Cite this article

Bechtel AJ, Brennan TM, Gurski K and Ansley J (2018)
Using anonymous probe-vehicle data for a performance indicator of bridge service.
Infrastructure Asset Management 5(3): 85–95,
<https://doi.org/10.1680/jinam.17.00015>

Research Article

Paper 1700015
Received 29/06/2017; Accepted 01/03/2018
Published online 13/04/2018

Keywords: bridges/management/
transport management

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Using anonymous probe-vehicle data for a performance indicator of bridge service

Andrew J. Bechtel

Department of Civil Engineering, The College of New Jersey, Ewing, NJ, USA (corresponding author: bechtela@tcnj.edu)
(Orcid:0000-0002-2133-8305)

Thomas M. Brennan Jr.

Department of Civil Engineering, The College of New Jersey, Ewing, NJ, USA (Orcid:0000-0003-2316-4983)

Kevin Gurski

Department of Civil Engineering, The College of New Jersey, Ewing, NJ, USA

Jessica Ansley

Department of Civil Engineering, The College of New Jersey, Ewing, NJ, USA

Anonymous probe-vehicle data are being used to evaluate travel time reliability and congestion conditions along roadways. These telematics data are collected from commercial and private cell phones, global positioning system devices and on-board vehicles computers. In the last few years, these data have been incorporated into reports of highway and arterial systems to measure congestion conditions. For this paper, anonymous probe-vehicle data were used to calculate a congestion metric, at bridge locations in New Jersey, USA, based on aggregated yearly congestion hours. The congestion metric was then compared to the functionally obsolete (FO) performance designation defined by the US National Bridge Inventory (NBI). These FO bridges represent structures that, according to the NBI, theoretically cause congestion. The comparison showed that the FO designation did not indicate high levels of congestion and vice versa. Consequently, when the congestion metric was implemented in a rudimentary management strategy, it provided a clearer decision-making process over the current traffic carrying metric in the NBI. The results of this study show that the aggregated congestion metric can serve as a useful performance indicator for bridge structures at a regional level, and it can provide value when incorporated into a bridge asset management programme.

Notation

C_{Hs}	congestion hours; number of 15 min bins whose speed drops below the threshold speed
N_s	15 min bin
T_s	threshold speed, the average space mean speed determined between 0200 and 0600 h
v_s	space mean speed

Introduction

Risk-based infrastructure management involves identifying, assessing and minimising unacceptable risk in the hopes of ensuring a desired level of performance or outcome. Assessing risk involves the implementation of measurable performance indicators (Carhart *et al.*, 2016; Dolan *et al.*, 2016). The risks to bridge structures can be due to extreme events, such as earthquakes, hurricanes, tornados and tsunamis, or involve catastrophic failure. The consequences of these types of events include the loss of life, money and mobility. There is also a risk associated with an asset performing improperly, which generally involves the loss of money (Proctor and Varma, 2012). For example, it was estimated that in the British, French, German and US economies over \$200 billion were lost due to traffic congestion in 2013. This number is expected to rise to US\$300 billion by 2030 (Anon, 2014).

Bridge structures are designed for strength and serviceability over their design life. The strength component ensures that the bridge will not experience structural failure. Serviceability is meant to ensure that the structure can carry the required type and number

of vehicles at the appropriate design speed. A bridge must perform well in each of these areas for it to be economically viable. There exist many forms of strength assessment for bridge structures ranging from visual inspection to proof loading. In the case of proof loading, a known load is applied to a bridge, and its response is directly measured. The serviceability in bridge structures has historically been evaluated indirectly using roadway geometry and average daily traffic (ADT). This indicates how, despite generally being managed separately, bridges are part of the transportation network. The roadway geometry that differs from the base condition theoretically reduces the calculated free-flow speed (National Research Council, 2016). In the presence of other vehicles, this reduction in the level of service for the bridge can be classified as congestion. The presence of congestion is an indicator of poor serviceability. However, conditions that in theory can result in congestion do not always produce congestion. Therefore, where the NBI might theoretically indicate the presence of congestions, once measured in the field, it may not be the case.

In the past, it had not been economically feasible to directly measure and quantify congestion. With the recent development of regionally dispersed commercially available anonymous probe-vehicle speed data, it is becoming possible to spatially and temporally evaluate congestion occurrence (Brennan *et al.*, 2014). Recent studies have applied performance measures based on these data to evaluate bridges, highway corridors, crash incidents and construction projects (Bechtel *et al.*, 2015; Brennan *et al.*, 2015; Lomax *et al.*, 2011, 2012; Remias *et al.*, 2012, 2013).

This paper presents an evaluation of 2211 bridges regionally dispersed in the state of New Jersey using a yearly congestion metric calculated from crowdsourced anonymous probe-vehicle data. The main goal of the work is to evaluate the yearly congestion metric as a performance indicator for bridge service that can be incorporated into bridge asset management strategies. The congestion metric is compared to the performance designation found in the US National Bridge Inventory (NBI). These performance designations evaluate bridge service using bridge and roadway geometry as well as ADT. The yearly congestion metric is then incorporated into a rudimentary management scheme to evaluate how the decision-making process changes using congestion performance measures.

NBI

The NBI is a comprehensive database containing information on the bridge structures in the US; it is openly available for anyone (FHWA, 2017). The NBI items are based on information from physical bridge inspections. The intent of the database is to represent the performance of bridges at a national level in a comparable way. The NBI contains a rating system with two performance designations: structurally deficient (SD) and functionally obsolete (FO). Structural deficiency is based on structural evaluations of the bridge's deck, super structure and substructure. The structural evaluation is based on the minimum capacity found between the deck, superstructure and substructure. The waterway adequacy is a comparison of the deck elevation and the elevation of a 100-year flood. A bridge is considered SD if any of the conditions shown in Table 1 are met. Likewise, a bridge is categorised as FO if any of the conditions in Table 2 are met. Based on NBI standards, structural deficiency supersedes functional obsolescence or, in other words, the risk of structural inadequacy outweighs the risk due to poor service. A bridge found to be FO may be due to low scores in the structural evaluation (S) or under clearances (U), which obstruct large heavy vehicles, requiring them to choose an alternate route. These types of obstructions will only minimally interfere in the daily flow of

traffic for the average passenger vehicle when compared over an entire year. Bridges classified as FO due to deck geometry (D), approach roadway alignment (A) or waterway adequacy (W) have geometries or obstructions that cause a reduction in speed.

A bridge determined to have poor deck geometry (D) does not have an adequate width or number of lanes to accommodate the ADT. A bridge with poor roadway alignment (A) is expected to require a speed reduction upon approach to improve throughput. A bridge with poor waterway adequacy (W) frequently floods, making it impassable during certain periods. Poor deck geometry can also be a function of insufficient under clearance (U). All these conditions, except lack of under clearance, are expected to result in a reduction in speed that can lead to congestion. Subsequently, improving these areas will help mitigate the risk of poor performance. An analysis of the 1992 NBI showed that the single leading cause for deficiency (including both SD and FO) was deck geometry (Dunker and Rabbat, 1995).

The designations in the NBI seek to mitigate poor performance. While the rating factors for deck geometry, road alignment and, to some extent, waterway adequacy are meant to represent areas where congestion might occur, they are in themselves not measures of congestion. The NBI uses ADT and bridge and roadway geometries to model conditions where congestion is likely.

New Jersey NBI data

The state of New Jersey serves as an excellent test bed for the evaluation of serviceability using congestion metrics. It is located on the eastern seaboard of the USA and has the highest population density of the 50 states. It is positioned between the first (New York, New York) and fifth (Philadelphia, Pennsylvania) most populated cities in the USA, as shown in Figure 1(a). The state of New Jersey is divided into 21 counties, which can be viewed in Figure 1(b). Within the state 6609 bridges were reported in the 2014 NBI. Of the 6609 bridges, 621 can be classified as SD and 1723 can be classified as FO. Consistent with the findings of Dunker and Rabbat (1995), an evaluation of the 2014 NBI data revealed that 62% of the bridges classified as FO and 44% of bridges classified as SD have deck rating less than or equal to 3. These structures should theoretically be causing congestion. Table 3 contains the total number of bridges as well as the number and per cent of SD and FO bridges within each county. Of the 21 counties, 16 have a total percentage of deficient bridge structures (Table 3) greater than the national average of approximately 25% (ASCE, 2013). Essex County has the highest

Table 1. SD NBI scoring categories (FHWA, 1995)

Category	NBI item number	Deficiency score
Deck condition	58	≤4
Superstructure	59	≤4
Substructure	60	≤4
Structural evaluation	67	≤2
Waterway adequacy	71	≤2

Table 2. FO NBI scoring categories (FHWA, 1995)

Category	Description	NBI item number	Deficiency score
Structural evaluation (S)	Capacity evaluation	67	≤3
Waterway adequacy (W)	Flood evaluation	71	≤3
Deck geometry (D)	Bridge width against ADT and number of lanes	68	≤3
Under clearances (U)	Height over roadway beneath	69	≤3
Approach roadway alignment (A)	Angle between bridge and approach	72	≤3

Figure 1. (a) State of New Jersey and (b) counties of New Jersey

Table 3. Deficient bridges per county in New Jersey

County	Bridges	SD		FO		Total per cent deficient
		Number	Per cent	Number	Per cent	
Atlantic	200	27	13.50	47	23.50	37.00
Bergen	553	49	8.86	194	35.08	43.94
Burlington	341	38	11.14	87	25.51	36.66
Camden	250	24	9.60	71	28.40	38.00
Cape May	64	7	10.94	6	9.38	20.31
Cumberland	98	5	5.10	4	4.08	9.18
Essex	497	36	7.24	207	41.65	48.89
Gloucester	242	15	6.20	36	14.88	21.07
Hudson	184	18	9.78	68	36.96	46.74
Hunterdon	365	47	12.88	93	25.48	38.36
Mercer	370	59	15.95	68	18.38	34.32
Middlesex	547	32	5.85	138	25.23	31.08
Monmouth	500	65	13.00	150	30.00	43.00
Morris	505	39	7.72	121	23.96	31.68
Ocean	237	15	6.33	41	17.30	23.63
Passaic	327	22	6.73	101	30.89	37.61
Salem	112	10	8.93	17	14.29	24.11
Somerset	387	33	8.53	74	19.12	27.65
Sussex	172	28	16.28	36	20.93	37.21
Union	402	22	5.47	110	27.36	32.84
Warren	256	30	11.72	54	21.09	32.81

percentage of deficient bridges, and it is tied with Bergen County for the most deficient bridges.

Table 4 organises the bridges by owner. Of the 6609 bridges in the state of New Jersey, approximately 36% are owned by the State Highway Agency, 39% are owned by the County Highway

Agency, 17% are owned by the State Toll Authority, 1% are owned by the local municipalities and the final 7% are owned by other agencies such as airport services and local toll authorities. The state of New Jersey, followed closely by its counties, owns the most deficient bridges in total. A greater percentage of bridges owned by other agencies are considered deficient.

Table 4. SD and FO bridges owned per agency

Owner	Total bridges	SD		FO		Total per cent deficient
		Number	Per cent	Number	Per cent	
State highway agency	2370	232	9.79	560	23.63	33.4
County highway agency	2589	277	10.70	512	19.78	30.5
State toll authority	1145	16	1.40	455	39.74	41.1
Local municipalities	86	5	5.81	18	20.93	26.8
Others	419	91	21.72	177	42.24	64.0

Determination of congestion metric

In order for a bridge's congestion to be evaluated using probe-vehicle data, it must be located adjacent to a traffic message channel (TMC). Of the 6609 bridges in the state of New Jersey, 2211 contain TMCs that span the structure. Only structures currently adjacent to TMCs were included in the current study. It is possible to request the addition of TMC segments, making the process explored in this study applicable to all bridges. The number of bridges with adjacent TMCs located in each county is given in Table 5. Table 5 also gives the number of bridges having SD and FO service designations. Half of these bridges are considered deficient due to deck geometry and ADT. Table 6

contains the number of SD and FO bridges owned by each agency located adjacent to a TMC. Figure 2 gives a visual comparison between the total numbers of SD and FO bridges located in the state of New Jersey compared to those that were analysed. The legend in Figure 2 gives the number of bridges in each category.

Commercially available crowdsourced anonymous probe-vehicle data was used to determine the congestion at bridge structures. These data are composed of timestamped speed data calculated in 1 min intervals for each TMC. The temporally and spatially defined speed data are derived from GPS signals. A timestamp is

Table 5. Deficient bridges per county in New Jersey with TMCs

County	Bridges	SD		FO		Total per cent deficient
		Number	Per cent	Number	Per cent	
Atlantic	48	6	12.50	15	31.25	43.75
Bergen	208	21	10.10	82	39.42	49.52
Burlington	151	16	10.60	49	32.45	43.05
Camden	132	13	9.85	40	30.30	40.15
Cape May	19	1	5.26	0	0.00	5.26
Cumberland	33	5	15.15	2	6.06	21.21
Essex	153	16	10.46	66	43.14	53.59
Gloucester	110	8	7.27	20	18.18	25.45
Hudson	75	9	12.00	27	36.00	48.00
Hunterdon	83	13	15.66	10	12.05	27.71
Mercer	154	24	15.58	33	21.43	37.01
Middlesex	201	18	8.96	66	32.84	41.79
Monmouth	153	25	16.34	52	33.99	50.33
Morris	154	10	6.49	45	29.22	35.71
Ocean	67	9	13.43	12	17.91	31.34
Passaic	138	11	7.97	51	36.96	44.93
Salem	34	2	5.88	10	29.41	35.29
Somerset	108	10	9.26	22	20.37	29.63
Sussex	28	6	21.43	6	21.43	42.86
Union	111	7	6.31	34	30.63	36.94
Warren	51	13	25.49	13	25.49	50.98

Table 6. Deficient bridges owned per agency with TMCs

Owner	Total bridges	SD		FO		Total per cent deficient
		Number	Per cent	Number	Per cent	
State highway agency	1211	135	11.15	314	25.93	37.1
County highway agency	559	82	14.67	144	25.76	40.4
State toll authority	326	5	1.53	145	44.48	46.0
Local municipalities	11	1	9.09	3	27.27	36.6
Others	104	20	19.23	49	47.12	66.4

Figure 2. New Jersey bridges reported in 2014 NBI: (a) total sufficient bridges, (b) analysed sufficient bridges near TMC, (c) total deficient bridges and (d) analysed deficient bridges near TMC

taken when a vehicle enters and leaves a TMC, and the difference in these timestamps gives the travel time along the TMC. An average speed is estimated by dividing the travel time by the length of the TMC. The averages are aggregated through a proprietary process and reported in 1 min increments. This study consisted of analysing approximately 2.4 billion speed records collected in 2014 for bridge structures in the state of New Jersey. The data were sorted into 15 min bins for each day of the year. Congestion is associated with a reduction in speed. For this study, congestion was assumed to occur when the speed dropped below a threshold speed. The threshold speed was calculated as the 70th percentile space mean speed (SMS) for each individual TMC, which was calculated using the average speed data between the hours 0200 and 0600 each day (Brennan *et al.*, 2015). In order to determine congestion hours, each SMS was compared to the congestion threshold speed calculated for each TMC and assigned a binary indicator. If the SMS fell below the threshold, the 15 min bin was assigned a value of one; if it was above the speed value, it was assigned a value of zero. This relationship is defined in Equation 1. C_{Hs} is the count of the 15 min bins (N_s) for a particular segment, where SMS (v_s) falls below the threshold speed (T_s) for the 15 min analysis period. The resulting values can then be summed and multiplied by 0.25 to calculate the congestion hours (C_H).

$$1. \quad C_{Hs} = 0.25 \times \sum N_s \quad [v_s < T_s]$$

The congestion hours for each TMC can then be grouped by hour, day, month or year. For this study, the C_{Hs} were aggregated into a yearly congestion metric. Once the numbers of bridges of concern have been reduced, the congestion hours can be visualised in different manners to evaluate the performance of individual bridges (Bechtel *et al.*, 2015).

The yearly congestion metric provides one aggregated number, which indicates how often a drop in free-flow speed occurs. It does not indicate why the speed has dropped or if the bridge is the cause for the drop in speed. In this way, the congestion metric is limited. There are many reasons why the free-flow speed adjacent to a bridge structure can decrease (construction, accidents, speed restrictions during school hours, an overabundance of vehicles etc.). However, it is possible for a bridge to have a high congestion metric due to conditions unrelated to itself. It needs to be considered that in the transportation network, bridges represent one of the most expensive elements. A linear foot of a highway bridge costs approximately five times more than a highway road of the same width. Using the yearly congestion metric at bridge locations not only helps highlight places in the transportation network experiencing congestion, but also highlights areas not experiencing congestion. This same limitation can be applied to the metrics for service implemented into the NBI. For example, if a bridge is considered to have insufficient width, but its width

matches the roadway conditions for 2 miles (3.21 km) in either direction, there is no benefit from just widening the bridge. Realistically, bridge service cannot ever be directly removed from the system behaviour of the transportation network.

Comparison of congestion metric to NBI performance designations

Figure 3 shows all of the analysed bridges with indicators scaled by the yearly congestion metric. The congestion metric does not necessarily indicate that the bridge is the cause of congestion: it is an indicator that there is a problem local to the bridge. Conversely, it also shows that there is not a problem at a bridge. To determine if the bridge is causing the congestion, each bridge must be looked at on a case-by-case basis. The bridges were broken into five arbitrary categories, which run from 0–500, 500–1000, 1000–2000, 2000–2500 and 2500–6500 h. An indicator that can be used to evaluate a significant number of congestion hours is the number of peak travel hours in a year. There are approximately six peak travel hours per day (7 a.m.–10 a.m. and 4 p.m.–7 p.m.) and approximately 258 workdays in a year. This gives about 1550 peak travel hours a year. Bridges approaching this value experience congestion every day during work commute periods. Many of the bridges with the highest yearly congestion metrics are located, as would be expected, close to New York City. From Figure 3(a), it can be seen that there are a number of sufficient bridges throughout the state with high yearly congestion metrics. Figure 4(b) shows that the SD bridges with high congestion metrics are mostly located near New York City and, to some extent, Philadelphia. FO bridges (Figure 4(c)) congregate in the same areas as the SD bridges.

Table 7 organises the bridges by NBI service designation and yearly congestion metric. Based on the information found in the New Jersey 2014 NBI data, it is expected, for the bridges analysed, that 50% of the deficient bridges, both SD and FO, would experience congestion. The results in Table 7 show that only 30% of deficient bridges have congestion metrics over 500 h. All SD bridges require consideration due to the risk associated with their strength, but FO bridges only pose a risk of poor performance. Based on the information found in the 2014 NBI, it is expected that 359 of the FO bridges analysed require consideration due to poor deck geometry and ADT. The ADT/AADT, in New Jersey, is calculated over a 48 h period, while the congestion performance measures are calculated 365 d a year, 24 h a day. High vehicle volume may occur at bridges, but if it does not result in a reduction in speed, there is no issue with bridge function. Only 16 of these bridges experienced congestion metrics over 500 h; that is 4% of what the FO service designation represents.

Figure 4 and Table 8 contain all 27 bridges that have congestion metrics over 2500 h. Eleven of these 27 bridges were considered sufficient according to the NBI; it is noted that most of these bridges are owned by the State Highway Agency. The majority of

Figure 3. Bridges scaled by yearly congestion metric: (a) sufficient bridges scaled by congestion metric, (b) SD bridges scaled by congestion metric and (c) FO bridges scaled by congestion metric

these bridges are located in Hudson County, which is adjacent to New York City. However, not all bridges were located near major metropolitan areas. There were bridges in Hunterdon and Ocean Counties that were both considered sufficient yet experienced congestion metrics over 2700 h. The ages of these bridges range from four to 100 years old, yet the average age of the bridges experiencing congestion metrics over 2500 h is 62. The two bridges with the highest congestion metrics are bridges 904151 and 901150. These bridges are a part of the Pulaski Skyway (Figure 4), which was under construction during the time analysed.

Table 9 categorises bridges by yearly congestion metric and county, while Table 10 categorises them by yearly congestion metric and owner. Hudson County contains nine bridges with congestion metrics in excess of 2500 h with the next highest being Bergen County. When looking at the data from the NBI, Bergen and Essex Counties were tied for the highest number of deficient (both FO and SD) bridges. Hudson County was well behind these counties in the number of deficient bridges, yet it experiences a large amount of congestion hours. If a general conclusion about bridge deficiency were made from the NBI, then

Figure 4. Bridges with yearly congestion metrics over 2500 h

Essex and Bergen Counties would contain the most deficient bridges. Hudson County was found to have the highest number of bridges with large yearly congestion metrics. The State Highway

Agency owns the largest amount of bridges with high congestion metrics. Of the bridges analysed and owned by the State Highway Agency, 12% had congestion metrics over 1000 h. This is double than that of the counties. Both the state and county agencies have approximately 26% of their bridges categorised, as FO (Table 6), but congestion is a larger problem for bridges owned by the state.

Implementation of congestion metric in a management strategy

In order to evaluate the usefulness of the congestion metric, a rudimentary bridge management strategy was implemented. The structural rating (NBI item 67) was used to represent the risk of structural failure while deck geometry (NBI item 68) was compared to the yearly congestion metric. The bridge length was incorporated to introduce a simple indication of cost. In the NBI, structural rating and deck geometry are ranked from zero to nine and are used to characterise a bridge's structural capacity and traffic capacity as a function of its ADT (FHWA, 1995). Figure 5 shows all the evaluated bridges in the state of New Jersey plotted by their structural and deck geometry appraisal rating factors as

Table 7. Bridges categorised by sufficiency and congestion hours

Category	Bridge at each congestion hours				
	2500–6500	2000–2500	1000–2000	500–1000	0–500
Sufficient	11	15	71	178	1038
SD	6	2	28	39	168
FO	10	13	60	117	455

Table 8. Bridges with yearly congestion metrics over 2500 h

Structure	County	Owner	Facility carried	Year built	Status	Congestion metric: h
904151	Hudson	State highway agency	NJ 139	1927	SD	6226.75
901150	Hudson	State highway agency	U.S. 1 + 9	1932	SD	6222.00
3800029	Hudson	Other state agencies	NJ-495 WB	1954	FO	3963.50
906161	Hudson	State highway agency	US 1&9T Ramp B	2011	Sufficient	3851.25
1504151	Ocean	State highway agency	US Route 9	1908	Sufficient	3815.75
3800027	Hudson	Other state agencies	NJ-495	1937	FO	3659.50
1410157	Morris	State highway agency	Route US 46	1940	Sufficient	3552.75
1514007	Ocean	County highway agency	County Route 528	1987	FO	3538.00
1402153	Morris	State highway agency	NJ Route 10	1931	SD	3204.25
709150	Essex	State highway agency	NJ 10	1959	Sufficient	3192.50
18G0404	Somerset	County highway agency	Blackwellsmills Rd	1994	Sufficient	3136.00
1208150	Middlesex	State highway agency	US 9 NB and NJ 35	1936	Sufficient	3107.50
1604158	Passaic	State highway agency	NJ Route 23 SBND	1967	Sufficient	2962.50
904154	Hudson	State highway agency	NJ 139 WB	1950	FO	2889.00
1213154	Middlesex	State highway agency	Route NJ 18 SB	1988	Sufficient	2854.00
1012154	Hunterdon	State highway agency	RT31	2005	Sufficient	2732.00
723151	Essex	State highway agency	Lyons Avenue	1976	FO	2709.50
1217150	Middlesex	State highway agency	NJ 27	1895	FO	2659.75
904152	Hudson	State highway agency	RT 139 EB Upper	1927	SD	2633.75
1103155	Mercer	State highway agency	Route US 1	2010	Sufficient	2604.00
221155	Bergen	State highway agency	US 46	1934	SD	2593.25
3800016	Bergen	State toll authority	I-95	1930	FO	2580.00
1100057	Mercer	County highway agency	Nottingham Way	1922	SD	2577.75
213151	Bergen	State highway agency	Terrace Ave. (CR 55)	1988	Sufficient	2543.00
3800026	Hudson	Other state agencies	NJ-495	1937	FO	2542.50
221156	Bergen	State highway agency	Route US46	1934	FO	2535.25
908150	Hudson	State highway agency	Paterson Plank Rd	1952	FO	2527.50

Table 9. Bridges categorised by yearly congestion metric and county

County	Bridges at each congestion metric level					Total
	2500–6500	2000–2500	1000–2000	500–1000	0–500	
Atlantic	0	0	1	4	43	48
Bergen	4	6	22	40	136	208
Burlington	0	2	3	10	136	151
Camden	0	1	15	27	89	132
Cape May	0	0	0	0	19	19
Cumberland	0	0	2	2	29	33
Essex	2	2	23	34	92	153
Gloucester	0	0	5	9	96	110
Hudson	9	4	20	15	27	75
Hunterdon	1	2	4	4	72	83
Mercer	2	2	4	23	123	154
Middlesex	3	4	17	40	137	201
Monmouth	0	1	9	9	134	153
Morris	2	1	10	35	106	154
Ocean	2	0	1	7	57	67
Passaic	1	1	12	31	93	138
Salem	0	0	0	1	33	34
Somerset	1	1	6	19	81	108
Sussex	0	0	0	0	28	28
Union	0	3	5	22	81	111
Warren	0	0	0	2	49	51

Table 10. Bridges categorised by yearly congestion metric and owner

Owner	Bridges at each congestion metric level					Total
	2500–6500	2000–2500	1000–2000	500–1000	0–500	
State highway agency	20	17	108	211	855	1211
County highway agency	3	5	28	63	460	559
State toll authority	1	7	16	45	257	326
Local municipalities	0	1	1	2	7	11
Others	3	0	6	13	82	104

defined in Table 11. The three different marks in Figure 5 represent bridge length as defined in Table 12.

Figure 5. All evaluated bridges plotted by structural and deck geometry rating

Since the structural and deck geometry rating values are whole numbers, the results of plotting them are a grid (Figure 5). As demonstrated in Figure 5, multiple bridges occupy each spot on the grid. As the bridges move up the y-axis, their structural rating decreases, which means that the bridges at the top of the graph require more attention structurally. As the bridges move right along the x-axis, their deck geometry rating decreases, which means that the bridges farthest to the right have inadequate deck

Table 11. NBI appraisal ratings (FHWA, 1995)

Code	Description
9	Superior to present desirable criteria
8	Equal to present desirable criteria
7	Better than present minimum criteria
6	Equal to present minimum criteria
5	Somewhat better than minimum adequacy to tolerate being left in place as is
4	Meets minimum tolerable limits to be left in place as is
3	Basically intolerable requiring high priority of corrective action
2	Basically intolerable requiring high priority of replacement
1	Not used
0	Bridge closed

Table 12. Length classifications for bridges

Type	Length
Short	0–14 m (0–45 ft)
Medium	14–46 m (45–150 ft)
Long	46 m and up (150 ft and up)

geometry as a function of their ADT. One logical management strategy is to improve structural safety first and then improve service second. In Figure 5, there are five bridges with a structural rating of zero, and 18 bridges with a structural rating of two. Of these 23 bridges, 18 belong to county highway agencies; none of these bridges is owned by the state highway agency. Only four of these bridges are long-span bridges. These bridges should be closed unless they serve a purpose; in which case, they should be replaced. Additionally, four of these bridges are medium span and one is short span; these bridges are slated for replacement.

Figure 6 shows all evaluated bridges with a structural rating of three plotted by their deck geometry rating and length. There are 27 bridges with a structural rating of three. Five of these bridges have a deck geometry rating of two, which indicates that they are a high priority for replacement (A–E in Figure 6). Three of these bridges are long-span bridges, and two are short-span bridges. Two bridges are owned by the state, one by a county and two by other agencies.

Figure 7 shows a breakdown of the Figure 5 grid structure, where the bridges are plotted by structural rating and the yearly congestion metric. Figure 8 shows all bridges evaluated with a structural rating of three plotted by length and yearly congestion metric. The labels of the five bridges with a deck geometry rating of two are carried over from Figure 5. These bridges do not experience congestion metrics over 1000 h. The bridge that experiences the highest congestion metric has a deck geometry

Figure 6. Bridges with a structural rating of three plotted by deck geometry rating and length

Figure 7. Bridges plotted by yearly congestion metric and deck geometry

rating of 3. Using the NBI ratings, five bridges, three of which are long span, would have been replaced before this bridge. When Figure 6 is compared to Figure 8, the benefits of the congestion metric become clear. For bridges with a high structural risk, it helps define the order which deficient bridge will be improved or replaced.

Summary and conclusions

Yearly congestion metrics based on anonymous probe-vehicle data were determined for 2211 bridges in the state of New Jersey. The analysis was performed at a large regional level without field evaluation. Without a field evaluation, the congestion metric cannot be directly tied to the bridge structure; it only indicates that the transportation system in the area is experiencing congestion. This congestion may or may not be caused by the bridge structure. When the yearly congestion metric was compared to the FO service designation found in the NBI, only

Figure 8. Bridges with a structural rating of three plotted by yearly congestion metric and length

4% of FO bridges analysed experienced congestion metrics over 500 h in 2014. Only 55% of the bridges found to have yearly congestion metrics over 2500 h were identified as FO or SD in the 2014 NBI. Roadway conditions, which theoretically cause congestion, do not always cause congestion and vice versa. Higher congestion metrics were observed closer to large cities and on bridges owned by the state of New Jersey. When the yearly congestion was implemented in a rudimentary management strategy, it showed an advantage because it was a continuous yearly measurement as opposed to a rating number based on site conditions and a 48 h ADT collection.

The yearly congestion metric offers advantages over the FO service designation found in the NBI. The congestion metric serves as a measurement of what is happening in the state, while the NBI FO service designation relies on geometry and traffic counts to predict congestion conditions. Large congestion metrics do not indicate that the bridge itself is causing the congestion, but it identifies bridges with and without a local congestion issue. With the congestion issue identified, a proper analysis and engineering judgement can be used to make decisions about the structure and surrounding areas. Congestion hours can be aggregated and used in different ways to evaluate individual bridges as shown by Bechtel *et al.* (2015). As part of a risk-based assessment plan, congestion hours calculated from anonymous probe-vehicle data can be used as a tool to evaluate the service of a bridge or roadway. Minimising congestion hours will improve the overall performance and travel time reliability of an agency's transportation infrastructure. For these reasons, the yearly congestion metric has been found to be a valuable performance indicator. The next step in this research is to evaluate the cost of congestion for a motorist, which will make it possible to weigh the cost of an intervention against the benefit of improved service.

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