure that the profiles for a given bridge included sufficient data to evaluate the approach slabs, data collection was initiated at least 30 m prior to the bridge and continued for at least 30 m beyond the end of bridge. In many cases, the relative proximity of the bridges made it practical to collect data on more than one structure in a single test. In these cases, the flags at the beginning of the deck slabs also reflected the Virginia Department of Transportation (VDOT) structure number.

IRI Analysis

The profiles that were collected during the field tests were used to generate estimates of ride quality. For this study, ride quality was reported in terms of the International Roughness Index (IRI). Although the IRI is new terminology for the bridge industry, it is a very common and widely used index for condition assessment and inventorying of pavements. ASTM E1926, “Standard Practice for Computing the International Roughness Index for Roads from Longitudinal Profile Measurements,” describes the simulation used to generate the IRI. A key component of this simulation is a “virtual” quarter vehicle, complete with all the basic parameters necessary to describe an actual vehicle. When this reference vehicle is applied to a profile, the simulated suspension motion is accumulated and divided by the distance traveled to yield the IRI (3). Smaller values (less roughness) imply a smoother ride, and higher values indicate a rougher one.

One summary IRI (representing both wheel paths) was generated and recorded for the portion of the bridge between the ends of the deck slab. IRI values were also produced to represent the 30 m immediately preceding the bridge and the 30 m immediately after the bridge. Another summary report provided an IRI value for the entire length of the bridge, including the approaches. Finally, a detailed analysis segmented the bridge and its approaches into 3-m intervals and provided IRI values for each interval. This report, coupled with the flags inserted at the beginning and end of the slab, was used to extract the roughness contributed by the interval including the beginning and ending joints.

Designed-in Camber

A parallel effort examined the potential for camber to affect bridge ride quality. Beam and girder camber, typically an upward curving “hump” shape under self-weight conditions, is necessary to offset the natural deflection attributable to the additional dead load imposed by other superstructure components, such as a concrete deck 200 to 250 mm thick, cross frames, and parapets. Although this pre-deflected shape is carefully designed to “flatten” with the additional dead load, the conservative nature of bridge design can occasionally lead to residual camber in completed structures.

The likelihood of encountering excessive camber may be at least partially responsible for a reluctance to apply the IRI for use in controlling bridge deck smoothness. To understand why, it is important to recognize that the IRI is most sensitive to surface features of 1 to 30 m in length (4). The average maximum span length of the structures tested for this study was approximately 24 m. Clearly, a surface wave that encompasses an entire bridge span (such as simple-span beam camber) would fall on the long end of the envelope of features that might register as roughness in an IRI analysis. To what extent, however, is not well understood. To address this issue, a short exercise was conducted to examine a couple worst-case over-cambering conditions. Two fictitious bridge geometries were created, and accompanying camber diagrams produced. These

camber diagrams were “fit” mathematically to allow the production of elevation profiles. Perfectly linear (and smooth) approach profiles were added to the camber profiles to provide a complete bridge profile. Last, with the use of software designed to generate road roughness estimates (IRI) from generic profiles, the potential impact on ride quality of beam camber was determined.

Simulated Straightedge Analyses

Data from the field survey were also used to review the quality of existing decks in terms of the current straightedge tolerance. Actually, this review employed a simulation of the conventional straightedge provision. This simulation involved passing a virtual rolling straightedge (approximately 3 m in length) over the relevant portions of the measured profiles and registering every instance in which the profile varied from this straight line a distance of 3 mm or more. It is important to point out that the rolling straightedge simulation incorporates different behavior than might be expected with a literal straightedge or a simulated perfectly rigid straightedge.

The following illustration helps distinguish the difference. Notice that the 3-m line that represents the (virtual) rolling straightedge in Figure 1 is allowed to pass through the profile (representing the highway surface). Mathematically, violations attributable to humps in the profile register identically (with reversed signs) with those that result from dips. For the perfectly rigid straightedge, however, the straight line, or bar, is not allowed to penetrate the modeled highway surface (as would be the case with an actual straightedge). However, this perfectly rigid straightedge is allowed to identify violations that would result through cantilevering the bar as also illustrated in Figure 1. In both cases (rolling straightedge or perfectly rigid straightedge), the simulations allow for much more thorough examination of a surface than is practicably possible with an actual straightedge. Typically, this results in the detection of far more violations than would be expected using traditional tools and methods.

When a simulated straightedge analysis is conducted, each elevation point on a profile becomes an opportunity for the profile to violate the tolerance. For that reason, the profile sampling rate is very important. If there are two elevation points per meter, there are twice as many failure opportunities as there would be on a profile with only one elevation point per meter. For this research, the longitudinal resolution of the elevation profiles was maintained at approximately 75 mm per sample. This yielded 40 elevation points within a 3-m distance, or 40 opportunities per 3-m straightedge to exceed the allowable tolerance. When the analyses were conducted, the number of failures (end slab to end slab) was recorded first. Then, the total distance of surface-in-violation was calculated by multiplying the number of failures by the distance between samples (75 mm). Finally, the total percentage of the deck failing the smoothness tolerance was calculated by dividing the total failed length (surface-in-violation) by the total length of the deck.

Development of New Smoothness Provision for Bridge Decks

As the planned field survey was nearing completion, an opportunity presented itself to formulate and pilot a new special provision for bridge deck smoothness. In particular, engineers from VDOT’s Northern Virginia District (NOVA) Bridge Office were interested in a tool that would help them promote smoothness on two of the longer ramp bridges at the Springfield Interchange project south of Washington, D.C. The length of the bridges and public prominence of the project made VDOT officials especially sensitive to final surface smoothness. Length was also a factor in questioning the practicality of the traditional provision (i.e., conventional straightedge).

In addition to general geometric data relating to the two future bridges at the Springfield interchange, the research team was referred to an “exemplary” ramp structure (on a nearby interchange) that had a desirable riding quality. Elevation profiles were collected from this exemplary bridge and examined using the concept of roughness profile (5). A roughness profile, as distinguished from an elevation profile, consists of a continuous line plot representing a series of roughness index values (e.g., IRI). These roughness numbers are generated from and centered on a moving base length of longitudinal profile. For example, in a roughness profile that uses the IRI from a 50-m base length, an IRI value would be generated at each running meter, combining 25 m of the elevation profile preceding this location with 25 m from beyond the location. The result provides a continuous assessment of ride quality for the entire length of the profile of interest.

The IRI has proven to be a very effective surrogate for assessing subjective ride quality of highway surfaces. However, by the time this “opportunity” presented itself, preliminary results of the analysis of camber effects had confirmed that it might be difficult to apply the IRI equitably to conventionally designed and constructed bridge decks. Fortunately, however, other early findings were suggesting that an adaptation of the traditional straightedge-based provision might well provide an interim solution. Specifically, this exercise combined the roughness profile concept (incorporating the IRI) with the simulated straightedge. First, the roughness profiles from the exemplary bridge were plotted and segmented into lots, which were arbitrarily established at 30 m (10 units of the 3-m straightedge). Then, a series of straightedge simulations were conducted in which the length of the straightedge was varied but the tolerance remained unchanged (3 mm). Assessing the capacity of a straightedge to recognize IRI roughness involved conducting each simulation and reviewing its results alongside the corresponding roughness profile. If an area of the deck was associated with high IRI values but little reaction from the straightedge simulation, the length would be considered too short. Likewise, a low IRI roughness that was accompanied by excessive violations to the simulation tolerance would imply that the straightedge was too long.

Once the necessary length-of-straightedge was established, a pay adjustment schedule was developed (borrowing a format from analogous pavement provisions). A scale against which to judge relative riding quality (in terms of IRI) built on the experience gained from this study and combined it with previous experience relating to pavements. The ride quality “targets” within the pay adjustment schedule were developed by reviewing the roughness profile from the exemplary bridge and observing the number of straightedge violations within excellent, good, fair, and poor riding regions of the deck.

With a draft set of pay adjustment targets established, a series of six more bridges was selected and subjected to the proposed criteria. These bridges, which were taken from the database constructed during the bridge roughness survey, were carefully selected to represent extreme existing conditions for bridge ride quality and to provide some real-world examples of structures like those targeted for the pilot provision. Two of the bridges were smooth in comparison to the remainder of the database, two were relatively rough, and two were moderately smooth and above average in length.

Finally, the actual pay adjustments were established through an informal series of expert elicitations. The goal was to use values that were not so large as to represent an unbearable burden on the contractor (or agency). At the same time, it was important that the values be large enough to encourage the builders to devote extra attention to achieving a smooth-riding final structure.

FINDINGS AND DISCUSSION

Overview of Ride Quality

When data collection efforts were ended, 289 bridges had been field tested for ride quality. Of this sample population, 228 were interstate bridges and 61 were from the primary system. Figure 2 presents the distributions for measured bridge ride quality (in terms of IRI). One of the distributions reflects the observed ride quality for just that portion of the bridge from deck end to deck end. The second distribution relates to ride values that incorporate the entire “bridge setting,” including 30 m of approach roadway (encompassing approach slabs) at each end of the bridge. To put the bridge IRI values into perspective, a third distribution that characterizes asphalt pavements is included. The basis for these pavement roughness values was an earlier study by the author (6). The pavement distribution represents approximately 500 projects awaiting new asphalt overlays. Although the average bridge deck (interstate and primary) has an IRI of 2766 mm/km, the average in-service asphalt pavement (all systems) is closer to 1740 mm/km.

Designed-in Camber

Figures 3 and 4 are elevation profiles that represent typical girder camber diagrams. Actually, these figures depict the cambered spans of a bridge, in addition to some nominal length of flat and smooth approach roadway. Figure 3 represents an approximately 30-m single, simple-span structure with 15 m of approach roadway at each end. Figure 4 represents two 50-m spans for a continuous girder bridge with 15-m approaches. Although the vertical scale in both examples is exaggerated, the maximum camber is limited to approximately 10 cm. Even with these relatively small vertical deviations, the ride quality simulation returned IRI contributions (for the cambered spans only) of approximately 2400 and 1700 mm/km for the single-span and two-span continuous bridges, respectively. Obviously, when the IRI targets for new roadway pavements are close to 1000 mm/km, potential contributions from bridge camber of 1500 mm/km and more raise serious questions regarding the practice of making unqualified comparisons between road and bridge ride quality.

Straightedge Simulation

The propensity for well-designed camber to contribute meaningful roughness (at least as measured by the IRI) makes reviewing the conventional 3-m straightedge requirements even more important. Figure 5 is a plot of bridge deck IRI versus the percentage of the corresponding deck that “theoretically” fails the conventional 3 mm in 3 m tolerance. Although there is obvious spread in the data, a very definite trend couples higher IRI values with a larger percentage of the deck failing the standard. It appears that it is possible to construct a deck that produces IRI values as high as 2000 mm/km without measurable violations of the straightedge tolerance. More often than not, however, increasing IRIs is accompanied by higher concentrations of violations to the simulated straightedge. This speaks favorably for the concept of adapting modern profiling to complement the traditional approach.

A New Smoothness Provision for Bridge Decks

The new special provision for bridge deck smoothness was crafted to address the specific needs of VDOT’s NOVA Bridge Office while incorporating the findings of this study that relate to camber effects and the simulated straightedge analysis. As discussed in “Methods,” the starting point for the pilot provision was an exemplary structure of similar character to those proposed

for the Springfield interchange. In particular, the Route 7 ramp structure onto Route 15 South in Leesburg, Virginia, was offered as a bridge with desirable ride quality. Figure 6 plots the roughness profiles for the left and right wheel paths of the entire 464 m of the Route 7 ramp. The figure also indicates the average ride quality measurements for Virginia pavements, as well as the average bridge deck IRI as determined through this study. Clearly, although the deck is rougher than the average pavement, the IRI remains well below that of the average bridge. Nonetheless, the roughness profile approach illustrates how even on an “exemplary” structure, the ride quality fluctuates dramatically.

Figure 7 reflects a typical response from a straightedge simulation as applied to a portion of the Route 7 ramp from 70 to 85 m into the slab. In this case, the analysis uses a 3-m virtual straightedge with the 3-mm maximum tolerance. Although the roughness profile in Figure 6 suggests that this area of the deck rides relatively well, it is interesting to note that there are still 19 violations in 15 m.

Experiments with varying straightedge lengths demonstrated that even using the shortest straightedge (3 m) could reveal an impressive number of imperfections. Figure 8, which again refers to the Route 7 ramp, shows the total number of violations (by wheel path) for each straightedge length. The 7-m test length identified an average of one violation for every 0.63 linear meters of deck. The 3-m length identified one violation every 3.3 m. Considering that this bridge was deemed to have good riding quality, it appears clear that the 3-m straightedge is more than sufficient to assure the quality of newly constructed decks.

Table 1 consolidates the roughness profile data from Figure 6 into 30-m lots. The table reports the mean roughness index (MRI, average IRI of both wheel paths) for each lot and the number of 3-m straightedge violations in the lot. It also includes qualitative assessments of ride quality and construction quality. The judgment of relative ride quality is based on the MRI, whereas construction quality reflects only violations to the straightedge. As one might expect given the earlier findings, good ride and good construction do not always correspond. It is not uncommon to see a lag of sorts between good construction quality and good riding quality. Perhaps this can be attributed to the delayed and/or damping effect of vehicle suspensions and the ability of the IRI simulation to reflect this effect.

Based partly on the observations indicated in Table 1 and partly on the relationship established earlier between straightedge violations and IRI, the schedule of pay adjustments presented in Table 2 was developed. Because the actual dollar amounts were established entirely outside of this study (incorporating little input from the author), the values are provided to express the degree of incentive/disincentive only.

With the criterion in Table 2 established, six more bridges were selected from the larger database and put through a regimen of analyses similar to that applied to the ramp on Route 7. Table 3 reports the average IRI for all seven bridges (including the Route 7 structure) and the average number of violations (of the 3 mm in 3 m limit). As mentioned previously, the average roadway pavement in Virginia measures approximately 1600 mm/km of IRI roughness and the average bridge measures closer to 2750 mm/km. In addition, these numbers were generated from in-service bridges and pavements (i.e., not new construction), and the special provision was intended to *improve* smoothness, not encourage or even condone average work. Accordingly, the results in Table 3 show more lots with disincentives than incentives on average-riding bridge decks and nothing but disincentive lots on the rough bridges. For the three bridges identified as very smooth, the number of incentive (bonus) lots exceeded the number of penalty lots, which is consistent with the concept.

CONCLUSIONS AND RECOMMENDATIONS

The findings from this study support the following conclusions:

- Residual camber can easily contribute in excess of 1000 mm/km of additional IRI roughness. IRI, therefore, may not be an equitable tool for assessing the construction quality of conventionally designed and constructed bridge decks.
- Inertial (and high-speed) profiling equipment can be applied to control bridge deck roughness with a simulation that mimics the traditional 3-m) straightedge.

FURTHER RESEARCH

This work confirmed the potential impact of designed-in beam camber on roughness as measured through the IRI. The simulated straightedge approach offered to control smoothness was clearly a compromise, since it is well known that features greater than 3 m in length contribute significant roughness. Further work is necessary before a common (and equitable) serviceability measurement can be established for all traveled surfaces (bridge decks, as well as roadway pavements).

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TABLE 1 Comparison of Ride Quality and Construction Quality for Route 7 Ramp

Interval	Average MRI (mm/km)	MRI Ride Quality	No. of Violations	Construction Quality
0-30	2088	Fair	19	Fair
30.1-60	1998	Good	3	Excellent
60.1-90	1793	Excellent	18	Fair
90.1-120	2060	Fair	30	Poor
120.1-150	2284	Poor	6	Good
150.1-180	1493	Excellent	2	Excellent
180.1-210	1971	Good	19	Fair
210.1-240	2141	Fair	21	Poor
240.1-270	1594	Excellent	1	Excellent
270.1-300	1650	Excellent	4	Excellent
300.1-330	2015	Fair	9	Good
330.1-360	1792	Excellent	28	Poor
360.1-390	1390	Excellent	0	Excellent
390.1-420	2130	Fair	27	Poor
420.1-450	1653	Excellent	0	Excellent
450.1-480	2351	Poor	22	Poor

TABLE 2 Pay Adjustment Schedule

No. Points Out of Tolerance in 30-m Section	Pay Adjustment (\$/m ²)
5 or less	Maximum incentive, \$5.00
6 to 10	Incentive, \$2.50
11 to 20	No incentive or disincentive
21 to 30	Disincentive, \$1.00
31 to 50	Disincentive, \$2.00
More than 50	Subject to corrective action and \$5.00

TABLE 3 Comparison of IRI and Straightedge Violations

Bridge	Ride Category	Length (m)	Average IRI (mm/km)	Average Violations (No./Lot)	Bonus Lots	100% Lots	Penalty Lots
Route 7	Smooth/long	464	1919	15	8	3	5
Route 19	Smooth/mid	65	1265	0	3	0	0
Route 29	Smooth/mid	73	1695	5	3	0	0
Route 64	Rough/mid	94	4341	63	0	0	4
Route 295	Rough/mid	56	3652	71	0	0	2
Route 64	Moderate/long	344	2355	35	0	1	11
Route 295	Moderate/long	595	2555	24	2	7	11

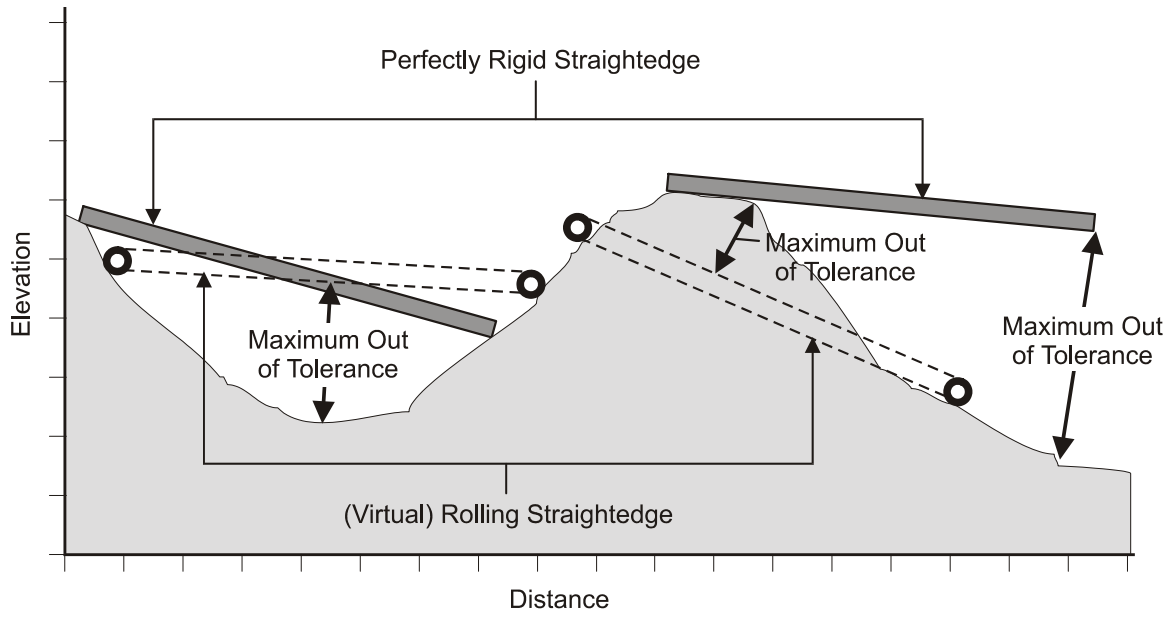


FIGURE 1 Straightedge simulations.

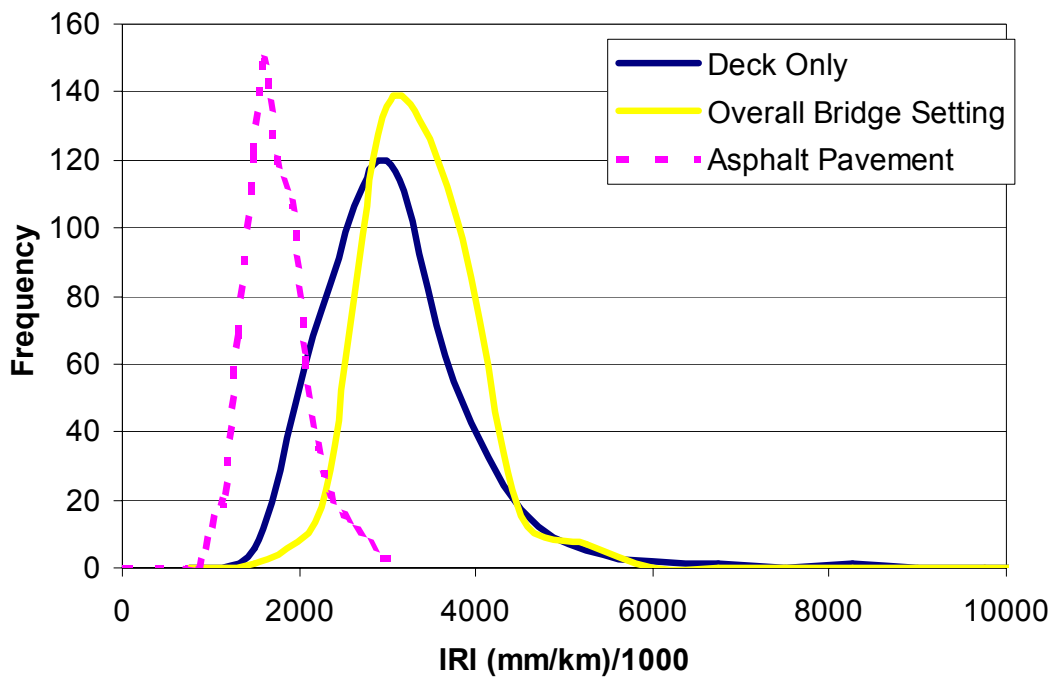


Figure 2. Distribution of Measured Ride Quality

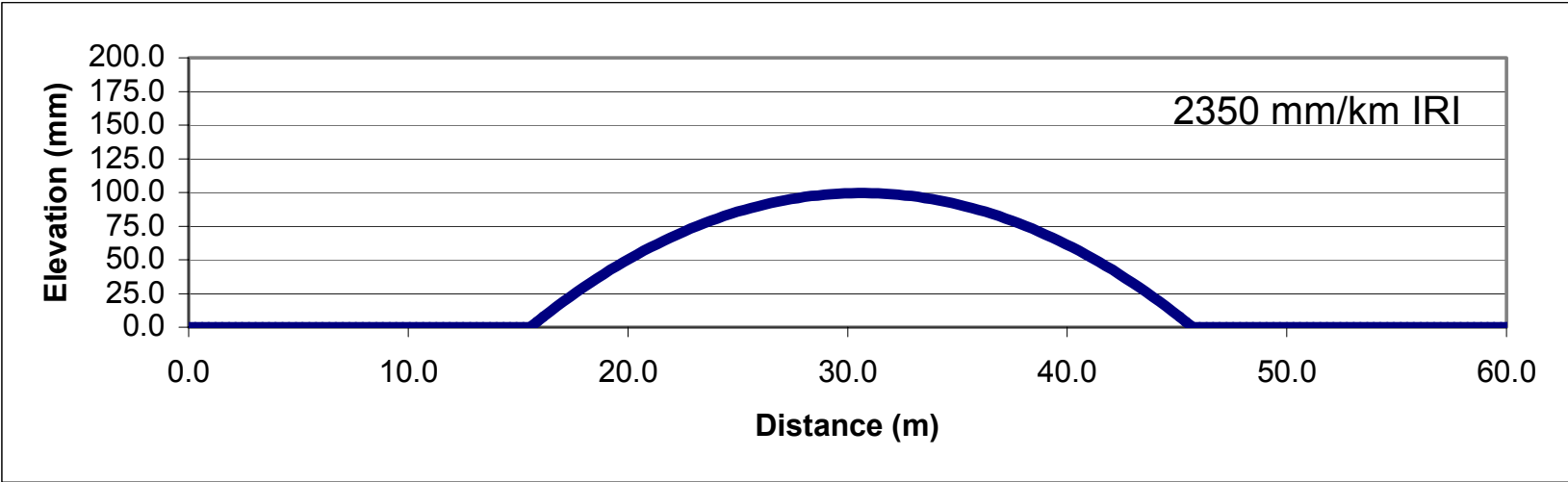


Figure 3. Single-Span Camber Diagram

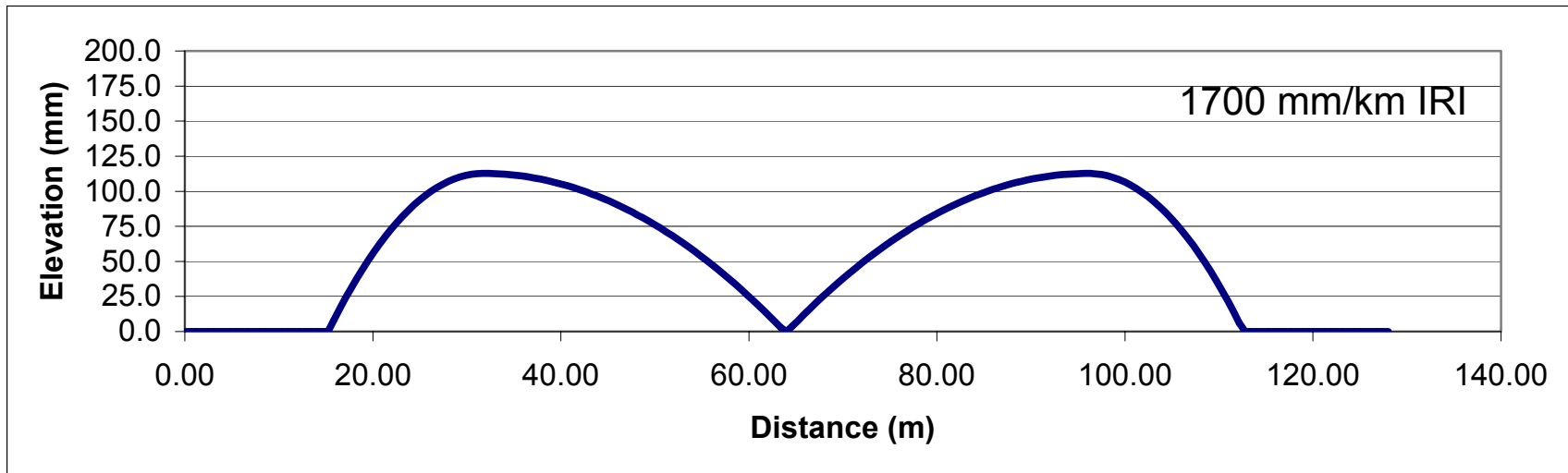


Figure 4. Two-Span Continuous Camber Diagram

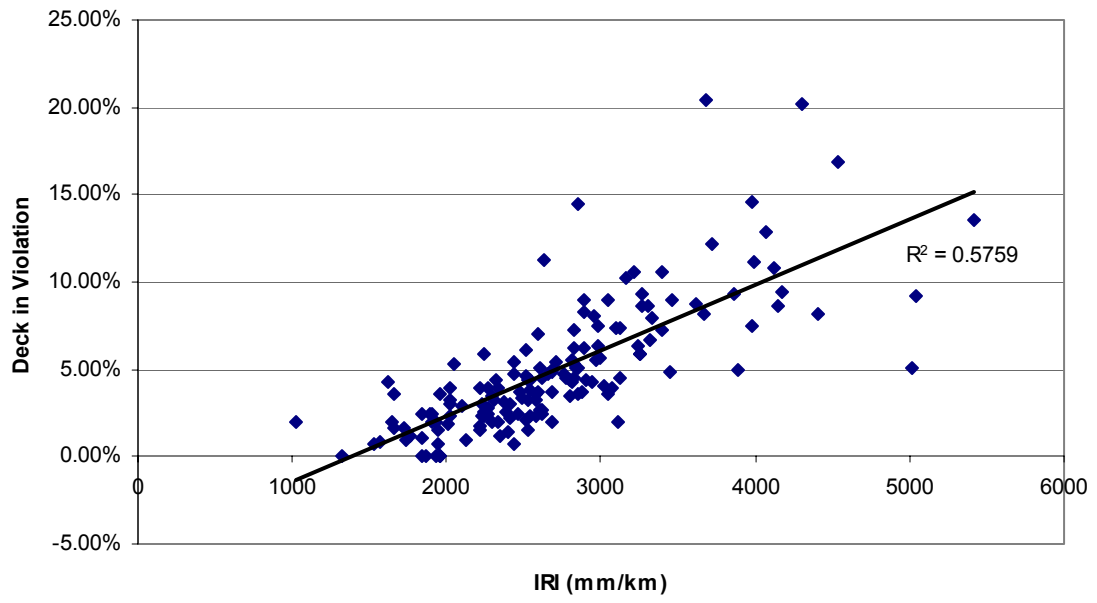


Figure 5. 3-Meter Straightedge versus IRI

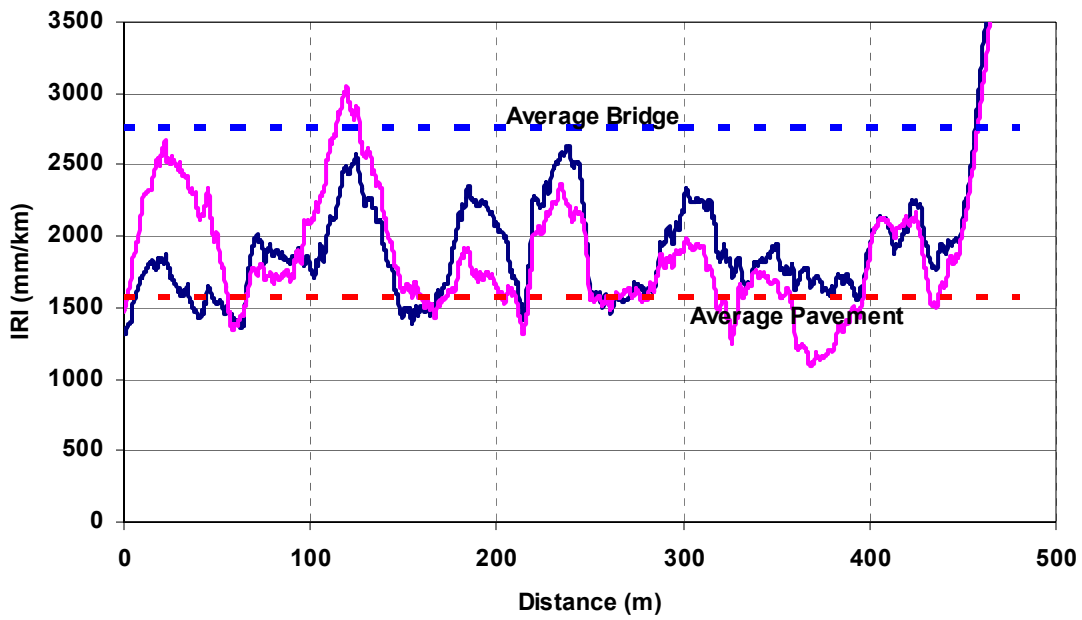


Figure 6. Roughness Profiles for "Exemplary" Bridge

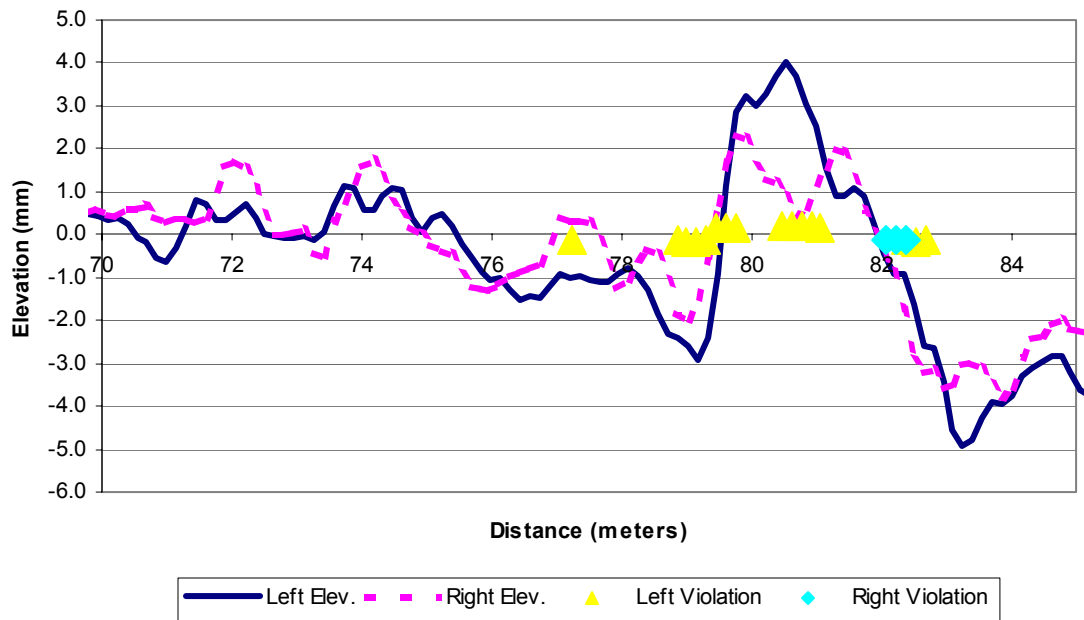


Figure 7. Example Results from 3-Meter Straightedge Simulation

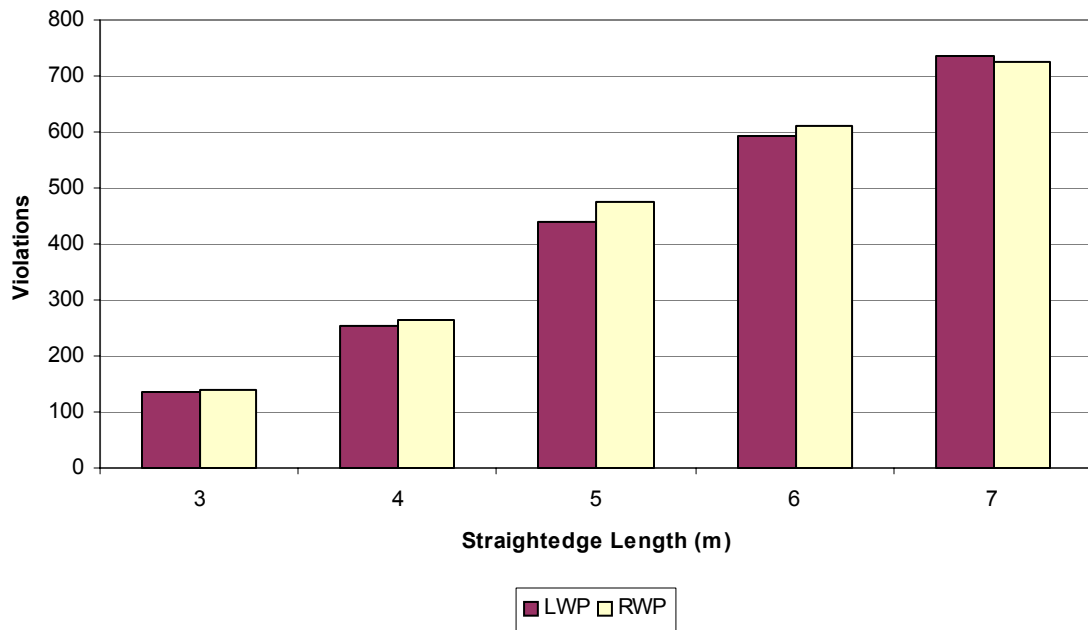


Figure 8. Number of Violations by Length of Straightedge (for 464-meter deck)