PennState | Center for Integrated Asset Management for MultiModal Transportation Infrastructure Systems

PROJECT SUMMARY

INVESTIGATION OF THE BENEFIT OF USING NOVEL CORROSION-RESISTANT STEEL IN NEW AND EXISTING BRIDGES IN PENNSYLVANIA

This document is a technical summary of the U.S. Department of Transportation report, *Investigation of the Benefit of Using Novel Corrosion-resistant Steel in New and Existing Bridges in Pennsylvania,* Report CIAM-UTC-REG6 (03.10.2022)

INTRODUCTION

The objective of this study was to investigate the benefit of using a novel corrosion-resistant steel, namely A709-50CR, for steel girder bridges in Pennsylvania. Previous investigations (Frangopol et al. 2020) indicate that using A709-50CR girders to conduct replacement can lead to a reduced maintenance budget compared with using new carbon steel girders under stringent requirement of lifecycle risk. As the research on lifecycle analysis of infrastructure systems is gaining momentum, the research scope of the application of corrosion-resistant steel in bridge maintenance actions should be extended from the individual bridge project level to the bridge network level.

The objective of this research was to investigate the cost-effectiveness of A709-50CR over carbon steel at a bridge network level.

The configuration of the bridge network investigated herein is shown in Figure 1. Two links in opposite directions connecting the same two nodes constitute one segment. Three pairs of bridges exist in this network, which are bridges B2/B3, B6/B7, and B9/B10. The two bridges in a pair carry the two-way traffic in opposite directions with the same or similar geometry as well as identical construction/reconstruction time.

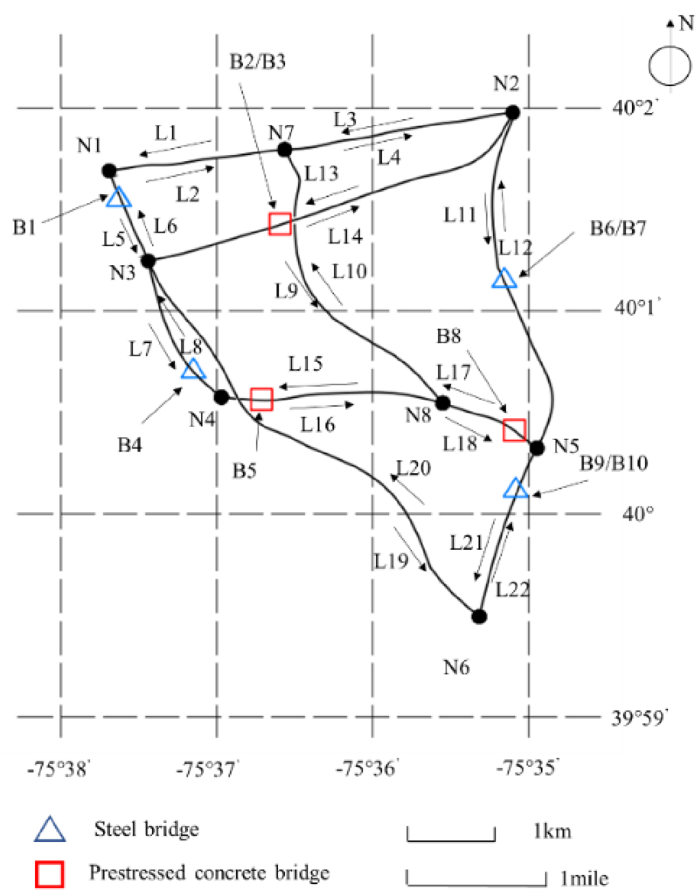


Figure 1. Bridge network in Chester County, PA.

METHODOLOGY

Optimal maintenance solutions associated with girder replacement using either A709-50CR or carbon steel girders were obtained herein through optimization processes. Corrosion modeling was considered to obtain time-variant girder resistances as well as time-variant correlation coefficients among girder resistances. Performance functions of girders were established based on AASHTO specifications (AASHTO 2017). System reliability analysis was then conducted to obtain time-variant system reliability profiles. Failure consequence evaluation was conducted to obtain time-variant risk profiles. Genetic algorithm was utilized to determine the optimal maintenance solutions for individual bridges or bridge networks.

In a bridge network, travelers' path choice behavior, i.e., which path the travelers will take when multiple paths are available for an O-D (origin-destination) pair, can influence the traffic volume on each link when the O-D demand matrix (which provides the information on the number of travelers associated with each O-D pair) is fixed. Different user equilibrium approaches have been proposed to characterize travelers' behavior (Bell and Lida 1997). These approaches can be categorized into two major types, namely the deterministic user equilibrium approach and the stochastic user equilibrium approach. The deterministic user equilibrium approach assumes that traffic users will definitely select the least-cost path (the path with the minimum travel time) when facing multiple path choices. The stochastic user equilibrium approach acknowledges the fact that due to the imperfect knowledge of traffic users on the path cost, the least-cost path will only be selected by the traffic users with a higher probability than higher-cost paths.

Among all the traffic assignment models associated with the stochastic user equilibrium approach, the logit assignment model (Dial 1971) is a widely used model that can be integrated into stochastic user equilibrium calculation. For a specific O-D pair with n paths, the probability that a specific path k is selected by traffic users based on the logit assignment is (Bell and Lida 1997)

$$P_k = \frac{\exp\left(-\theta C_k\right)}{\sum_{j=1}^{n} \exp\left(-\theta C_j\right)} \tag{1}$$

where C_k is the travel cost on path k; C_j is the travel cost on path j; n is the number of available paths; and θ is the dispersion factor characterizing traffic users' sensitivity to the travel cost. A very large θ (e.g., larger than 10^3) indicates that traffic users will choose the least cost path, while $\theta = 0$ indicates that traffic users will choose all the paths with an equal probability. $\theta = 1$ is adopted herein, which indicates a moderate sensitivty toward the path cost.

DATA SUMMARY

Table 1. Information on bridges in the network.

Bridge ID	Structural Number in NBI database	Latitude (degree)	Longitude (degree)	Bridge	Material of Superstructure	Length (m)	Width (m)	Year Built	Time of Last Renovation	Years in Service before 2020
B1	10066	40.02769	-75.6278	MGS	S	9.5	38.7	1954	Reconstr. 2000	20
B2	10003	40.02414	-75.6089	MGS	PC	27.9	13.3	1994	-	26
B3	10001	40.02392	-75.6090	MGS	PC	27.9	13.3	1994	-	26
B4	10060	40.01152	-75.6156	MGS	S	32.3	9.8	1968	Reconstr. 2009	11
B5	10402	40.00949	-75.6144	BGS	PC	28.0	13.9	1968	1990	30
B6	10112	40.01926	-75.5861	MGC	S	35.7	13.4	1968	1998	22
B7	10111	40.01936	-75.5859	MGC	S	35.7	13.4	1968	1998	22
B8	10403	40.00548	-75.5824	BGS	PC	17.7	13.4	1968	2000	20
B9	10109	40.00163	-75.5848	MGS	S	15.1	14.7	1968	1998	22
B10	10108	40.00177	-75.5844	MGS	S	15.1	13.4	1968	1998	22

Note: MGS means multi-girder simply supported, MGC means multi-girder continuous, BGS means box girder simply supported, S means steel, PC means prestressed concrete.

Table 2. Information on links in the network.

Link Number	First Node	Second Node	Free Travel Time(min)	Length of Link (km)	Critical Capacity (cars/h)	Number of Lanes	Free Speed (km/h)
1(2)	1	7	1.3	1.60	2000	1	72
3(4)	2	7	1.8	2.12	2000	1	72
5(6)	1	3	0.7	0.89	8000	4	72
7(8)	3	4	0.6	0.75	4000	2	72
9(10)	7	8	3.2	2.96	2000	1	56
11(12)	2	5	2.2	3.31	4000	2	90
13(14)	2	3	2.4	3.69	4000	2	90
15(16)	4	8	3.1	2.91	2000	1	56
17(18)	5	8	1.2	0.82	2000	1	56
19(20)	3	6	2.8	4.24	4000	2	90
21(22)	5	6	1.4	2.09	4000	2	90

Note: Free speed is the speed of vehicles traveling if there were no congestion or other adverse conditions.

Table 3. Daily Traffic flow on each link.

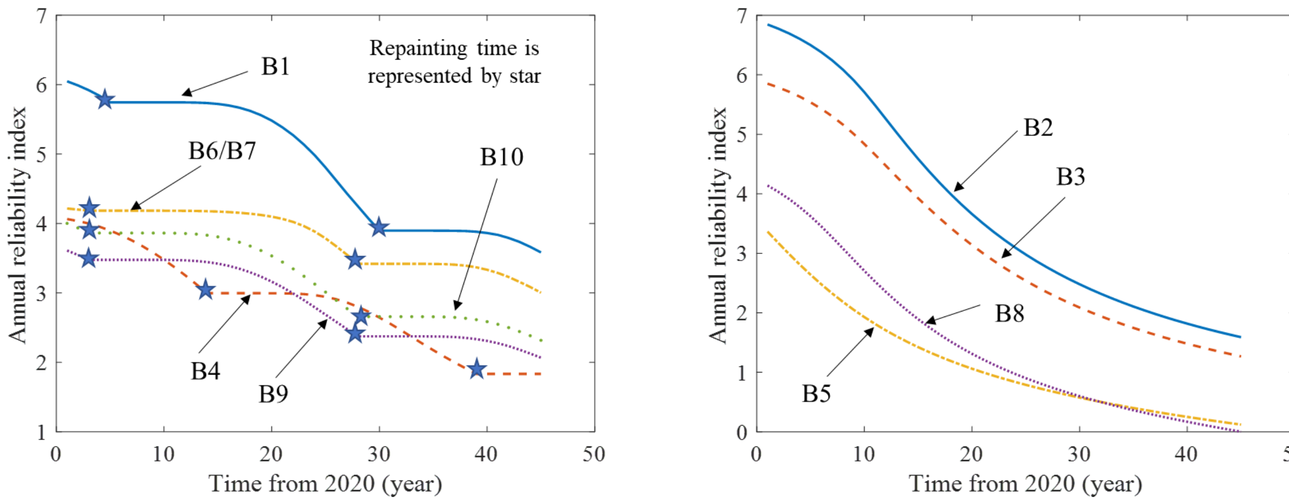
Link Number	Car	Truck
1	7274	460
2	7661	456
3	3960	262
4	4010	260
5	20254	1579
6	22560	1176
7	8742	476
8	7190	367
9	3069	94
10	3017	94
11	13630	1561
12	13146	1654
13	14372	2163
14	13430	2295
15	4631	142
16	4623	144
17	6235	542
18	6277	546
19	13980	2486
20	14449	1997
21	20467	587
22	19919	661

Source: PennDOT (2021).

EVALUATION RESULTS

Cost premium of A709-50CR over carbon steel is also an influence factor on the cost-effectiveness of A709-50CR. As A709-50CR is a relatively new construction material, its cost is subject to fluctuations and estimation of its cost premium over carbon steel has a considerable dispersion. The cost premium of A709-50CR over carbon steel has been determined as 16.4% (Kogler 2015). Annual discount rate of money is assumed to be 2%.

Time-variant annual reliability index profiles of all 10 bridges in the bridge network are shown in Figure 2. It can be seen that the safety level of steel bridges in the bridge network (Figure 2(a)) is higher than that of prestressed concrete bridges (Figure 2(b)) due to the repainting actions (time of repainting actions is represented by a star in Figure 2(a)).



(a) steel bridges (b) prestressed concrete bridges

Figure 2. Annual reliability profiles of individual bridges (time of repainting of steel bridges is marked by stars).

Two cases were investigated to determine the influence of the user equilibrium approach on the user cost; namely

- Case I: Deterministic user equilibrium (all-or-nothing assignment is used)
- Case II: Stochastic user equilibrium (logit assignment with $\theta = 1$)

Time-variant risk profiles associated with Cases I and II are plotted in Figure 3. It can be seen that as user cost estimation using the deterministic user equilibrium approach (i.e., Case I) leads to an overestimation of failure consequence, an overestimation of risk will occur if the deterministic user equilibrium approach is used.

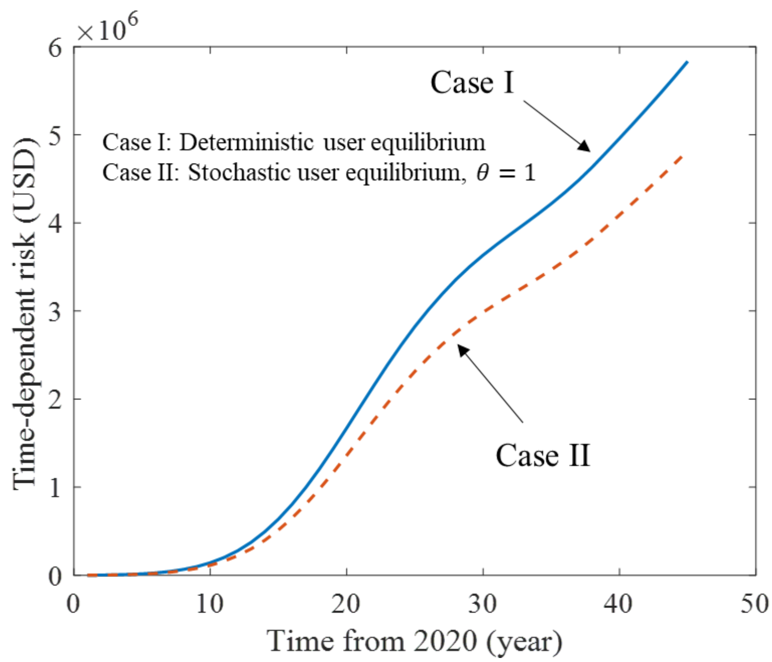
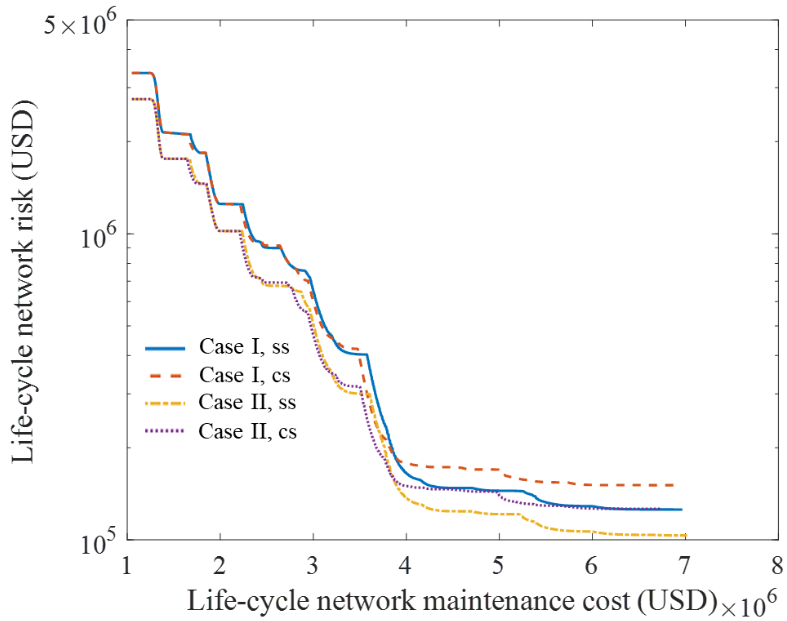


Figure 3. Time-dependent risk profiles.

The optimal Pareto fronts associated with lifecycle management of the bridge network in Chester County, PA, are shown in Figure 4. The two Pareto fronts associated with Case I are termed as “Case I, ss” and “Case I, cs”, where “ss” and “cs” refer to A709-50CR steel and carbon steel girders, respectively. Similarly, the two Pareto fronts associated with Case II are referred to as “Case II, ss” and “Case II, cs”.

Taking Case I as an example, for the two Pareto fronts associated with the same type of user equilibrium, when the target lifecycle risk is low (smaller than 2.27×10^5 USD in this case), using A709-50CR steel to perform replacement leads to a lower cost than using carbon steel. When the target lifecycle risk is higher, the Pareto front of “Case I, ss” overlaps that of “Case II, cs” at several risk level ranges (from 1.23×10^6 USD to 1.59×10^6 USD, from 2.14×10^6 USD to 2.56×10^6 USD, from 3.16×10^6 USD to 4.44×10^6 USD), which indicates that if the target risk falls in these ranges, the cost-effectiveness of using A709-50CR or carbon steel is the same. Comparison between the two Pareto fronts associated with using the same type of materials shows that due to an overestimation of the life-cycle risk by using deterministic user equilibrium approach, more costly maintenance plans may be requested under a fixed target life-cycle network risk.



Note: Case I and Case II are associated with deterministic user equilibrium and stochastic user equilibrium, respectively. “ss” refers to A709-50CR steel; “cs” refers to carbon steel.

Figure 4. Risk-based optimal Pareto fronts.

CONCLUSION AND IMPLEMENTATION

- Using deterministic user equilibrium approach to estimate life-cycle network risk can be very conservative. Therefore, adopting the maintenance strategy determined using this equilibrium may lead to a waste of financial and human resources. The traffic users’ sensitivity to the travel cost may play a crucial role in the user cost estimation in the stochastic user equilibrium approach. Therefore, parametric analysis on the value of θ in the logit assignment model may be worth carrying out.
- When the target life-cycle risk is low, using A709-50CR steel can lead to a lower maintenance budget for the management of bridge network compared with using carbon steel to conduct replacement. The target risk level at which using carbon steel or A709-50CR for steel bridge replacement is equally cost-effective is contingent upon multiple factors, such as the failure consequence of the bridges in the network and the failure probabilities of each bridge, among others. The user equilibrium estimation approach adopted may also have an impact on this specific target risk level.
- Further research work should include failure consequences evaluation in terms of user cost under other stochastic assignment models (e.g. probit assignment (Daganzo and Sheffi 1977)). Conducting on-site survey to have a better understanding of traveler’s behavior when facing multiple paths may be worthwhile for large-scale networks. Failure consequences associated with injuries and fatalities as well as extra greenhouse gas emissions may be considered to conduct risk analysis in a more comprehensive manner.

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