How Bridges Affect Ride Quality on Ohio's Interstate Highway System

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WORD COUNT: 3,056 + 6 TABLES + 2 FIGURES = 5,056

ABSTRACT

It is commonly understood that bridges and/or pavement-bridge interfaces generally have a detrimental effect on highway ride quality. The focus of this study was to objectively quantify the extent to which bridges reduce highway ride quality, to attempt to identify contributing factors of this reduced ride quality, and to geographically present the data for use as a highway system evaluation/diagnostic tool.

The approach included analysis of road profiles collected on Ohio's interstate highway system for the Highway Performance Monitoring System (HPMS) and linking this information with the Ohio Department of Transportation's Bridge Management System (BMS) files. The road profiles were processed to generate ride quality indices of Half Car IRI (HCI), and Ride Number (RN) first excluding then including all bridge segments system wide then a third time exclusively for bridge segments. BMS inventory file attributes that could potentially be associated with ride quality (i.e. bridge length, type, alignment, etc.) as well as all BMS condition rating attributes (i.e. general appraisal rating, wearing surface condition, etc.) were placed in a relational database along with the ride quality indices. The relational database was utilized to geographically present the information and to analyze potential contributing factors of bridge roughness/smoothness.

Findings/Conclusions

Bridges accounted for a 7.6% increase in average HCI system wide while representing only 4% of the system by length. Bridge segments were 145% higher by average HCI than pure pavement sections. Bridge specific profile analysis is necessary to identify bridge attributes that contribute to ride quality reductions.

BACKGROUND

It is commonly recognized when traveling across our highway network that we generally experience a rougher ride as we traverse bridges as opposed to the ride we experience when traversing our pavements. This is the case for most any motor vehicle we may be riding in or driving. Since the guidelines for reporting the International Roughness Index (IRI) found in the Federal Highway Administration's (FHWA) Highway Performance Monitoring System (HPMS) Field Manual dictate we exclude the roughness associated with bridges (*1*), we have no objective measure of how rough our bridges are.

Objectively quantified bridge roughness would be beneficial when determining user satisfaction. The motoring public becomes increasingly dissatisfied by the increased frequency and/or severity of bumps they feel in the highway regardless of whether bumps are due to pavement distresses/irregularities or the presence of bridges. Likewise, this information would be useful in the management of our bridges. Higher levels of roughness would likely be associated with higher loads that the bridges must sustain due to dynamic loading.

It became obvious the longitudinal road profiles collected on our interstate system to satisfy HPMS requirements could be reprocessed with additional effort to include the bridge segment locations. This would yield objective ride quality information on our bridges and thus the impetus for this work was born.

SCOPE AND OBJECTIVES

The work of this study was conducted in-house at the Ohio Department of Transportation (ODOT) with minimal resources. This required utilization of routinely collected road profile and Bridge Management System (BMS) data. The objectives were as follows:

- Objectively quantify the decrease in ride quality of the interstate system due to the presence of bridges.
- Link ODOT's road profile indices to its BMS files.
- Geographically present and query the linked data.
- Identify specific causes and/or contributing factors of reduced ride quality due to bridges.

METHODOLOGY

Longitudinal Road Profiles

ODOT has utilized road profilers since the early 1980's to collect and report the International Roughness Index (IRI), Half Car IRI (HCI), and more recently Ride Number (RN) for use in HPMS and ODOT's Pavement Management System (PMS). ODOT has profiled its entire network annually for several years in order to attain objective ride quality information on its pavements. For divided highways such as the interstates, the entire length of the mainline is profiled once each year in both up and down directions according to mileposts. Profile indices are generated for each 0.16 km (0.10-mile) section profiled. These 0.16 km (0.10-mile) roughness segments are used to compare, classify, and help make decisions regarding ODOT's pavements. This study leverages these longitudinal road profiles to quantify the ride quality effects of our interstate bridges.

The interstate highway system was the most logical choice for this study not only for the capacity it carries and service it provides but also for its compatibility with longitudinal road profile collection. Generically, high-speed profilers have a low-end threshold speed below which they do an inadequate job of collecting and reporting the surface profile of the road. That speed is in the neighborhood of 16-24 kmph (10-15 mph) depending on the characteristics of the specific profiler. Since the interstates are expressways free of stop signs, traffic lights, and at grade crossings, the only real risk of falling below minimum speed would be due to traffic congestion. (Profiling congestion prone areas at off peak times mitigated this.) All of the profile data used in this study was collected by the same ODOT owned high-speed profiler.

The profiler continuously collects profile points once a data collection run has begun. When a bridge is encountered, the profile is manually *marked* by the operator prior to the entry approach and then *marked* again once the profiler has traversed past the exit approach. In this manner the software used to calculate profile indices can ignore the profile points within the bounds of the marks thus removing the bridge influence on the highway's roughness values. (As mentioned earlier, this conforms to HPMS guidelines.) In order to consider the influence the bridge has on the highway system, the *marks* in the profile must be removed, and the profile processed again to recalculate the indices. This approach was applied to all of the profiles collected on Ohio's interstate system. Results from both scenarios were used to objectively quantify the system wide effect bridges have on ride quality. The profiles were processed a third time to calculate the indices between the marks in the profile in order to quantify the ride quality of the bridge segments themselves.

Link to Bridge Information

Two ODOT BMS files contain bridge attributes that could potentially be associated with ride quality. They are the bridge inventory file (*2*) and the bridge inspection file (*3*). After consulting the respective manuals for file descriptions and attribute definitions, a list of attributes were compiled for analysis purposes. ODOT Office of Structural Engineering personnel then screened this list for legitimacy. The attributes used are found in Table 1.

TABLE 1 Bridge Attributes Considered for Analysis

Attribute	Bridge Managament File
Structure File Number	Inventory and Appraisal
Overall Structure Length	
Approach Alignment Appraisal	
Approach Pavement Grade	
Deck Type	
Expansion Joint	
Main Span Structure Material	
Main Span Structure Type	
Main Span Structure Description	
Skew Angle	
Wearing Surface	
Age	
Structure File Number	Inspection
Date of Inspection/Rating	
General Appraisal	
Approach Summary Rating	
Approach Pavement Rating	
Approach Slab Rating	
Relief Joint Rating	
Deck Summary Rating	
Floor Rating	
Wearing Surface Rating	
Expansion Joint Rating	
Superstructure Alignment Rating	

Geographic Information System (GIS) software was then used to link the bridge information with road profile information. Functions of the GIS software allowed each bridge and its attributes to be associated with its corresponding ride quality information. The GIS software then provided a user friendly means of both querying and presenting the linked data.

ANALYSIS AND FINDINGS

Ohio's Interstate Highway System

ODOT is responsible for 2,150 centerline kilometers (1,330 centerline miles) of interstate highways. That translates into 4,290 *directional* mainline kilometers (2,660 *directional* mainline miles). If one were to drive all 4,290 directional kilometers (2,660 directional miles), as the ODOT profiler did in the fall of 2001, one would drive across or *encounter* 1,910 bridges. Of these encounters, 260 are bridges that carry both directions of traffic while 1,390 are a separate bridge structure by direction. The decks of the bridge encounters total 150 kilometers (94 miles) in length with an average length of 80 meters (261 ft.). The total represents 3.5% of the interstate system. If it is assumed each bridge has two 7.6 meter (25-ft.) approaches, then the bridge segments represent 4.2% of the interstate system.

(Comprehensive information on approach slab lengths was not available in BMS.) These facts are exclusive of culverts and culvert locations were not *marked* during profile collection.

Road Profiles With and Without Bridge Segments

When the profiles were processed excluding the bridge segments (not considering the *marked* profile points) there were 25,928 0.16-km (0.10-mile) roughness segments. When they were reprocessed including the bridge segments (removing the *marked* profile points) there were 26,314 0.16-km (0.10-mile) roughness segments. The difference, 386 roughness segments, represent segments that were purely bridge in length. There were 22,972 roughness segments that were purely pavement by length (87.3% of the system). This leaves 2,956 roughness segments that were partially pavement and bridge. This occurs when a bridge segment falls entirely within a roughness segment or overlaps multiple roughness segments. Adding the pure and partial bridges segments yields 3,342 bridge affected roughness segments (12.7% of the system). In both cases, 1.1% of the interstate system was under construction at the time profiling and was not considered in the analysis.

When the profiles were processed for just the bridge segments (between the *marked* profile points) there were 1,665 segments of variable length totaling 211 kilometers (131 miles). This is short of the total number of bridge encounters on the system because some of the bridges were within construction zones and some segments included more than one specific bridge. The latter occurred when short distances separated multiple bridges.

The HCI and RN indices were chosen for the analysis because they utilize both the left and right wheel-path profiles. This made sense since the vast majority of vehicles traveling the interstates are dual wheel-path vehicles. The HCI uses the ¼ car IRI algorithm that simply averages the corresponding left and right wheel-path profile point elevations prior to index calculation (*4*). It is a linear index in that a weighted average by segment length can be applied to it (*4*). HCI represents the summed vertical distance of movement between the rear axle and body of a simulated car traveling at 81 kmph (50 mph) over the road profiles. Its units are vertical millimeters of roughness per longitudinal kilometer (vertical inches of roughness per longitudinal mile) of travel. Lower numbers are indicative of better ride quality while higher numbers are indicative or poorer ride quality (increased roughness). Table 2 describes the HCI interstate system comparisons.

TABLE 2 Ohio Interstate System HCI Statistics

	HCI inches/mile					Segment
	Average	Median	Minimum	Maximum	Std Dev	Count
Excluding Bridges	66	60	20	379	29	25,928 - 0.10 mile segments
Including Bridges	71	62	20	379	34	26,314 - 0.10 mile segments
Increase	7.6%					
Bridge Segments	162	163	43	405	45	1,665 - variable length

note: bridges represent 4% of the system by length
bridges affected 13% of the system segments

RN is non-linear but was chosen due to its heightened sensitivity to shorter wavelengths over IRI indices and for its high correlation to user satisfaction *(4*). RN ranges from 0 the poorest to 5 the best ride. Table 3 describes the RN interstate system comparisons.

TABLE 3 Distribution of RN on Ohio's Interstate System

Description of Ride Quality	RN range	Interstate System Excluding Bridges	Interstate System Including Bridges	Bridge Segments Only
Excellent	4.00 - 5.00	40%	37%	1%
Good	3.70 - 3.99	30%	27%	2%
Fair	3.40 - 3.69	14%	13%	3%
Poor	3.00 - 3.39	8%	10%	8%
Very Poor	2.30 - 2.99	6%	10%	45%
Poorest	0.00 - 2.29	2%	3%	41%

note: bridges represent 4% of the system by length
bridges affected 13% of the system segments

Roughness Segments Linked to Bridge Attributes
When the GIS software was used to associate the bridge segment ride quality data (1,665 records) with bridge attribute data, fewer linked records remained (specifically 1,569 records). The link was not 100% complete due to unresolved compatibility issues (format errors, coding errors, etc.). Unlinked records with incomplete information were discarded and not used in the bridge attribute/ride quality analysis.

Correlation analysis was performed between various bridge attributes and HCI. The attributes had to be numeric and linear in nature (ex. Skew angle, bridge age, etc.) or numerically scaled ratings (ex. General Appraisal rated 0 to 9 or Wearing Surface Rating scaled 1 to 4). Table 4 shows the results of the correlation analysis. It should be noted that summary ratings (General Appraisal, Approach Summary, and Deck Summary) were scaled 9 to 0 with 9 being the best (Excellent) to 0 the poorest (failed). All other ratings were from 1 to 4 with 1 the best (Good) and 4 the poorest (Critical). No single attribute had an absolute value of its correlation coefficient above 0.19 and most were below 0.10 meaning the attributes had very weak to no correlation to HCI.

TABLE 4 Correlation Analysis of Bridge Attributes vs. HCI

Bridge Attribute	Correlation Coefficient	Attribute Average	Attribute Std Dev	HCI Average	HCI Std Dev	Number of Records
Overall Structure Length (feet)	-0.09	260	375	166	44	1569
Approach Alignment Appraisal	0.10	8.0	0.6	166	44	1569
Approach Pavement Grade Rating	0.08	1.4	0.6	166	44	1569
Skew Angle (degrees)	-0.01	19	17	166	44	1528
Age (years)	-0.06	35	7	166	44	1569
General Appraisal	-0.03	6.4	0.9	166	44	1569
Approach Summary Rating	-0.17	6.6	0.9	166	44	1569
Approach Pavement Rating	0.17	1.5	0.5	166	44	1569
Approach Slab Rating	0.12	1.5	0.5	166	44	1558
Relief Joint Rating	0.03	1.4	0.5	165	40	388
Deck Summary Rating	-0.07	6.5	0.9	166	44	1569
Floor Rating	0.02	1.7	0.6	166	44	1569
Wearing Surface Rating	0.19	1.6	0.6	166	44	1569
Expansion Joint Rating	0.10	1.5	0.7	168	44	1184
Superstructure Alignment Rating	0.03	1.0	0.2	166	44	1568

It may be more appropriate to analyze the specific portions of the profiles relating to the specific attribute rather than the entire profile of the bridge segment. For example, the portions of the profiles representing the approach slabs and expansion joints would represent much less of the bridge than perhaps the deck and wearing surface). In short, network level inventory profiles are limited in their usefulness to identify specific bridge attributes responsible for reduced ride quality.

HCI analysis was performed with respect to many bridge attributes. Figures 1 and 2 show plots of average bridge roughness by bridge length and age respectively.

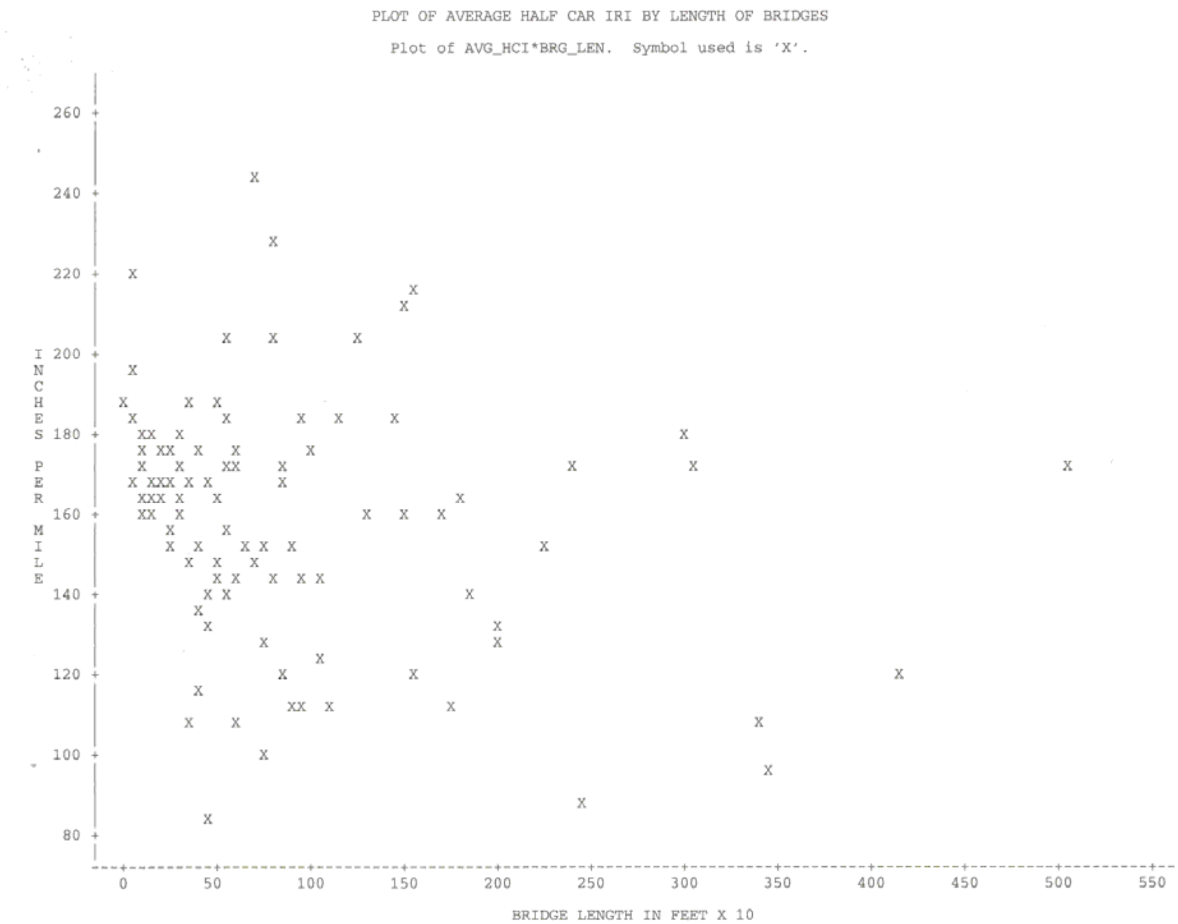

FIGURE 1 Plot of Average HCI by Bridge Length

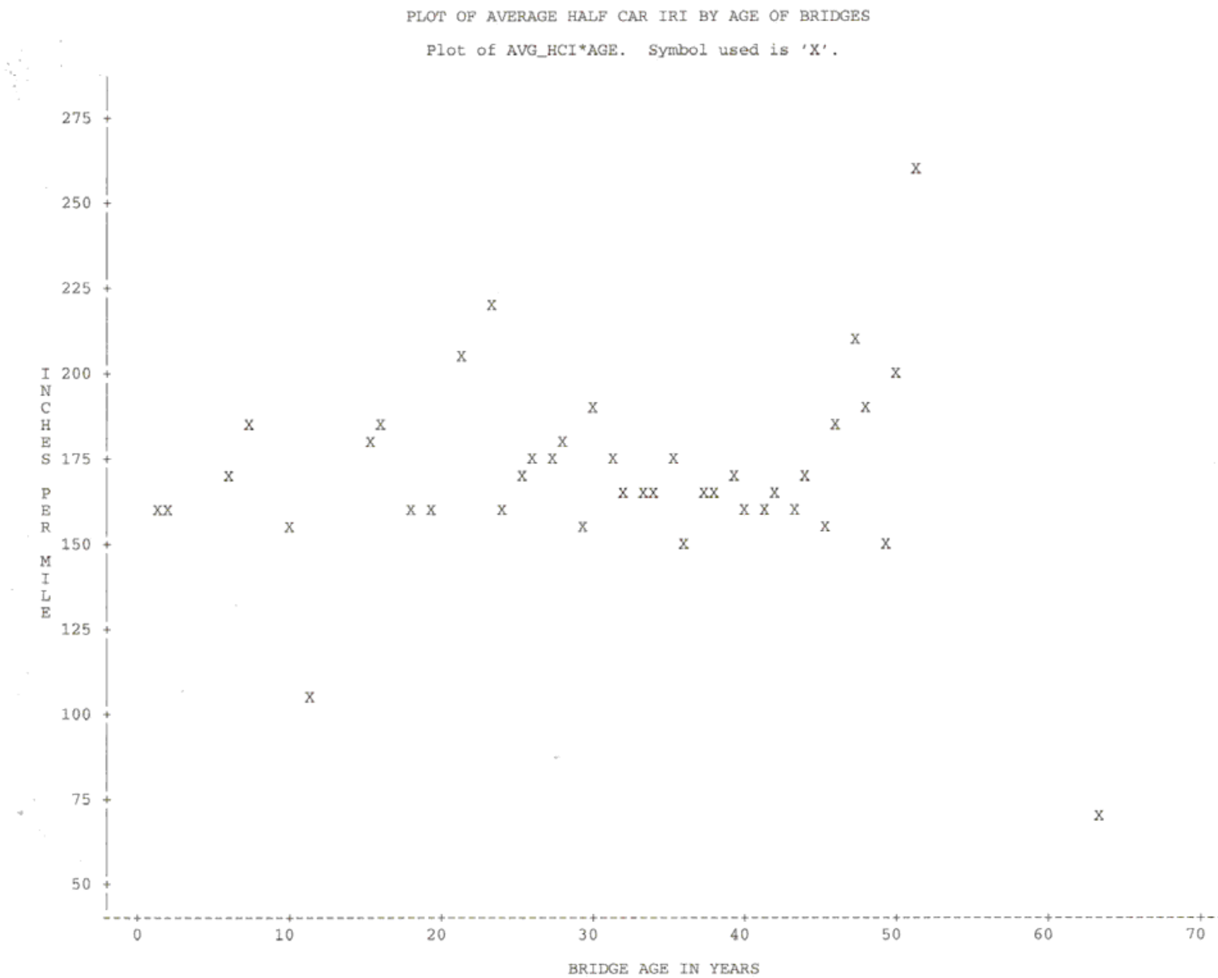

FIGURE 2 Plot of Average HCI by Bridge Age

There is no clear relationship between either length or age and HCI. Table 5 describes HCI statistics by various bridge attributes. The average HCI of bridge segments is 2,590 mm/km (167 in./mile) [2,510 mm/km (162 in./mile) when weighted by length]. Deck span bridges are the smoothest on average while simple span bridges are the roughest. Bridges with bituminous overlays are noticeably smoother on average than all other concrete surfaced bridges. Similar observations are found when looking at the RN analysis of the bridge segments. Table 6 describes the RN distributions of various bridge attributes. Most concerning is 94% of the bridges fall in the *Poor or below* ride quality categories.

TABLE 5 HCI Statistics by Bridge Attribute

	Bridge Attribute			Average	Half Car IRI inches/mile Minimum	Maximum	Std Dev	N - # of records
Main Structure	material	span type	span description					
	concrete	slab	simple span	191	51	326	66	16
	concrete	slab	continuos	163	43	405	48	323
	concrete	frame	simple span	176	175	177	1	2
	prestressed concrete	beam	simple span	210	118	294	71	6
	prestressed concrete	box beam	continuous	137				1
	steel	beam	simple span	205	121	288	42	38
	steel	beam	continuous	166	48	344	42	1153
	steel	truss	deck	155	132	190	21	5
	steel	girder	deck	145	88	210	37	20
	steel	girder	thru	152	116	171	31	3
	steel	girder	movable-bascule	160	154	166	8	2
Main Span Material								
			concrete	164	43	405	49	341
			prestressed concrete	200	118	294	71	7
			steel	167	48	344	43	1221
Main Span Type								
			slab	165	43	405	49	339
			beam	167	48	344	43	1197
			box beam	137				1
			truss	155	132	190	21	5
			girder	147	88	210	34	25
			frame	176	175	177	1	2
Main Span Description								
			simple span	201	51	326	51	62
			continuous	165	43	405	44	1477
			deck	147	88	210	34	25
			thru	152	116	171	31	3
			movable-bascule	160	154	166	8	2
Approach Alignment Appraisal								
		5	> minimum tolerable	152	109	219	39	10
		6	= present minimum criteria	150	65	224	46	25
		7	> present minimum criteria	154	44	288	45	143
		8	= present desirable criteria	167	43	405	46	1114
		9	> present desirable criteria	172	91	323	36	277
Approach Pavement Appraisal								
			good	163	43	405	43	1014
			fair	173	52	323	47	499
			poor	167	87	216	22	52
Wearing Surface								
		A overlay	superplast. dense concrete	166	87	323	37	244
		C overlay	microsilica mod. concrete	166	88	283	37	265
		1 overlay	concrete (seperate)	166	114	268	37	29
		2 not overlay	integral concrete (monolithic)	176	58	333	44	292
		3 overlay	latex mod.concrete	172	52	405	47	439
		4 overlay	dense concrete (Iowa system)	177	109	312	37	66
		5 overlay	epoxy overlay	179	143	230	38	5
		6 overlay	bituminous (AC)	140	43	294	49	216
All Records				167	43	405	45	1569

note: all Deck Types were reinforced concrete

TABLE 6 Distribution of RN by Attribute on Interstate Bridges

	Bridge Attribute			Excellent	Good	Ride Number Ranges Fair	Poor	Very Poor	Poorest
Main Structure	material	span type	span description						
	concrete	slab	simple span	6%			6%	44%	44%
	concrete	slab	continuos	1%	3%	6%	12%	51%	28%
	concrete	frame	simple span					50%	50%
	prestressed concrete	beam	simple span				33%	17%	50%
	prestressed concrete	box beam	continuous				100%		
	steel	beam	simple span				3%	39%	58%
	steel	beam	continuous	1%	1%	2%	6%	46%	44%
	steel	truss	deck					20%	80%
	steel	girder	deck			5%	10%	50%	35%
	steel	girder	thru					33%	67%
	steel	girder	movable-bascule						100%
Main Span Material									
			concrete	1%	3%	5%	11%	51%	28%
			prestressed concrete				43%	14%	43%
			steel	1%	1%	2%	6%	45%	45%
Main Span Type									
			slab	1%	3%	5%	12%	51%	28%
			beam	1%	1%	2%	6%	45%	45%
			box beam				100%		
			truss					20%	80%
			girder			4%	8%	44%	44%
			frame					50%	50%
Main Span Description									
			simple span	2%			6%	39%	53%
			continuous	1%	2%	3%	8%	47%	41%
			deck			4%	8%	44%	44%
			thru					33%	67%
			movable-bascule						100%
Approach Alignment Appraisal									
		5	> minimum tolerable				30%	30%	40%
		6	= present minimum criteria		4%	4%	16%	52%	24%
		7	> present minimum criteria	1%	4%	6%	7%	40%	43%
		8	= present desirable criteria	1%	2%	3%	7%	47%	41%
		9	> present desirable criteria			1%	7%	49%	44%
Approach Pavement Appraisal									
			good	1%	1%	2%	9%	49%	38%
			fair		2%	3%	6%	41%	48%
			poor		2%			50%	48%
Wearing Surface									
		A overlay	superplast. dense concrete			2%	3%	45%	50%
		C overlay	microsilica mod. concrete			1%	8%	56%	35%
		1 overlay	concrete (seperate)				3%	45%	52%
		2 not overlay	integral concrete (monolithic)				9%	48%	43%
		3 overlay	latex mod.concrete		3%	3%	8%	42%	44%
		4 overlay	dense concrete (Iowa system)				2%	55%	44%
		5 overlay	epoxy overlay					20%	80%
		6 overlay	bituminous (AC)	4%	6%	11%	12%	39%	29%
All Bridges				1%	2%	3%	8%	46%	41%

note: all Deck Types were reinforced concrete
system wide 6% of the bridges are in the Fair and above categories, 94% are Poor and below

Geographic Analysis and Presentation

It is difficult to describe, within the bounds of a paper, the usefulness of GIS software to both query and present the bridge and roughness information. The software allows the ride quality levels of the interstate highway to be geographically "seen." It is a powerful tool to be able to immediately recognize both high and low levels at a glance of a map. This is amplified when the data is queried via the software. For example, the file can be queried for all poor riding bridge segments. When the segments are displayed on the map, a click of the mouse allows every attribute of the bridge and associated roughness values to be displayed. The geographic presentation and analysis only expands the ability to utilize the data.

CONCLUSIONS

It is clear bridges have a significant detrimental effect on ride quality as measured by HCI and RN. Bridges account for a 7.6% increase in average HCI from 1,020 mm/km (66 in/mile) excluding the bridges to 1,100 mm/km (71 in/mile) including the bridges on Ohio's interstate highway system. Bridges are 145% rougher on average than the pure pavement segments of the network with an average HCI of 2,510 mm/km (162 in/mile). Likewise, the system reflects a 7% increase in *Poor and below* ride quality categories of RN, from 16% excluding to 23 % including the bridges. The decrease in ride quality on the system due to the presence of bridges is more consequential since they account for only 4% of the system by length. The vast majority of bridges, 94%, fall in the *Poor and below* RN categories.

It is difficult to use network level road profile data to identify specific bridge attributes that contribute to increased roughness. Specific attributes of bridges cannot easily be isolated/identified within the profiles in order to account for their specific contribution to ride quality, particularly on a system wide basis. Thus, no strong correlation between specific bridge attributes and ride quality could be found.

Although bridges are rougher than the pavement sections of the system, analysis of bridge segments revealed the following:

- Simple span bridges are the roughest of all bridges with an average HCI of 3,120 mm/km (201 in/mile).
- Deck spans are smoother on average than all other span types by a HCI range of 78-840 mm/km (5-54 in/mile).
- Bituminous overlays are smoother on average than all other wearing surfaces by a HCI range of 400-600 mm/km (26-39 in/mile).

Bridge smoothness specifications at ODOT do little to account for ride quality. ODOT has historically used a 3 meter (10-ft.) rolling straightedge specification for smoothness in bridge construction. A 3 meter (10-ft.) straightedge can not account for wavelengths in surface profile much longer than its base length of 3 meters (10 ft.). Ride quality indices are sensitive to a wider range of wavelengths. IRI is sensitive to wavelengths between 0.61 meters to 91 meters (2 ft. to 300 ft.) with peak sensitivity at 1.8 meters and 17 meters (6 ft. and 55 ft.). Similarly, RN is sensitive to wavelengths from 0.3 to 50 meters (1ft. to 165 ft.) with peak sensitivity at 6.1 meters (20 ft.) (*4*). Clearly the 3 meter (10-ft.) straightedge specification is accounting for only a small percentage of the wavelengths that are critical to ride quality.

Geographic presentation and analysis of ride quality data when linked to other data such as bridge information, is an extremely powerful tool. It increases the ability to leverage the data.

FUTURE WORK

1. Collection and detailed analysis of bridge specific profiles is needed to identify specific contributing factors/attributes of bridge roughness.
2. Investigation into bridge design details and bridge construction procedures may reveal good and bad practices for bridge projects with respect to ride quality.
3. Ride quality should be considered in the bridge design, construction, maintenance and acceptance processes. Development of new ride quality based smoothness specifications for bridges would benefit ODOT's highway system.

ACKNOWLEDGEMENTS

The author would like to express his sincere gratitude to Tom Ramsay of ODOT's Office of Technical Services. Mr. Ramsay supplied the GIS expertise, which made it possible to graphically link the separate data files. The genesis of this work came from conversations with Mr. Ramsay while working on another project. He envisioned the benefits of being able to "see" the effects of bridge roughness and was responsible for all geographic data presentations. He was critical to this work!

The author extends thanks to Dale Blosser, ODOT Office of Pavement Engineering's field staff member and primary road profiler operator, for his help in quality data collection and efforts in the work to reprocess files with bridge segments included.

Finally, the author extends thanks to ODOT's Office of Pavement Engineering, particularly Andrew Williams, Matthew McKenney, and the rest of the Pavement Management Section staff, for their support and contributions.

REFERENCES

1. Highway Performance Monitoring System Field Manual. December 2000. http://www.fhwa.dot.gov/ohim/hpmsmanl/hpms.htm. Accessed January 16, 2002.
2. State of Ohio Department of Transportation Office of Structural Engineering. *Bridge Inventory and Appraisal Coding Guide.* Published in-house, Columbus, June 2000.
3. State of Ohio Department of Transportation Office of Structural Engineering. *Bridge Inspection Manual.* Published in-house, Columbus, 2001.
4. Sayers, M. W., and Karamihas, S. M. *The Little Book of Profiling*. University of Michigan Transportation Research Institute, Ann Arbor, 1998.

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