University Transportation Research Center - Region 2

Final Report

Transportation Infrastructure Robustness: Joint Engineering and Economic Analysis

Performing Organization: City University of New York (CUNY)

November 2017

Sponsor:
University Transportation Research Center - Region 2

University Transportation Research Center - Region 2

The Region 2 University Transportation Research Center (UTRC) is one of ten original University Transportation Centers established in 1987 by the U.S. Congress. These Centers were established with the recognition that transportation plays a key role in the nation's economy and the quality of life of its citizens. University faculty members provide a critical link in resolving our national and regional transportation problems while training the professionals who address our transportation systems and their customers on a daily basis.

The UTRC was established in order to support research, education and the transfer of technology in the field of transportation. The theme of the Center is "Planning and Managing Regional Transportation Systems in a Changing World." Presently, under the direction of Dr. Camille Kamga, the UTRC represents USDOT Region II, including New York, New Jersey, Puerto Rico and the U.S. Virgin Islands. Functioning as a consortium of twelve major Universities throughout the region, UTRC is located at the CUNY Institute for Transportation Systems at The City College of New York, the lead institution of the consortium. The Center, through its consortium, an Agency-Industry Council and its Director and Staff, supports research, education, and technology transfer under its theme. UTRC's three main goals are:

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The research program objectives are (1) to develop a theme based transportation research program that is responsive to the needs of regional transportation organizations and stakeholders, and (2) to conduct that program in cooperation with the partners. The program includes both studies that are identified with research partners of projects targeted to the theme, and targeted, short-term projects. The program develops competitive proposals, which are evaluated to insure the mostresponsive UTRC team conducts the work. The research program is responsive to the UTRC theme: "Planning and Managing Regional Transportation Systems in a Changing World." The complex transportation system of transit and infrastructure, and the rapidly changing environment impacts the nation's largest city and metropolitan area. The New York/New Jersey Metropolitan has over 19 million people, 600,000 businesses and 9 million workers. The Region's intermodal and multimodal systems must serve all customers and stakeholders within the region and globally.Under the current grant, the new research projects and the ongoing research projects concentrate the program efforts on the categories of Transportation Systems Performance and Information Infrastructure to provide needed services to the New Jersey Department of Transportation, New York City Department of Transportation, New York Metropolitan Transportation Council , New York State Department of Transportation, and the New York State Energy and Research Development Authorityand others, all while enhancing the center's theme.

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16. Abstract

The objectives of this study are to develop a methodology for assessing the robustness of transportation infrastructure facilities and assess the effect of damage to such facilities on travel demand and the facilities users' welfare. The robustness of transportation facilities is related to two types of damage: a) longitudinal deterioration in facility engineering quality; and b) sudden shock due to unexpected extreme events. This study focuses on the first determinant and its economic implications. Achieving the stated objectives requires reviewing the basic principles of infrastructure durability, modeling the relation between travel demand and infrastructure damage, and analyzing users' economic welfare. Economic welfare is expressed in terms of Consumer Surplus (CS) which is defined as the difference between what users of a transportation facility are willing to pay in terms of travel time and associated direct costs such as the cost of fuel and what they actually spend. When deterioration occurs in one facility within the network, the equilibrium travel time and associated costs on this facility will increase and thus travelers' CS will drop.

To illustrate the proposed analysis procedure, this study implements the basic concepts using a numerical example that assesses the robustness of an infrastructure system consisting of a two-bridge network comprising the Whitestone Bridge and the Throgs Neck Bridge that connect the boroughs of Queens and the Bronx of New York City. The two bridges are found to be substitute facilities as the total traffic on the combined network remains essentially constant. Peak traffic volume on each facility was found to be directly related to the condition of the bridge deck riding surface. The condition of the deck surface is expressed by the Deck Condition Rating (DCR) reported by bridge inspectors. As the deck surface condition deteriorates and DCR decreases, peak traffic volume on the deteriorating facility also decreases while traffic volume on the substitute facility increases. These changes in peak traffic volumes and riding surface conditions increase travel time on both facilities leading to higher users costs.

The results of the analysis show that when the DCR of one of the two facilities composing the network decreases by 1% from its best condition, the facility consumer's surplus decreases by 2.41% due to preventing some users from using the facility. At the same time, the consumer surplus of the substitute facility will also decrease by 5.91% due to the congestion resulting from the additional users who migrate from the deteriorated facility. The consumer surplus of the entire network will diminish by 2.47 %. Where a drop of one level on the 1-7 condition rating scale used by New York State represents a 14% decrease in DCR.

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Executive Summary

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The numerical results of the investigation of the Whitestone/Throgs Neck Bridge network are summarized in Table A. The results of the analysis show that when the DCR of one of the two facilities composing the network decreases by 1% from its best condition, the facility consumer's surplus decreases by 2.41% due to preventing some users from using the facility. At the same time, the consumer surplus of the substitute facility will also decrease by 5.91% due to the congestion resulting from the additional users who migrate from the deteriorated facility. The consumer surplus of the entire network will diminish by 2.47 %. Where a drop of one level on the 1-7 condition rating scale used by New York State represents a 14% decrease in DCR.

Table A: Impact of riding surface deterioration of Whitestone/Throgs Neck Bridge Network

Consumer Supply for the Two-Bridge Network			
	Whitestone	Throgs Neck	**Total Network**
Pre-deterioration (riding surface condition rating = 7)			
Peak-hour volume (vehicles/minute)	8083	6907	**14990**
Consumer Surplus ($)	$763	$12.80	**$775.8**
Post Deterioration (riding surface condition rating =6)			
Peak-hour volume (vehicles/minute)	7808	6963	**14771**
Consumer Surplus ($)	$500	$2.00	**$502**
Welfare changes			
Change in peak-hour volume (vehicles/mn)	- 275	56	**-219**
Change in Consumer surplus ($)	- $263	$-10.80	**-$273.8**
Elasticity of CS w.r.t deterioration (%)	**2.41**	**5.91**	**2.47**

Chapter 1

Introduction

1.1 Background

This study deals with the modeling and measurement of the factors that underlie the robustness of transportation infrastructure facilities and networks. In general, the concept of transportation system robustness encompasses two main determinants: a) the level of service provided by transportation facilities in face of “normal” deterioration in primary engineering factors, such as the quality of the facility’s surface or structural damage; b) the ability of the system to withstand a major natural disaster such as an extreme severe storm. In this study, we focus on the first determinant, namely overtime decline in facility engineering quality. Specifically, we combine engineering, traffic and economic analysis by studying longitudinal changes in facility engineering structural factors and, as a consequence, their implications on travel and economic welfare of users.

In the literature, the terms facility “robustness”, “durability” and “resiliency”, often are used interchangeably to indicate a system’s ability to endure longitudinal structural damage and sudden disastrous changes relative to its optimal functioning state and output level. In the present study, we choose to use the term robustness. It is noted that a transportation facility, such as a bridge, is normally a link in a larger network or system of facilities. Thus, what affects the level of output of a single facility has bearings on the entire network’s level of output. These relationships need to be regarded when analyzing the robustness of the facility and the system it belongs to but are beyond the scope of this study.

A key policy implication from this study is the issue of optimal maintenance scheme of transportation infrastructure facilities aimed at keeping them in a state of good repair. Given the limited resources available for maintaining the Nation’s infrastructure,[1] defining non-subjective measures of infrastructure robustness is essential for establishing benchmarks that will help policymakers develop approaches for prioritizing the allocation of funds to particular systems to yield the highest economic returns. Currently there is no consensus among researchers and stakeholders on acceptable and non-subjective measures for evaluating the impact of investing in infrastructure robustness**.** The analysis and development of such measures is a major objective of this study.

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[1] As an example, in the year 2015, 58,495 bridges out of the 609,539 bridges in the United States have been rated as structurally deficient. These represent 9.6 percent of the bridge stock in the nation as reported in the article entitled “Analysis Reveals 58,495 U.S. Bridges Are Structurally Deficient” published in Civil Engineering, The journal of the American Society of Civil Engineers, March 15, 2016.

1.2 Research Objectives and Report Outline

The main objectives of this study are to develop a methodology for assessing the robustness of transportation infrastructure facilities and assess the effect of damage to such facilities on travel demand and the facilities users' welfare. Achieving these objectives requires a review of the basic principles of infrastructure durability, the relation between travel demand and infrastructure damage and economic users' welfare and methods to measure each of these factors. For this aim, Chapter 2 of this Report reviews the definitions of these main factors. Chapter 3 presents an analytical framework for measuring transportation facility robustness. Chapter 4 presents current methods for evaluating infrastructure damage. Chapter 5 describes traffic demand modeling. Chapter 6 discusses economic welfare models as they pertain to transportation facilities. Chapter 7 describes how to implement the concepts described in Chapters 1 through 6 using a numerical example that assesses the robustness of an infrastructure system consisting of two-bridge network connecting the boroughs of Queens and the Bronx of New York City. Chapter 8 gives the conclusion.

Chapter 2

Elements of Infrastructure Durability

We distinguish between two types of analysis in measuring the robustness of transportation facilities: engineering and economic. For the purpose of this review, we refer to the first as engineering durability; the second is travel and welfare analysis.

2.1 Durability Concepts

We measure the output from a transportation facility by the Level of Service (LOS) it produces, which in turn is measured as the number of vehicles (or users) that can travel a unit distance at a given speed level. The quantification of the effect of a facility's (e.g., a bridge) structural deterioration on LOS reduction requires the use of engineering analysis that examines causes for and the level of erosion over time, and it effects on traffic flow. In this study, we focus on bridges, which are complex systems with various components that are susceptible to damage.

Researchers have proposed several models that relate the LOS and the performance of various components of the transportation infrastructure facilities to different physical phenomena. A Markov Chain approach is commonly used to evaluate over-time changes in the main components of a bridge and their effects on its performance [Madanat et al. (1997), Morcous (2006), Agrawal et al. (2010)]. However, the time-dependent deterioration of each component influences traffic flow in a different way. In general, it is the deterioration of the bridge's riding surface that has the most noticeable long-term effect on LOS, thus on traffic flow. Although we are not aware of any model that evaluates the effect of a bridge's riding surface on traffic, there are several models that describe the performance level of pavements and that can be used for assessing the effect of bridge riding surface condition on the facility's LOS.

The most commonly used model to quantify the quality of a pavement is the Present Serviceability Index (PSI) developed by the American Association of State Highway and Transportation Officials (AASHTO) [HRB (1962), AASHTO (1993)]. Further modifications of this model are due to Madanat (1994), Madanat et al. (1995), Prozzi (2004) and Shoop et al. (2006). An alternative measure of pavement performance is the International Roughness Index (IRI) [Sayers et al. (1986), Huang (2004), Ihs (2004), Greene (2013), HDM-4]. Hall and Munoz (1999) have developed a model to convert PSI values into IRI for flexible and rigid pavements to simplify comparisons of pavements rated by the two measures.

Changes in bridge component condition ratings are available through databases such as the National Bridge Inventory (NBI) or the AASHTO Bridge Management System (BMS) previously known as Pontis. Most states use the scale proposed by the Federal Highway Administration (FHWA). However, New York State (NYS) has its own scale. In this report, we use the New York State scale for Condition Rating of Bridge Components as discussed further below.

2.2 Travel Analysis

Given the importance of bridges and road networks for the US transportation infrastructure system, their level of robustness, in terms of their ability to maintain a required Level of Service is of prime significance to decision-makers (Shiomi et al, 2011; Ben Immers et al, 2005; Tierney 2007). In the economic literature, it is widely accepted that the effect of changes in LOS of a transportation infrastructure facility is best measured in monetary units (Berechman et al, 2007, 2009). This, in turn, requires the quantification of users' travel times and direct costs, as well as the costs of reliability and uncertainty. Loss of wider economic benefits, such as effects on jobs, must also be considered (Banister and Berechman, 2000). Since travel time is a key component in assessing the economic value of LOS loss, its monetization has received much attention in the literature. Three approaches for measuring the Value of Time (VOT) dominate the literature. These include:

a) "Formal" VOT as used in studies of benefit-costs analysis (Rouwendal, 2003);
b) The subjective value of time (SVOT), which relates actual travel time to users' perceived value of it (Armstrong et al., 2001);
c) The social price of time (SPOT), which evaluates VOT for society, which is different from the VOT for individual users.

In addition to travel time, reduced LOS caused by the decline in system's robustness has direct impacts on: travel safety; fuel consumption; reduced labor productivity; environmental costs; and, through downstream impacts, on logistics chains. This compounding makes VOT for freight transport considerably higher than any of the other categories of individual travel (NCHRP, 1999; Weisbrod et al, 2003). Finally, risk and uncertainty from LOS changes play a major role in transportation analysis (Berechman and Chen, 2011).

2.3 Economic Welfare Measures of Durability

When the robustness of transportation infrastructure (e.g., a major bridge), deteriorates it will have effects on travel conditions, mainly peak-time travel volumes. This, in turn, will increase users' costs of travel (time and money), thereby affecting the users' welfare. Welfare is measured by Consumers Surplus (CS), which indicates the level of loss of welfare from worsened market conditions (i.e., the increased costs of travel). In the application section of this report, we demonstrate this argument through an empirical analysis of two key bridges in New York. Changes in CS, caused by declining robustness conditions, are used as our measure of consequent welfare changes of users on specific facilities.

2.4 Linking Engineering, Travel and Economic Models

How can we link the engineering, travel and welfare models so that one may answer policy questions such as: "what is the optimal maintenance program?" Pablo and Pattharin, (2009) have formulated the problem of developing optimal maintenance policies for a multi-facility transportation system as a Quadratic Program (QP).[2] In their formulation, each facility's deterioration and travel demand components are represented as linear systems using an autoregressive moving average model with exogenous inputs (ARMAX).[3] The model proposed by Pablo and Pattharin (2009) explicitly captures the linear relationship between travel demand and infrastructure deterioration. In addition, the elements that comprise the system are interdependent because the state of a single facility can affect the demand at other facilities. This phenomenon is known as functional dependencies.

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[2] QP is the problem of optimizing a quadratic function with several variables, subject to a set of linear constraints on these variables.

[3] ARMAX models provide a description of a stationary stochastic process in terms of two polynomials, one for the auto-regression and the second for the moving average.

Chapter 3

Analytical Framework for Measurement of Transportation Facility Robustness

3.1 Theoretical Considerations

As explained earlier, the quantification of infrastructure robustness requires an understanding of the relationships between the economic factors associated with LOS changes and the underlining engineering factors such as the structural condition and material properties of individual components. We regard the transportation infrastructure to be in a state of good repair when the system is able to provide adequate Peak–Hour Level of Service (LOS). We measure LOS in units of traffic (vehicles), that traverse a unit distance (1 mile), per unit time (1 hour) at a minimum required speed (miles/hour) and at a minimum safety level (collision rates). We distinguish between two main factors that jointly define infrastructure's robustness. These are system's durability and system's resiliency.

Durability of an infrastructure facility is defined as the accumulated periodical (e.g., annual) costs due to the decline in peak-hour LOS. Durability is a function of:

a) Natural deteriorating factors such as long-term weather and other environmental causes
b) Changes in traffic volume levels over a facility
c) Changes in traffic composition such as increase in the percentage of heavy trucks

Resiliency of an infrastructure transportation facility is defined as the ability of the system to endure an extreme external shock (e.g., a major storm), measured by the time and costs required for the system to return to its pre-shock LOS. This study focuses on the durability component. Measurement of the economic impacts of a transportation network's durability constitutes the main objective of this study. In the application section of this report, we empirically illustrate how changes in engineering factors affect travel demand, which in turn, is translated in the economic model into changes in social welfare.

In order to carry out the analysis, the study combines three model types: First, an engineering model that links the physical deterioration in the infrastructure with the LOS it produces. Second, a traffic model that, following the change in LOS, redistributes total travel demand among other facilities that belong to the same transportations network. Third, an economic-welfare model, that links the redistribution of the network travel demand to changes in welfare. Figure 1 shows this modeling framework.

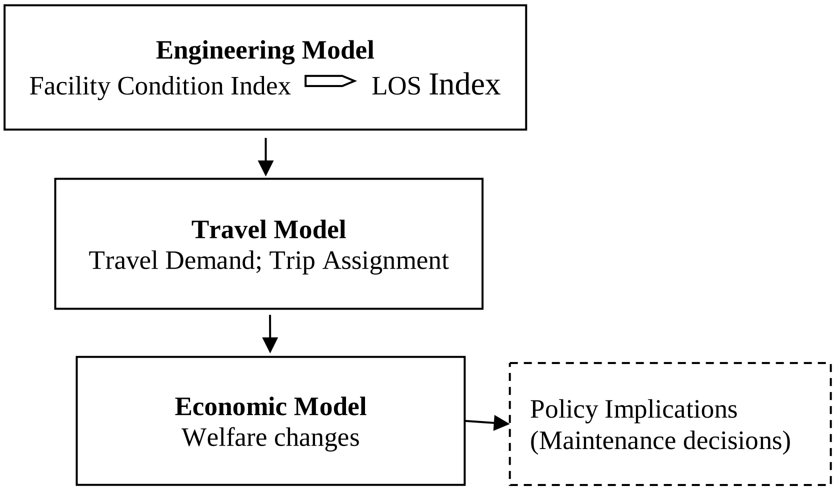

Figure 1: Model Framework

The three models describe the process of temporal decline in LOS, caused by facility deterioration, through its effect on travel demand and, subsequently, on users' welfare. Specifically, the *engineering* model assesses the relationships between overtime changes in structural and surface conditions of a facility and the LOS it produces. To that end, it rates the facility's physical condition, mainly its riding surface to travel condition. Subsequently, this rating is functionally linked to the facility's LOS, which is used as input into the *travel* demand model. Thus, LOS information is used to assign travel demand volume on each facility (link) in the relevant network. Given travel demand changes at a facility, the *economic* model computes the consequent welfare effects. Changes in welfare can ultimately be used as a metric for designing *policies* such as making maintenance and investment prioritization decisions. This kind of policy analysis is beyond the scope of the present study.

The key underlying hypothesis of the work done in this study is that the lower is the durability of the transportation facility, the higher are the average travel times and costs, which cause congestion and/or travel cancellations. Specifications of the three models (engineering, travel demand and economic-welfare), the data set and the empirical analysis are described in subsequent sections.

Chapter 4

Engineering Model

4.1 Background

According to the American Association of Civil Engineers (ASCE), the physical condition of the USA infrastructure is in a bad state of disrepair. Overall, about 10 percent of the 609,539 bridges in the United States are currently rated as “structurally deficient” meaning one or more of their main structural components do not meet acceptable structural standards. Another 14 percent are considered as “functionally obsolete,” meaning they are no longer suited to their current task because of overuse or a lack of safety features; yet they are still in use. While the above classifications relate to bridge structure and traffic safety, the most important function of a bridge is to meet travel demand at an optimum peak-hour level of service (LOS).

There is conflicting evidence on which highway and bridge features has the most influence on traffic flow. While the actual conditions of the underlying structural components do not directly affect traffic flow, studies (Ihs, 2004) have shown that traffic flow is affected by the condition of the riding surface.[4] For pavement analysis, engineers have mostly been using the International Roughness Index (IRI), which is a scale for roughness based on the simulated response of a generic motor vehicle to the surface roughness in a single wheel path of the road surface. For bridges, the quality of the riding surface can be evaluated using the top of the bridge Deck’s Condition Rating (DCR). Studies (e.g., Cady & Weyers, 1983) have shown that concrete bridge decks deteriorate due to corrosion of the embedded steel reinforcing bars, which are heavily affected by the application of chlorides through deicing salts or saline environments in coastal areas. Also, location and environmental conditions are important as they may cause freeze-thaw deterioration, or carbonation of the concrete deck (Nelson, 2014). There are also indications that the number of heavy vehicle crossings may affect deck conditions although direct relationships have been difficult to establish. On the other hand, regular maintenance activities, like crack sealing and overlays, help extend the life of bridge decks. Appendix A reviews engineering factors, which affect the deterioration of bridge decks.

While researchers (Modjeski & Masters Inc. 2015) have developed analytical and empirical models to consider the effect of deterioration factors and maintenance activities on bridge deck conditions, these models can only give general trends. None of the existing models seems capable of representing actual deck conditions on specific bridges as observed in situ. This is due to the particular structural features of each bridge deck and the specific environmental conditions. For instance, the vast majority of US bridges have concrete decks that transfer the traffic load to the supporting structure. Yet, many long-span bridges have orthotropic decks, which include steel plates that provide additional longitudinal or transverse stiffening to the deck. This makes the latter type susceptible to different types of cyclic loading fatigue, corrosion and environmental damage

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[4] A recent study has shown some but “not substantial effect” of improved traffic speeds with higher quality riding surfaces (Wang et al. 2013).

than regular concrete decks. For these reasons, bridge deck conditions are still evaluated using in-situ mostly visual inspections that provide a qualitative numerical Deck Condition Rating (DCR). In the analysis carried out in this study, we will make use of the DCR scale adopted by the State of New York (see Tables 2 and 3).

The US Federal Highway Administration (FHWA) uses a scale, which ranges from 9 to 1 to rate bridge components where 9 represents excellent condition and 1 imminent failure. Table 1 shows general descriptions of deck condition for DCR level. The New York State uses a scale that varies between 7 (very good quality) and 1 (poor quality). Table 2 shows the expected state of a bridge deck for each DCR level according to New York State's rating scale. As mentioned earlier and in Appendix A, studies have shown that the rate at which bridge deck deteriorates over time are very difficult to predict and depend on many factors whose particular damage contributions are difficult to model particularly when they occur in combination.

Plots of DCR values extracted from different sources including the National Bridge Inventory (NBI) files show that DCR levels reduce, at an exponential rate, with large drops in rating in early years followed by slower drop in rating levels. Figure 2 provides an example of the longitudinal change in DCR for the George Washington Bridge (GWB) that connects New York City with the state of New Jersey as assembled in this study using the data in the NBI files.

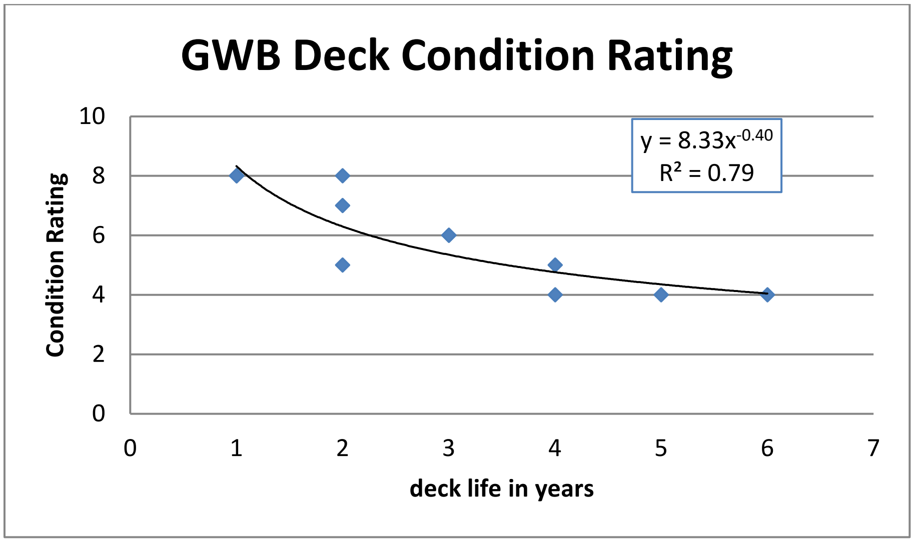

Figure 2 – Change in the George Washington Bridge Deck Condition Rating over Time (scale 1-9) **Source**: Authors work

Table 1: FHWA Deck Condition Rating Scale

Deck Condition Rating	**Condition of Deck Item**
9	Excellent condition – no noticeable or noteworthy deficiencies, which can affect the condition of the deck item. Usually new decks.
8	Very good condition – Minor transverse cracks with no deterioration, i.e., delamination, spalling scaling or water saturation
7	Good condition – sealable deck cracks, light scaling. No spalling or delamination of deck surface, but visible tire wear. Substantial deterioration of curbs, sidewalks, parapets, railing or deck joints (need repair). Drains or scuppers need cleaning.
6	Satisfactory condition – Medium scaling. Excessive number of open cracks in deck (5 ft intervals or less). Extensive deterioration of the curbs, sidewalks, parapets, railing or deck joints (requires replacing deteriorated elements).
5	Fair condition – Heavy scaling. Excessive cracking and up to 5% of the deck area is spalled; 20-40% is water saturated and/or deteriorative. Disintegrating of deck edges or around scuppers. Considerable leaching through deck. Some partial depth failures, i.e. rebar exposed (repairs needed).
4	Poor conditions – More than 50% of the deck area is water saturated and/or deteriorated. Leaching throughout deck. Substantial partial depth failures (replace deck soon).
3	Serious condition – More than 60% of the deck area is water saturated and/or deteriorated. Use this rating if severe or critical signs of structural distress are visible and the deck is integral with the superstructure. A full failure or extensive partial depth failures (repair or load post immediately).
2	Critical condition – Some full depth failures in the deck (close the bridge until the deck is repaired or holes covered).
1	“Imminent” failure condition – Substantial full depth failures in the deck (close the bridge until deck is repaired or replaced).
0	Failed condition – Extensive full depth failures in the deck (shut down bridge until the deck is replaced).

Table 2: New York State Deck Engineering Elements Condition Rating (DCR) Scale

Deck Condition Rating	Condition of Deck Item
7	New condition: Indicates no cracks, delaminations or spalls
6	Used as shade between rating
5	Minor deterioration, but functioning as originally designed: Indicates beginning of a spalling problem with no more than two or three isolated, moderate spalls or delaminations. Pavement with only scattered tight cracks and moderate surface wear with good riding quality would also be rated 5.
4	Used as shade between rating
3	Serious deterioration: Indicates a more serious spalling and delamination problem with about 25 percent of one lane affected and poor riding quality. Pavement with no cracks or spalls but with a well-worn wearing surface of polished aggregate could also be rated 3.
2	Used as shade between rating
1	Indicates a spalling and delamination problem with about 50 percent or more of one lane affected. The ride would be extremely rough

In the application section of this study, the concepts presented in this Report are applied to two parallel bridge facilities to illustrate these concepts using numerical examples. Specifically, we will evaluate the economic impact of damage to the riding surfaces (using the NYS scale summarized in Table 2) of the Throgs Neck Bridge and the Whitestone Bridge built to meet traffic demand between the boroughs of the Bronx and Queens in New York City. In the example, we use actual DCR data provided by the New York MTA Bridges & Tunnels of the Metropolitan Transit Authority. New York State rates bridge quality conditions on a 7-point scale, with 1 representing a totally failed condition, 3 representing serious deterioration indicating that a bridge component is not functioning as originally designed, 5 representing minor deterioration to a component that otherwise is functioning as originally designed, and 7 representing an element in new condition with no deterioration. The even-numbered ratings (2, 4, and 6) are used to shade between odd-numbered ratings (i.e., 4 between 3 and 5). The average condition rating of all highway bridges in the State is 5.37 on the New York state rating scale. Table 2 explains the New York rating scale.

Another riding surface scaling that is used by many agencies to rate road pavement conditions is the International Roughness Index (IRI). The IRI is a profile-based statistic that was initially established in a study by the World Bank. It is used worldwide as the index for comparing pavement smoothness. The IRI is developed mathematically to represent the reaction of a single tire on a vehicle suspension (quarter-car) to roughness in the pavement surface when the car travels at 50 mph (80 km/h) (Sayer, 1995)[5] .

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[5] Sayers, M.W. “On the Calculation of International Roughness Index from Longitudinal Road Profile,” Transportation Research Record 1501, 1995, pp 1-12.

In this report, we use DCR even though the IRI provides a more objective measure of the quality of the riding surface, because current bridge deck surface conditions are primarily evaluated using visual inspections based on the DCR scale which has been found to be directly related to traffic volume and thus applicable to achieve the objectives of this study. For example, Figure 3 illustrates the percent increase in the traffic volume on the bridges of the MTA Bridge and Tunnel Authority (also known by the acronym TBTA) as the deck condition expressed in terms of DCR improves. In Figure 3, the base line for 100% traffic is normalized to correspond to a DCR value equal to 5.0 on the New York scale of 1-7. Although the scatter in the data is quite high, the upward trend in the percent of traffic volume with improvement in deck condition is clear. Similar data assembled for the Throgs Neck and Whitestone Bridges in New York are used in the implementation section of this report.

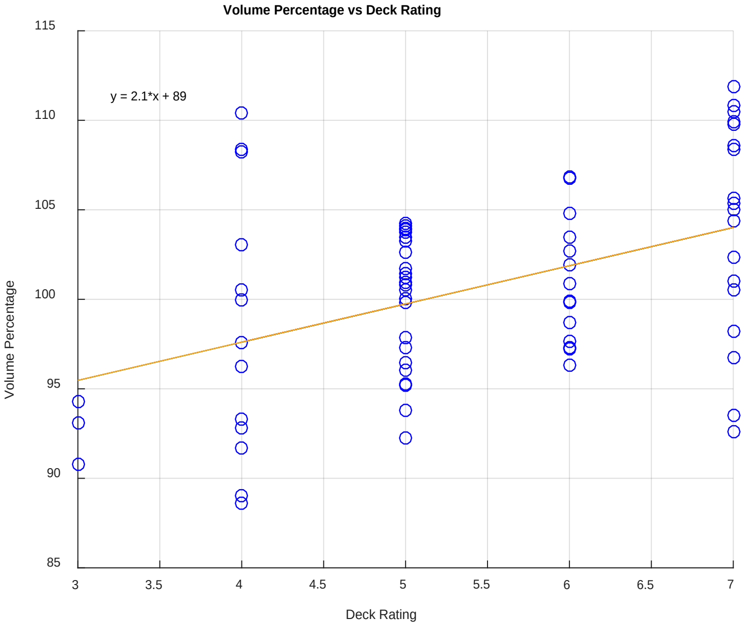

Figure 3: Change in Percent of Traffic Volume on TBTA Bridges with DCR
Source: Authors' work

Improvements in deck condition rating expressed in terms of DCR are also known to improve traffic safety. For example, Figure 4 depicts the reduction in the rate of accidents on TBTA bridges with improvements in deck condition ratings using data provided by TBTA for this study. The ordinate gives the number of collisions for every million miles traveled. Although the figure shows large scatter in the data, the negative trend in accident rate with increased DCR is noticeable.

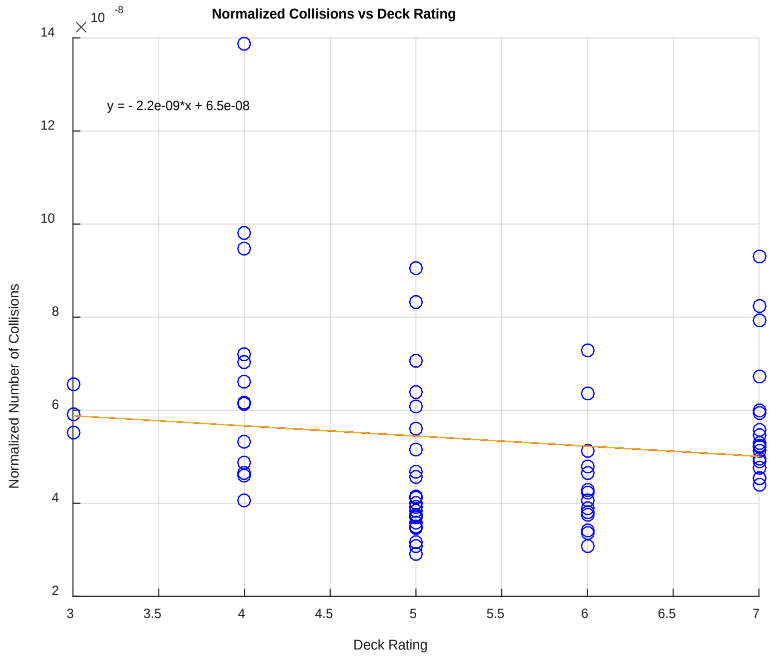

Figure 4: Change in Accident Rate on TBTA Bridges with DCR
Source: Authors' work

Chapter 5

Travel Model

5.1 Background

The Travel Demand (TD) model has two major functions. First, it estimates how a facility's engineering level of surface deterioration affects travel demand through its effect on travel time and costs. The lower is the quality of the surface (lower value of DCR), the higher are travel costs, which negatively affect travel demand.

$$TD = f(cost, DCR) \qquad \text{with: } \frac{\partial TD}{\partial DCR} > 0. \tag{1}$$

While Figure 3 shows a clear relation between traffic on a bridge and its condition, normally a facility is part of a network. Therefore, in order to assess changes in travel demand on a specific facility, we need to consider travel conditions on other facilities of the same network. Thus, the second function of the model is to compute how total travel demand on the network is redistributed among substitute facilities when the surface deterioration level of a particular facility changes. Thus, the cost of travel on a facility is affected by its level of deterioration *and* the level of deterioration of other facilities. We specify travel costs on facility "*i*" given facility "j"as $Cost_i$ = *f*(DCRi, DCRj), and thus:

$$TDi = f(DCRi, DCRj; \forall i \neq j) \tag{2}$$

In the application section, we will estimate an explicit form of Eq. (2) following the approach describe by = (2009).

For illustration purposes, we consider the case of a network composed of two bridges. We assume that the two facilities are *substitutes* i.e., an increase in bridge '1" deck rating will positively affect its demand level, while an increase in the deck rating of facility "2" (holding 1's rating as constant) will negatively affect the demand level on facility 1.

Total Origin-Destination (O-D) demand, V, on this simple network, is expressed as a linear function of the type:

$$V = V_0 - \beta P \quad . \tag{3}$$

where,

V = travel volume

P = travel price in the network (in units of travel time)

V_0 = free flow speed,

β = a parameter that reflects the impact of the travel price on travel volume.

To estimate the parameters in Eq. (3), we make use of the *observed* values of the volume of demand on the network denoted by v' the observed travel price (in time units), denoted by P'and the reported demand price elasticity, η. Thus, the facility's current demand, V, is expressed as:

$$V = (1+\eta)v' - \eta\left(\frac{P\prime}{v'}\right)P \tag{4}$$

where in (3):

$$v_0 = (1+\eta)v'$$
$$\beta = \eta\left(\frac{\mathrm{P}'}{v'}\right)$$

Below, in the welfare model, we use Equation (4) to compute the change in users' surplus resulting from the increase in average peak hour travel time on the network due to facility deterioration.

There are two scenarios of demand elasticity:

a) Origin-Destination (O-D demand is elastic ($\eta > 0$), implying that total demand will be:
$$V = (1+\eta)v' - \eta\left(\frac{\boldsymbol{P'}}{v_1}\right)P$$
b) O-D network demand is totally inelastic ($\eta = 0$), implying that total demand is constant:
$$V = v' = v_0$$

5.2 Trip Assignment Model

Because travel price in the network is measured in travel time units(t), we rewrite Equation (3) as:

$$V(t) = v_0 - \beta\,.\,(\mathrm{t})^{\gamma} \qquad \beta, \gamma > 0 \tag{5}$$

where β and γ are empirically derived parameters.

The free flow speed (v_0) can be obtained in relation with road roughness quality through Equation (6)

$$v_0 = m_0 + m_1 \times \mathrm{IRI} \tag{6}$$

From a study by Wang et al. (2013), free flow speed (V_0) changes linearly with the International Roughness Index, IRI. In Equation 6, m_0 is the initial free flow speed and m_1 is a negative number that reduces the free flow speed as IRI increases (or quality of the riding surface decreases). Wang et al. (2013) found that m_0 ranges between 50 mph and 80 mph for major highways, while m_1 ranges between − 0.30 mph × mile and − 0.47 mph × mile.

In the case of a two-facility network, equilibrium volume and travel time are determined at the point where travel time on each facility, for an additional user, are equal i.e., $t = t_1 = t_2$. The logic is that, when a new user needs to choose a facility, he would select the facility with the lower travel time, so this facility will attract more travelers. At equilibrium, there is no incentive, in travel time terms, to switch between facilities as travel times are the same on both facilities.
Travel time on each of the two facilities is expressed as:

$$t_1(v_1) = a_1 + b_1 \cdot (\frac{v_1}{c_1})^{\alpha_1} \qquad a_1, b_1, \alpha_1 > 0 \tag{7}$$

$$t_2(v_2) = a_2 + b_2 \cdot (\frac{v_2}{c_2})^{\alpha_2} \qquad a_2, b_2, \alpha_2 > 0 \tag{8}$$

where:
t_i = travel time on facility i,
v_i = demand volume on facility i,
a_i = constant
c_i = capacity of facility i,.[6]
b_i and α_i are parameters,

We obtain the two facilities' network equilibrium solution by solving the following minimization problem:

$$\min.\ t(v_1, v_2) = \int_0^{v_1} \left[a_1 + b_1 (\frac{v_1}{c_1})^{\alpha_1} \right] dv_1 + \int_0^{v_2} \left[a_2 + b_2 (\frac{v_2}{c_2})^{\alpha_2} \right] dv_2 \tag{9}$$

$s.t.$
$v_1 > 0;$
$v_2 > 0$
$v_1 + v_2 = V(t)$

The output of the minimization problem is the equilibrium travel volume and time on each facility of the network. The deterioration of one facility affects the travel demand on this facility and, consequently, affects the equilibrium travel time and volume of each facility in the network. The

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[6] Capacity is defined as the maximum number of vehicles that can traverse a distance of one mile, in one hour, at a pre-specified speed level (e.g., 40 mph).

change in the equilibrium travel time and volume on each facility affects travelers' surplus according the economic welfare model, which is explained next.

Chapter 6

Economic Welfare Model

6.1 The Welfare Model

As stated at the outset, the main objective of this study is to assess the robustness of transportation infrastructure facilities and its effect on travel demand and the economy, where the latter is defined in terms of users' welfare. The overall analysis is carried out in three main stages. First, we assess the engineering deterioration rating ($\boldsymbol{DCR}$) of a facility using a deterioration scale. Second, we use this information to assess the impact of DCR on the level of service (LOS) of a facility and consequently on travel demand (TD) on this and on substitute facilities. Third, given the adjustments in demand, following facility deterioration, the economic model assesses changes in the Consume Surplus (CS) of users. CS is a common measure of changes in Social Welfare (SW). Using DCR, Equation (10) expresses, in general modeling terms, the above-listed three stages:

$$\Delta SW = \Delta CS; \qquad \Delta CS = f\big(TD(LOS)\big); \qquad LOS = g(DCR) \tag{10}$$

6.2 Evaluating Social Welfare

We define Consumer Surplus (CS) as the difference between the total cost that consumers are willing to pay, and the total cost that they actually do pay (i.e., at the equilibrium price). In our case, CS is the difference between what users of a transportation facility are willing to pay in terms of travel time and associated costs (e.g., fuel) and what they actually spend. When deterioration occurs in one facility within the network, the equilibrium travel costs (time) on this facility will increase and thus travelers' CS will drop.

To determine how the increase in travel time on one facility might affect the network travelers' CS, we need to determine whether travel demand is elastic or inelastic. In the first case, the number of vehicles demanding travel on the network between Origin-Destination (O-D) pair will decline as travel costs increase. In the second case, demand on the network for the O-D pair remains unchanged but it would redistribute between the various facilities in response to the deterioration of one facility. Demand for the deteriorated facility will decrease while the demand for the other facilities will increase. In the application section we assume a fixed Origin-Destination demand.

Chapter 7

Application

The objective of this study is to assess the impact of facility deterioration, caused by engineering factors, on travel demand and consequently on user's welfare. We hypothesize that the deterioration of a facility, or reduced durability, brings about reduced travel and, simultaneously, traffic redistribution on the germane network. These, in turn, result in welfare loss and reduced economic activity. To test these hypotheses, we implement the models introduced in the previous chapters to study a simple network composed of two bridges which are used to provide a numerical example of the application of the models to real world cases.

7.1 The Test Case

The models introduced in this study are applied to a simple network composed of two New York bridges: the Throgs Neck and the Whitestone Bridges, which were built to meet traffic demand between the boroughs of the Bronx and Queens in New York City. Figure 5 shows the location of these bridges and the surrounding highways on a Google map. Actual long term data on deck deterioration of these two bridges as well as traffic data were provided by the TriBorough Bridge and Tunnel Authority (TBTA).

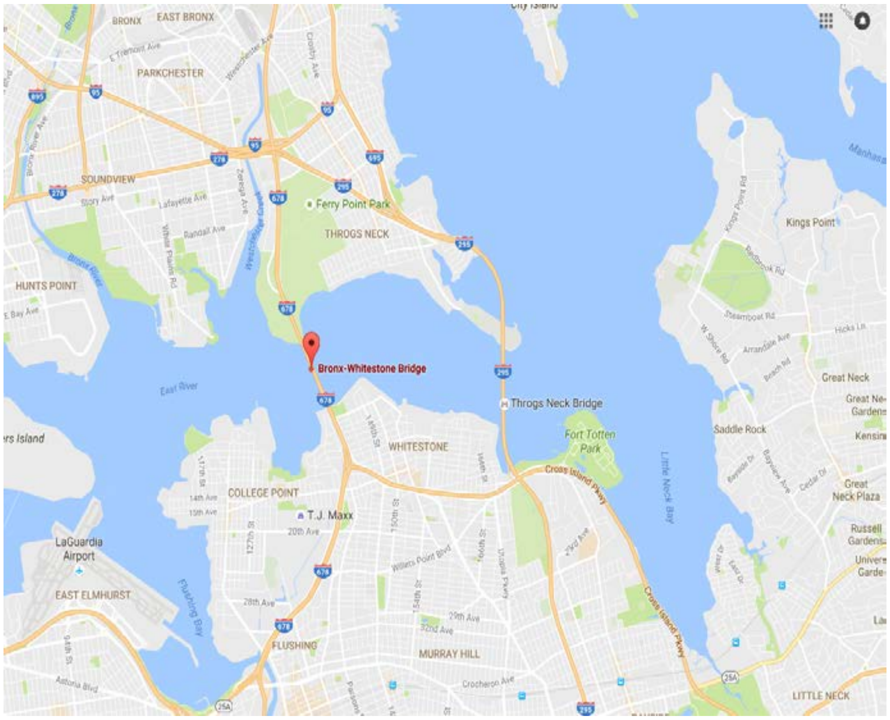

Figure 5: Location of the Throgs Neck and Whitestone Bridges on Google Map

As can be seen from Figure 5, and as corroborated below by the available traffic data, these two bridges are substitutes for traffic between the Origin-Destination (O-D) pair of two New York City Boroughs. That is, the two bridges provide parallel alternatives for traffic between the east ends of the Bronx and Queens.

The Throgs Neck Bridge is a 2,910-ft long suspension bridge that carries 6 lanes, 3 lanes in the direction of Queens and 3 lanes in the direction of the Bronx. The width of each lane is 12 ft. The 3,770-ft long Whitestone Bridge is also a suspension bridge that carries 6 lanes, 3 of which are Queens bound and 3 are Bronx bound. The deck of the Whitestone bridge was replaced, before its replacement the lane widths were 11’, 10’-5 ½”, and 9’-4” in each direction. However, after the replacement the lane widths became 11’, 10’-5 ½”, and 9’-10”. This would sum up to be 62’ before deck replacement and 63’ after deck replacement[7].

7.2 Data

The traffic data used in this study was collected over a period of 12 years during the period: 1993-2015. The data provided by the Revenue Management division at TBTA and the TBTA library include:

a) Average daily traffic
b) Average peak-hour traffic
c) Total yearly traffic
d) Total annual vehicle-mile
e) Deck Deterioration Rating DCR extracted from inspection reports available in the TBTA library. The biennial data was interpolated to cover the missing years.

The average peak hour volume data for both bridges are presented in Table 3. Table 4 also lists the Deck Condition Rating (DCR) data for both bridges as extracted from the bridge inspection reports provided by the New York TriBorough Bridge and Tunnel Authority (TBTA).

7.3 Analysis of Facility Substitution

In this section, we verify that traffic on the two bridges is essentially constant and that the two bridges can be considered to be substitutes for each other so that traffic volume on one bridge is inversely related to the volume on the other. In the following, the Whitestone Bridge is labeled Facility 1 and Facility 2 is the Throgs Neck Bridge,

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[7] Currently the approaches to the bridge are under construction to expand each lane to 12 ft and create shoulders on both sides to meet current traffic safety regulations. But the actual bridge lanes remain as stated above.

Queens–Bronx Inelastic network demand

The peak hour traffic volume on the network between Queens and the Bronx over the Whitestone and Throgs Neck bridges between 1992 and 2015 is presented in Table 3. It is observed that the total peak hour traffic volume ranges between 13,865 and 14,986 vehicles/hour. This narrow range of 8% shows a relatively inelastic demand on the network compared to the 24% and 16% range observed for each bridge. The two bridges can then be considered to be substitutes. For instance, between 1992 and 1993 the peak hour volume on the Whitestone Bridge decreased from 8,271 to 8,209 vehicles/hour and the peak hour volume on the Throgs Neck increased from 6,660 to 6,696 vehicles/hour. The network total demand has decreased only very slightly from 14,931 to 14,905 veh/hr.

Linear regression fits are performed on the data of Table 3 to verify the relation between peak hour traffic on the Whitestone Bridge (labeled Peak1) to that of the Throgs Neck Bridge (labeled Peak2). The regression yields the following relationships with the associated coefficient of regression R^2:

$$\text{Peak1} = 16{,}087 - 1.21\ \text{Peak2} \qquad R^2 = 0.54 \tag{11}$$

$$\text{Peak2} = 10{,}434 - 0.45\ \text{Peak1} \qquad R^2 = 0.54 \tag{12}$$

The results in Eq. (11) and (12) confirm that peak hour traffic on facility 1 is negatively related to peak hour traffic on facility 2, and vice versa. Given the observation of constant longitudinal total traffic volume for facility 1 and 2, these results indicate facility substitution. Traffic that "leaves" facility 1 (e.g., due to higher deterioration level) will shift to facility 2 and vice versa.

Table 3: Peak Volume on Whitestone and Throgs Neck Bridges (Both directions)

Year	Whitestone Peak Volume (Volume1) (veh/hour)	Throgs Neck Peak Volume (Volume2) (veh/hour)	Network Total Peak Volume
1992	8,271	6,660	14,931
1993	8,209	6,696	14,905
1994	8,114	6,732	14,846
1995	8,086	6,760	14,846
1996	8,019	6,796	14,815
1997	7,957	6,832	14,789
1998	7,890	6,868	14,758
1999	7,828	6,897	14,725
2000	7,406	6,649	14,055
2001	7,519	6,746	14,265
2002	7,902	7,081	14,983
2003	7,982	6,914	14,896
2004	8,004	6,982	14,986
2005	7,270	7,393	14,663
2006	6,934	7,778	14,712
2007	7,329	7,533	14,862
2008	7,428	7,276	14,704
2009	7,426	7,161	14,587
2010	7,095	6,996	14,091
2011	6,491	7,374	13,865
2012	6,939	7,114	14,053
2013	6,876	7,271	14,147
2014	6,651	7,397	14,048
2015	7,268	7,474	14,742
min	6,491	6,649	13,865
max	8,271	7,778	14,986
average	7,537	7,058	14,595
(max-min)/ave.	24%	16%	8%

7.4 Travel Demand Analysis

The Travel Demand model establishes the relationships between the level of a facility's deterioration and the demand for this facility, as well as the demand for other facilities in the pertinent network.

As explained above, demand for travel on a facility (e.g., a bridge) is a down-sloping function, describing how much traffic wishes to use the facility for a given Level Of Service (LOS) which reflect the costs per mile direct travel expenses (e.g., gasoline) in monetized travel time units. We have hypothesized that LOS is a function of the deterioration level of the facility, which affects the unit cost of travel. Thus, as the deterioration level worsens, unit cost goes up and less traffic will be demanding this facility's services. Therefore, we estimate the demand as a function of a deterioration index like DCR.[8] Obviously, demand is also affected by the deterioration level at substitute facilities. For the application case, we assume that the network is formed by two substitute facilities (n=2), which are the Whitestone and Throgs Neck Bridges.

We first examine whether traffic on each bridge is sensitive to a relative deterioration index DCR defined as the ratio of DCR of the bridge being evaluated to the DCR of the alternative bridge. The DCR data for both bridges are shown in Table 4. A linear regression, gives the models in Eq. (13) and Eq. (14) that establish the relation between the peak traffic volume on the Whitestone Bridge (Peak1) and DCR1/DCR2 where DCR1 is the deck condition rating of the Whitestone bridge (facility 1) and DCR2 is the deck condition rating of the Throgs Neck Bridge (facility 2). A similar relation is established for the peak traffic volume on the Throgs Neck Bridge (Peak2) and the same ratio DCR1/DCR2.

<u>Regression 1:</u> $$\text{Peak 1} = 6159 + 1374\,(\text{DCR1/DCR2}) \quad (13)$$

$R^2 = 0.29$

<u>Regression 2:</u> $$\text{Peak 2} = 7632 - 573\,(\text{DCR1/DCR2}) \quad (14)$$

$R^2 = 0.13$

Or $$\text{Peak 2} = 6573 + 468\,(\text{DCR2/DCR1}) \quad (14.b)$$

Even though the coefficient of regression R^2 is rather low, regressions 1 and 2 in Eq. (13) and (14) confirm that as DCR1 rating improves (e.g. from 5 to 6) given a value for DCR2, traffic on facility 1 increases and traffic on facility 2 decreases.

Another set of regressions is performed to study the combined effects of DCR and the peak flow on the alternate bridge on each facility leading to the following relationships:

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[8] Notice that the New York State DCR deterioration index defines a high level of deterioration as level 1, and no deterioration as level 7.

Regression 3: Peak 1 = 13987 – 1.026 Peak2 + 787 (DCR1/DCR2) (15)

$R^2 = 0.62$

Regression 4: Peak 2 = 10469 – 0.46 Peak1 + 60.4 (DCR1/DCR2) (16)

$R^2 = 0.54$

As expected, regressions 3 and 4 indicate that the observed peak-hour traffic on facility 1 is negatively related to peak-hour traffic on facility 2. The positive coefficient in Eq. (16) however is counterintuitive and highlights the need for additional data and more accurate representation of deterioration rates.

Table 4: Traffic Volume and DCR for the two Bridges

Year	Whitestone Peak Volume (Volume1) (veh/hour)	Whitestone DCR1	Throgs Neck Peak Volume (Volume2) (veh/hour)	Throgs Neck DCR2	DCR1/DCR2
1992	8,271	5	6,660	4	1.25
1993	8,209	5	6,696	4	1.25
1994	8,114	5	6,732	4	1.25
1995	8,086	5	6,760	4	1.25
1996	8,019	5	6,796	4	1.25
1997	7,957	5	6,832	4	1.25
1998	7,890	5	6,868	4	1.25
1999	7,828	5	6,897	4	1.25
2000	7,406	5	6,649	5.5	0.91
2001	7,519	5	6,746	7	0.71
2002	7,902	5	7,081	6.5	0.77
2003	7,982	5	6,914	6	0.83
2004	8,004	4.5	6,982	5.5	0.82
2005	7,270	4	7,393	5	0.80
2006	6,934	5	7,778	5	1.00
2007	7,329	6	7,533	5	1.20
2008	7,428	5	7,276	5	1.00
2009	7,426	4	7,161	5	0.80
2010	7,095	4	6,996	5	0.80
2011	6,491	4	7,374	5	0.80
2012	6,939	4.5	7,114	5	0.90
2013	6,876	5	7,271	5	1.00
2014	6,651	5	7,397	5.5	0.91
2015	7,268	5	7,474	6	0.83

7.5 Welfare Measurements

Welfare is expressed in terms of Consumer Surplus (CS) which shows the price that consumers are willing to pay compared to the price they actually pay. Technically, it is measured as the area under the relevant demand curve between maximum price that consumers are willing to pay (quantity is zero) and the price they actually pay. Changes in CS (e.g. before and after deterioration) which affect travel costs show the welfare results from facility deterioration.

To compute demand on each bridge, first we standardize the data relative to each bridge physical and speed dimensions using the speed limits and bridge lengths listed in Table 5.

Table 5: Bridge Speed limits and Lengths [9]

	Whitestone Bridge	**Throgs Neck Bridge**
Length (Miles)	**3,770 feet =0.714 miles**	**2,910 feet=0.551 miles**
Speed limit (mph)	**50**	**50**
ϴ (minutes to cross bridge at maximum speed allowed)	**0.86 min.**	**0.66 min**
Average speed at peak travel time	**15 mph**	**15 mph**
t (minutes to cross bridge at average peak travel speed)	**2.86 minutes**	**2.20 minutes**

Travel time, t, on each bridge is computed using its relationship with traffic volume, V, which is normalized by traffic capacity, C:

$$t = \theta\left(1.0 + \alpha\left(\frac{V}{C}\right)^{\beta}\right) = \theta\left(1.0 + 0.15\left(\frac{V}{C}\right)^{4}\right) \qquad (17)$$

where α=0.15 and β=4 are the values recommended in the highway capacity manual, Vis the traffic volume; C is the traffic capacity; and ϴ is the minimum possible travel time when peak

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[9] - The source for the data for the speed limit and bridge's length is New York City Department of Transportation Traffic Rules" (PDF), New York City Department of Transportation. December 17, 2009. Section 4-04(e)(2)
- Average speed at peak time is estimated by monitoring TBTA bridge travel time on line http://traveltime.mta.info/traveltime/index_pc.html

volume is equal to zero. In other words, it is the travel time that it takes a vehicle to travel at the speed limit to cross the facility. Θ is calculated as:

$$\Theta = \text{facility length in miles} / (\text{Speed limit mph}/60\text{min/hr}) \tag{18}$$

Applying Eq. (18) to the Whitestone Bridge yields $\Theta_1 = 0.714/ (50/60) = 0.857$ min and for the Throgs Neck Bridge, $\Theta_2 = 0.551/ (50/60) = 0.661$ min.

The parameters $\alpha = 0.15$ and $\beta = 4$ used in Eq. (17) are obtained from the Highway Capacity Manual.

Traffic capacity can be estimated for each bridge using Eq. (17) given the time it takes a vehicle to cross the bridges during peak travel time when V=Peak volume. Thus, assuming as shown in Table 5, an average speed of 15 mph during peak travel time it takes t1=2.86 minutes to cross the Whitestone Bridge, and t2=2.20 minutes to cross the Throgs Neck. These yield the capacities C1=3800 veh/hr for the Whitestone and C2=3725 veh/hr for the Throgs Neck.

Given the values of Θ and C obtained above, we estimate travel time on the Whitestone Bridge (t1), and the Throgs Neck Bridge (t2) for every peak travel volume using Eq. (17) and list the results in the fourth and fifth columns of Table 6.

Table 6: Estimated Travel Time on Both Bridges[10]

Year	White-stone Peak Volume (veh/hr)	Throgs Neck Peak Volume (veh/hr)	White-stone travel time (minutes)	Throgs Neck travel time (minutes)	Whitestone Slope of travel demand (Volume/minutes)	Throgs Neck Slope of travel demand (volume/minutes)
	Peak1	Peak2	t1	t2	b1	b2
1992	8,271	6,660	3.74	1.67	663.45	1196.41
1993	8,209	6,696	3.66	1.70	672.87	1181.65
1994	8,114	6,732	3.53	1.72	689.58	1174.19
1995	8,086	6,760	3.49	1.74	695.07	1165.52
1996	8,019	6,796	3.41	1.76	705.48	1158.41
1997	7,957	6,832	3.33	1.78	716.85	1151.46
1998	7,890	6,868	3.25	1.81	728.31	1138.34
1999	7,828	6,897	3.17	1.83	740.82	1130.66
2000	7,406	6,649	2.71	1.67	819.85	1194.43
2001	7,519	6,746	2.83	1.73	797.07	1169.83
2002	7,902	7,081	3.26	1.96	727.18	1083.83
2003	7,982	6,914	3.36	1.84	712.68	1127.28
2004	8,004	6,982	3.39	1.88	708.32	1114.15
2005	7,270	7,393	2.58	2.20	845.35	1008.14
2006	6,934	7,778	2.28	2.55	912.37	915.06
2007	7,329	7,533	2.64	2.32	832.84	974.09
2008	7,428	7,276	2.73	2.10	816.26	1039.43
2009	7,426	7,161	2.73	2.02	816.04	1063.51
2010	7,095	6,996	2.42	1.89	879.55	1110.48
2011	6,491	7,374	1.95	2.18	998.62	1014.77
2012	6,939	7,114	2.29	1.98	909.04	1077.88
2013	6,876	7,271	2.24	2.10	920.89	1038.71
2014	6,651	7,397	2.06	2.20	968.59	1008.68
2015	7,268	7,474	2.58	2.27	845.12	987.75
Average	**7,537**	**7,057.5**	**2.90**	**1.95**	**796.76**	**1092.69**

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[10] - "t" is the average travel time per vehicle, "b" is the slope of the travel demand function (if linear model is assumed then Peak volume = a – b t).

- Facility 1 is the Whitestone Bridge. Facility 2 is the Throgs Neck Bridge.

7.5 Consumer Demand

While Eq. 17 establishes traffic capacity, the consumer surplus analysis needs to compare travel capacity to ravel demand. The consumer surplus analysis seeks to determine how a change in the bridge deck condition, DCR, affects consumers' surplus. Essentially, a decrease in deck condition rating DCR will lead to a decrease in actual peak hour travel demand. A relationship between peak volume demand and travel time can be expressed as Peaki = function (t_i) which in its linear form can be expressed as:

$$Peakj=aj -bj \times t \tag{19}$$

Where j takes the value of 1 for the Whitestone Bridge and 2 for the Throgs Neck Bridge. To estimate the slope bj of Equation 19, we use the elasticity of the travel demand which is the percent change in travel volume over the percent change in travel time divided by the average volume over travel time or $E = \frac{\Delta V / \Delta t}{average(V/t)}$ where the average is evaluated at the midpoint of ΔV and Δt.

The elasticity of travel demand in the literature is usually set at a value of 0.3. This elasticity can be used to calculate the slope of the demand function in Equation 19 where the slope, b_i, is equal to the elasticity multiplied by the average travel volume over travel time such that:

$$bj = E \times average\left(\frac{V}{t}\right) \tag{20}$$

The results of the calculations of the slope for the demand model of Eq. (19), $b_{i,}$ are listed in columns 6 and 7 of Table 6 which produce an average slope b1 = 797 veh/hr which is rounded up to 800 veh/hr for the Whitestone Bridge and b2 = 1093 veh/hr which is rounded up to 1100 veh/hr for the Throgs Neck Bridge. However, because the slope changes for different values of t, the simple linear model may not be appropriate. Therefore, we calculate b as shown in Eq. (20) for each value of t and determine the peak volume for that value of t using:

$$Peakj_{i+1}=Peakj_i - bj_i \times (t_{i+1}-t_i) \tag{21}$$

According to Regression 1 of Eq. 13, the peak hour volume for the Whitestone Bridge can be expressed as Peak1 = 6159 +1374 DCR1/DCR2; We can estimate the value of aj in Eq. 19 by realizing that a1 is the maximum possible travel demand volume which ideally would take place when the travel time t_i is equal to zero; or we may say that a1 is the maximum possible travel volume when the deck condition of the Whitestone DCR1 is at its best condition, i.e. when DCR1= 7 and the deck of the Throgs Neck is near its lowest condition which is herein taken to be DCR2=2. Thus, the Whitestone Bridge's maximum peak volume is calculated as: $Peak1_0$ = 6159 + 13274 * 7/2 = 10,968 veh/hr which is rounded up to 11,000 veh/hr. Given $Peak1_0$ at time t_0=0, and the slopes in Table 6, the value of $Peak1_{i+1}$ is obtained for each value of time t_{i+1} using $Peak1_{i+1}=Peak1_i-b1_i(t_{i+1}-t_i)$.

The resulting time-demand curve is plotted in Figure 6. Using regression fit, the linear Equation in (19) is replaced by a logarithmic model which for the Whitestone demand equation can be written as:

$$t = 95.57 - 10.28 \ln(\text{Peak1}) \quad (22)$$

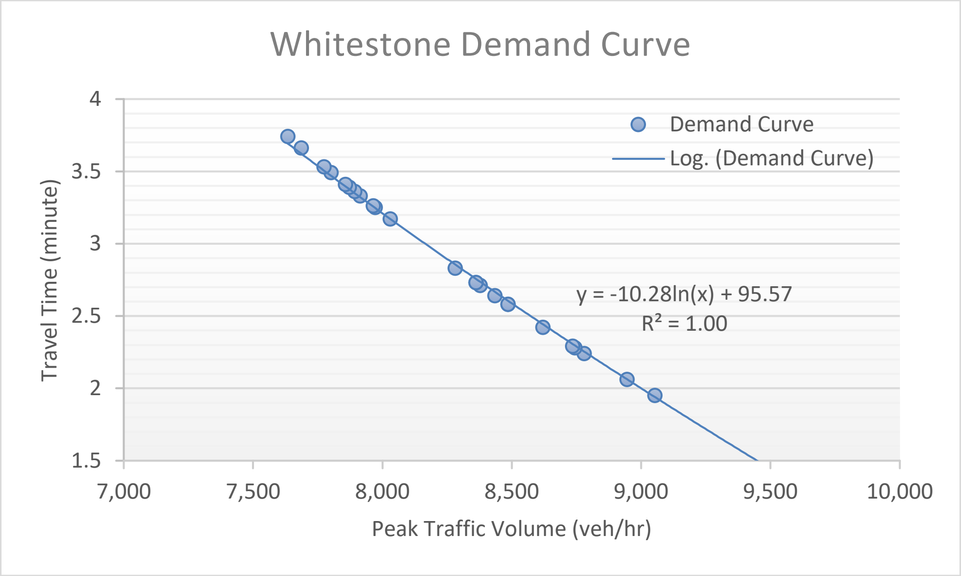

Figure 6 – Whitestone Bridge Supply and Demand Curves

A similar approach is used to obtain the demand curve for the Throgs Neck Bridge. Specifically, a2 is the maximum possible travel volume when DCR2 is at its best condition, i.e. DCR2= 7 and DCR1 is close to its worst condition at DCR1=2. Using Equation 14.b Peak2_0 is calculated as $\text{Peak2}_0 = 6573 + 468 * 7/2 = 8211$ veh/hr rounded down to 8200 veh/hr. The Throgs Neck demand curve plotted in Figure 7 leads to an equation that can be written as:

$$t = 52.13 - 5.78 \ln(\text{Peak2}) \quad (23)$$

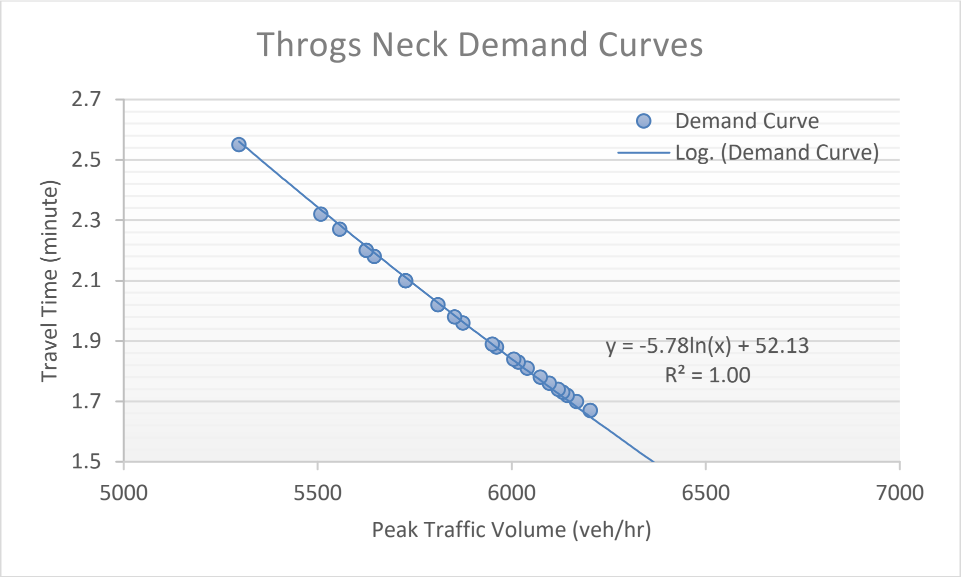

Figure 7 – Throgs Neck Bridge Supply and Demand Curves

7.6 Computation of Consumer Surplus

Consumer Surplus of Whitestone Bridge

The computation of Consumer Surplus requires the following steps:

Evaluation of travel time:

Consumer Surplus (CS) for the Whitestone Bridge is computed by first equating the relationships of the peak volume of Eq. 13 and the one given in Eq. 22 which are respectively given as:

Peak 1 = 6,159 + 1,374 DCR1/DCR2

And

t = 95.57 – 10.28 ln(Peak1)

These two equations allow us to obtain the relationship between DCR1/DCR2 and travel time as follows:

$$t = 5.87 - 10.28 \times \ln(1.0 + 0.223\ DCR1/DCR2) \qquad (24)$$

Equation (24) shows that a decrease in the Whitestone Bridge’s DCR implies an increase in travel time and, hence, a decrease in consumers’ surplus.

Pre-deterioration travel time:

If the Whitestone Bridge is at an ideal condition where DCR1 = 7 and assuming an average value for the Throgs Neck Bridge DCR2 = 5 which is approximately equal to the average value over the years, and using Equation 13, the peak-hour volume on the Whitestone Bridge would have been 8083 veh/hr. Using Equation 24, the travel time would be 3.08 minutes.

Post-deterioration travel time:

If DCR1 drops from 7 to 6 and DCR2 remains at the same DCR2=5 level and using Equation 13, the peak-hour volume would have been 7808 veh/hr. Using Equation 24, the travel time during peak hours is calculated to be 3.43 minutes.

In order to calculate CS the value of travel time when travel volume is at its minimum value needs to be calculated. The travel volume on the Whitestone Bridge (Peak1) will be at its minimum when DCR1=2 where bridge deterioration is at its lowest value before requiring the shutdown of the facility. Using Equation 24, and using the average value of DCR2 across all the years, which is very close to 5, the peak hour volume on the Whitestone Bridge would be reduced to 6709 veh/hr and from Eq. (24), the average travel time per vehicle would be 5.00 minutes.

Value of travel time:

To calculate the value of time for every level of travel time, we make use of NYS value of time set at \$35/hour or 0.58 \$/minute. The total value of travel time is then the product of travel time and the value of time.

As an example, the total value of travel time pre-deterioration is found to be 3.08 * 0.58 = \$1.79 while the total value of travel time after one level decrease in DCR1 or one level increase in deterioration is equal to 3.43 * 0.58 = \$1.99. The total value of travel time for the minimum volume is: 5.00* 0.58\$ = \$2.90.

In general the value of travel time on the Whitestone Bridge can be represented by Eq. (22) multiplied by \$0.58 or:

$$\text{Cost} = 55.43 - 5.96 \ln(\text{Peak1}) \tag{25}$$

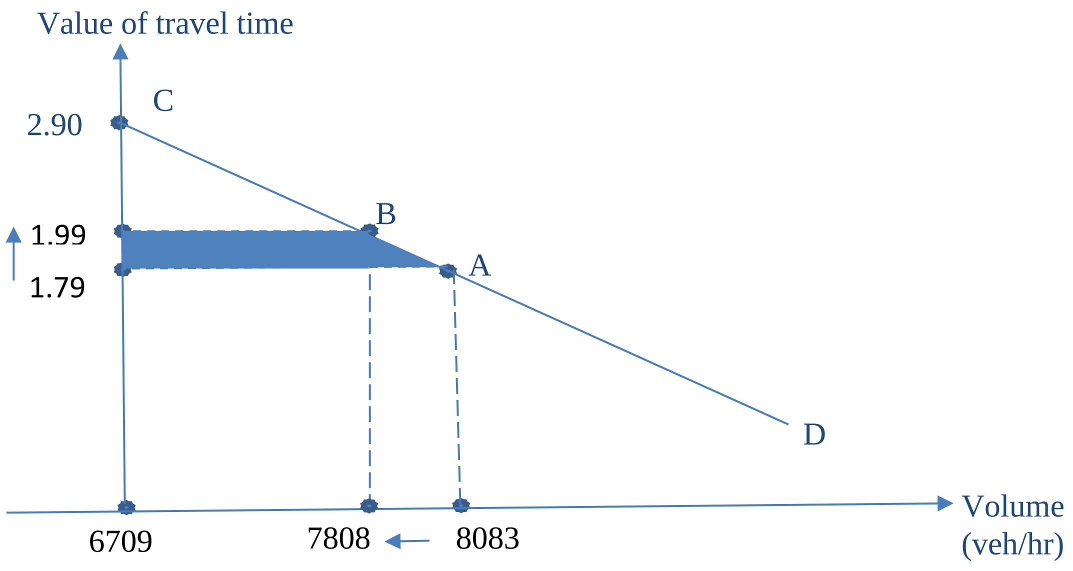

Figure 8: Impact of Decline in Whitestone Bridge's DCR1 on its Consumer Surplus

Consumer Surplus:

The cost impact of the decline in traffic volume due to the reduction in the Whitestone's deck condition expressed in terms of DCR1 is graphically presented in Figure 8. The consumer surplus is the area under the area delineated by the peak volume and corresponding value of time and the lowest volume and its corresponding value of time. The loss in CS is the difference between the CS when the bridge is in its ideal condition state and when it is in its current condition.

If we assume that the demand curve can be approximated by a straight line, then the areas of interest are triangular in shape and the calculations of the Consumer Surplus (CS) for the Whitestone Bridge are calculated as follows:

- Pre-deterioration CS = ½ (8083-6709) * (2.90 – 1.79) = $763
- Post-deterioration CS = ½ (7808-6709) * (2.90 – 1.99) = $500
- The decline in CS due to the deterioration of the Whitestone Bridge deck condition from level 7 to level 6 which can be represented by the shaded area in Figure 8, which can then be approximated as= $763 - $500 = $263

Alternatively and more accurately, Consumer Surplus for using the Whitestone Bridge pre-deterioration can be obtained by integrating Eq. (25) between the peak volume values of 8082 and 6709 veh/hr for the part above $1.79. After deterioration, the area delineated by 7808 and 6709 veh/hr and $2.90 and $1.99 can also be obtained by integrating Eq. (25). The results of the integrations lead to a pre-deterioration consumer surplus of $760 and a consumer surplus of $508 for post-deterioration. These values are very similar, within small rounding errors, to those calculated assuming a linear demand curve. Therefore, from here on, this report will use the costs associated with triangular areas to estimate consumer costs.

Elasticity of traffic volume with respect to deterioration

The Whitestone Bridge's CS Elasticity with respect to deterioration can be found using the equation:

$$\text{Elasticity1} = \frac{\%\,\Delta\, CS}{\%\,\Delta\,(\frac{DCR1}{DCR2})} = \frac{263/763}{\left(\frac{6}{5}-\frac{7}{5}\right)/\frac{7}{5}} = 2.41 \qquad (26)$$

This indicates that for every one percent decrease in the facility condition rating, the consumer surplus of the facility users will decrease by almost 2.41 percent.

Table 7: Pre-and post-one-level-deterioration results for Whitestone Bridge

Whitestone Bridge Consumer Surplus	
Pre-deterioration	
Peak-hour volume (veh/hr)	8083
Consumer Surplus	$763
Post Deterioration	
Peak-hour volume (fixed demand)	7808
Consumer Surplus (fixed demand)	$500
Welfare changes	
Change in peak-hour volume (veh/hr)	- 275
Change in Consumer surplus	- $263
Elasticity of CS w.r.t deterioration	**2.41**

Consumer Surplus of Throgs Neck Bridge

As previously noted, a decrease in DCR1 will reduce the peak volume on the Whitestone Bridge as the travel volume shifts to the substitute Throgs Neck when vehicles that avoid the deteriorating Whitestone Bridge migrate to the better conditioned substitute. Thus, traffic volume demand on the Throgs Neck will increase and the demand curve that gives the cost of time versus volume pivots counterclockwise indicating that we will have a higher volume for the same users cost. Pivoting of the demand curve can be represented by the shift from the demand curve D1 to the new curve D2 as shown in Figure 9. This shift will result in a new equilibrium point at the intersection of the demand curve with the supply function where the equilibrium shifts from point A to point B as shown in Figure 9.

Original Throgs Neck Bridge peak volume curve:

The first step of the analysis of the Consumer Surplus of the Throgs Neck Bridge consists of establishing the original demand curve D1[11]. This process uses Eq. (12) that established the relationship between the peak volume of Throgs Neck (Peak2) and that of the Whitestone (Peak1) as Peak2 = 10,434 – 0.45 Peak1. Before deterioration occurs in the Whitestone, Peak1 was found to be equal to 8083 veh/hr, leading to a value for Peak2 = 6796 veh/hr.

Travel time equilibrium of the Throgs, t_2, at this demand level can be obtained from Throgs Neck demand function of Eq. (23) which gives t=52.13 – 5.78 ln(Peak2). Substituting Peak2=6796 veh/hr, into Eq. (23) we find t_2 =1.13 minutes. The dollar value of this travel time is equal to 1.13 min * 0.58$/min = 0.66$.

Travel cost at minimum traffic volume for original peak volume curve:

To estimate travel cost at minimum traffic volume for the D1 demand function, we use Equation 14.b giving Peak 2 = 6573 +468 (DCR2/DCR1). Also, we recall Eq. (23) which gives t=52.13 – 5.78 ln(Peak2). From these two equations, we can obtain the relationship between DCR2/DCR1 and travel time on the Throgs Neck Bridge as follows:

$$t = 1.32-5.78 \ln(1.00+0.0712 \times DCR2/DCR1) \qquad (27)$$

Travel time when travel volume is at its minimum value occurs when the deck deterioration condition for the Throgs Neck Bridge is DCR2 = 2 and the Whitestone Bridge has a DCR1=7 which is the value before its deterioration. Using Eq. (27), we obtain t = 1.20 min. These represent the travel time required for all vehicles to cross the Throgs Neck Bridge when it is almost functionally obsolete and the Whitestone is in its best condition with DCR2/DCR1 = 2/7. At 0.58$/minute, the value of this time to the bridge users is equal to 0.70$=1.20 min * 0.58$/min). Using Eq. (14.b), the expected peak traffic volume in this case is 6707 veh/hr.

Updated Throgs Neck Bridge peak volume curve:

As the Whitestone Bridge deteriorates, the demand curve for the Throgs Neck Bridge will pivot as depicted in the curve labelled D2 in Figure 9. The equilibrium value of Peak2, which is the point at which travel demand is equal to supply, will increase by the number of vehicles that leave the Whitestone due to its deterioration. For example, when the Whitestone Bridge's deck rating is DCR1=7 and the Throgs Neck's deck rating is DCR2=5 and using Eq. (14.b) with DCR2/DCR1=5/7 the peak traffic volume on the Throgs Neck Bridge is Peak2=6907 vehicles/hr which from Eq. (27) gives t=1.03 minutes at a travel time value = $0.60.

After the deterioration of the Whitestone Bridge, its deck condition becomes DCR1=6 with the Throgs Neck condition at DRC2=5. When these values ate substituted into Eq. (14.b) the peak volume on the Throgs Neck is increased to 6963 veh/hr.

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[11] The curve D1 represents the demand on the Throgs Neck Bridge before deterioration of the Whitestone Bridge.

The change in travel time resulting from the change in the travel volume will depend on the slope of the supply function. In Figure 9, the movement from point A to point B illustrates the change in travel time resulting from the change in travel volume. Applying Eq. (17) with θ_2=0.661 and C_2=3725, leads to:

$$t_2 = \theta_2\left(1.0 + 0.15\left(\frac{V}{C_2}\right)^4\right) = 0.661\left(1.0 + 0.15\left(\frac{V}{3725}\right)^4\right) \qquad (26)$$

The slope of the supply function is $\Delta t_2=0.661*0.15 * 4\,(\frac{V}{C})^3\Delta(\frac{V}{C})$ which gives the change in travel time when the normalized travel volume changes by one unit. Hence, when C_2=3725 and Peak2 increases from 6796 to 6907 veh/hr, the travel time which was originally 1.13 minutes will increase by 0.04 minutes=$0.15*0.661*4\,(\frac{6963}{3725})^3(\frac{6963-6907}{3725})$. Hence, the new travel time on the Throgs Neck Bridge t after the deterioration of the Whitestone Bridge becomes t= 1.13 + 0.04 = 1.17 minutes. The dollar value of this travel time is \$0.68= 1.17 * 0.58\$/minute.

Consumer Surplus:

As shown in Figure 9, the new demand function for the Throgs Neck Bridge will pivot counter clockwise to become flatter. This means that the Throgs Neck demand elasticity decreases or, in other words, the demand on the Throgs Neck becomes more inelastic when the Whitestone Bridge deteriorates. The Throgs Neck Consumers Surplus (CS) will thus decrease due to the increase in travel time caused by the additional vehicles that shift from the Whitestone. Graphically, the impact of decline in DCR1 on CS is shown in the shaded area of Figure 7. Assuming that the demand curve is approximately linear in this range, the effect of the decline in DCR1 on the Throgs Neck Bridge is summarized in Table 8 based on the following calculations:

- Pre deterioration CS = ½ (6963-6707) *(0.70-0.60) = \$12.80
- Post deterioration CS = ½(6907-6707) *(0.70-0.68) = \$2.00
- The difference between the two which is the shaded area is the change in Throgs Neck travelers CS due to a one unit drop in the deck condition of the Whitestone Bridge. The loss in CS on the Throgs Neck is equal to \$-10.80=\$2.00-\$12.80

Elasticity of traffic volume with respect to deterioration

The elasticity of the Throgs Neck Bridge's CS w.r.t to deterioration in the Whitestone Bridge can be found as:

$$\text{Elasticity2} = \frac{\%\,\Delta\,CS}{\%\,\Delta\,(\frac{DCR1}{DCR2})} = \frac{10.80/12.80}{(\frac{6}{5}-\frac{7}{5})/\frac{7}{5}} = 5.91\text{[12]} \qquad (32)$$

This indicates that for every one percent decrease in the condition rating of facility1 (i.e. Whitestone Bridge's condition), the consumer surplus of the travelers on the Throgs Neck Bridge will decrease by 5.91 percent.

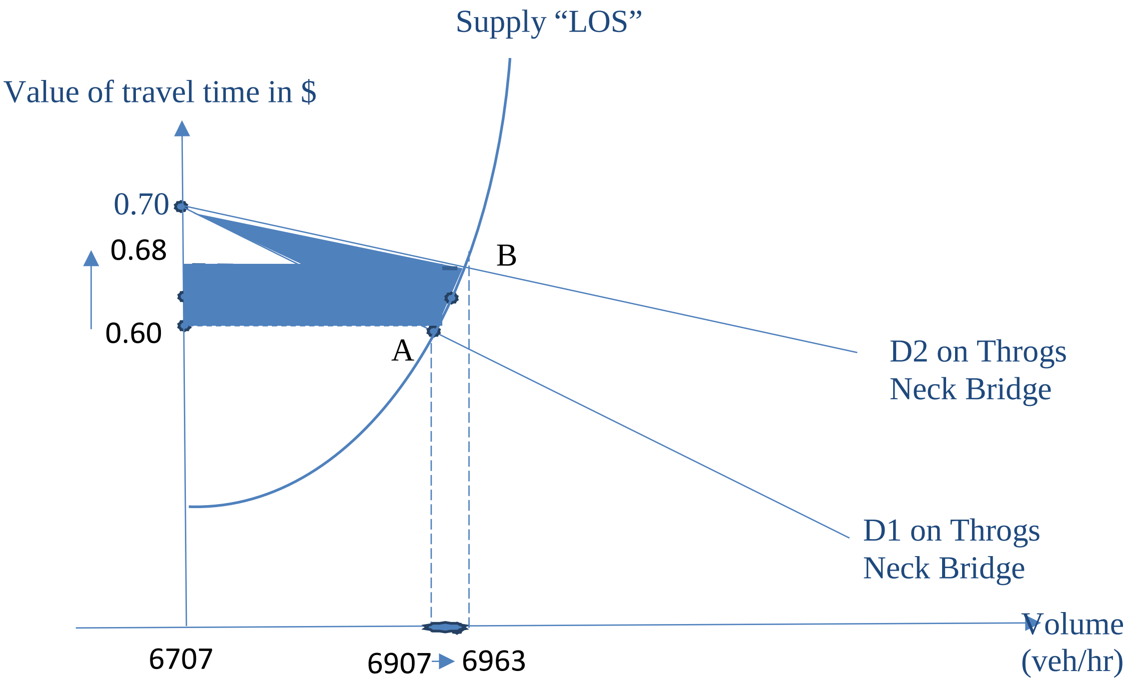

Figure 9: Impact of Decline in Whitestone's DCR1 on Throgs Neck's Consumer Surplus

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[12] The values for the Throgs Neck CS analysis are listed in Table 8.

Table 8: Throgs Neck Results

Throgs Neck Bridge Consumer Surplus	
Pre-deterioration	
Peak-hour volume (veh/hr)	6907
Consumer Surplus	$12.80
Post Deterioration	
Peak-hour volume (fixed demand)	6963
Consumer Surplus (fixed demand)	$2.00
Welfare changes	
Change in peak-hour volume	56
Change in Consumer surplus	$-10.80
Elasticity of CS w.r.t deterioration	**5.91**

Chapter 8

Conclusion and Future Work

8.1 Conclusion

The robustness of transportation facilities can be considered to be composed of two determinants: a) longitudinal deterioration in facility engineering quality; and b) sudden shock due to unexpected extreme events such as a major storm. This study focused on the first determinant and its economic implications.

Specifically, we have linked an engineering model of facility surface condition with travel demand on this facility and substitute facilities. Consequently, we were able to measure the welfare (consumer surplus) results of these changes in the engineering quality (infrastructure riding surface roughness) of the studied facilities.

We have applied the methodology developed in this Report to a two-bridge network example in New York. We showed that when facility quality (one of the two bridges) deteriorates there are major welfare losses in this two-bridge system. Specifically, we showed that a 1 percent decline in the quality of one facility as represented by the deck condition rating (facility deterioration) leads to changes of -2.41% and -5.91% in the welfare of the two facilities measured in units of consumer surplus for each traffic peak hour.

Table 9: Summary of impact of network deterioration on Network CS

Consumer Supply for Two-Bridge Network			
	Whitestone	Throgs Neck	**Total Network**
Pre-deterioration			
Peak-hour volume (veh/hr)	8083	6907	**14990**
Consumer Surplus $	$763	$12.80	**$775.8**
Post Deterioration			
Peak-hour volume (fixed demand)	7808	6963	**14771**
Consumer Surplus (fixed demand)	$500	$2.00	**$502**
Welfare changes			
Change in peak-hour volume	- 275	56	**-219**
Change in Consumer surplus	- $263	$-10.80	**-$273.8**
Elasticity of CS w.r.t deterioration	**2.41**	**5.91**	**2.47**[13]

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[13] The elasticity of the network consumer's surplus with respect to one level deterioration in the Whitestone bridge's deck is calculate by dividing the percent of change in the network consumers surplus over the percent of change in the Whitestone DCR ($\frac{273.8/775.8}{(\frac{6}{5}-\frac{7}{5})/\frac{7}{5}} = 2.47$)

8.2 Future Work

The analysis performed outlined an approach to study the effect of deterioration of one bridge on in an entire two-parallel-bridge system. The same analysis can be repeated to study the effects of the deterioration of the other facility on the entire system.

Because of the nature of the problem and the difficulty in collecting data on traffic and deck deterioration levels, the available data contained a lot of noise and thus the analysis is based on expected average performance. Future research should seek to collect more refined data on bridge deterioration to better correlate traffic patterns with bridge deterioration levels.

The work done in this study should be extended to measure the welfare effects from an entire network. That is, the engineering deterioration of transportation facilities should be measured at the network level with multiple facilities, such as a network of bridges. This, in turn, requires two major steps: First, the expansion of the models to cover an entire network; and second, the creation of a database with engineering and traffic data representing this network. Future work should extend this study in these directions.

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Appendix A: Engineering Factors Affecting Bridge Surface Deterioration Level

by Marie Couturier

Decks are the bridge components most prone to deterioration due to their exposure to severe environmental, chemical, and loading stressors. Maintaining smooth riding surfaces is important for facilitating travel flow, maintaining travel safety, reducing travel costs and ensuring the economic wellbeing of the community served. For these reasons, significant effort has been expended over the last few years to study the factors that control bridge deck deterioration and to develop models for predicting bridge deck service lives and maintenance needs. For example, based on stake-holder input, the ongoing Long-Term Bridge Performance Program (LTBPP) has initially been focusing on bridge decks (Modjeski and Masters, Inc. (2015). The report acknowledges that "the lack of quality information regarding the change in serviceability over time for bridges in different environments and traffic conditions is a continual challenge". The Report also notes that several studies developed analytical and empirical models to predict changes in bridge deck conditions over time. However, analyses of the national database summarizing the results of the National Bridge Inspection system provided in the National Bridge Inventory (NBI) condition data could not establish clear direct link between the known stressors and unsatisfactory serviceability performance.

Several studies such as the one by Hu et al. (2013) and Lin et al. (2012) have observed that the major causes of reinforced concrete deck deteriorations consist of chloride induced or carbonation induced corrosion of reinforcing steel, and freeze-thaw which when combined with mechanical loading from vehicular traffic, especially heavy truck loads, lead to damage to the riding surface and reduction in the level of service to bridge users. As part of this study, the research team explored models for assessing the effects of chloride-induced corrosion, freeze-thaw and repetitive truck loading on bridge deck deterioration. A typical bridge deck was analyzed and the analytically estimated damage was compared to the damage estimated by bridge inspectors as reported in the condition rating listed in the NBI file.

Chloride-induced Damage

The first and primary bridge deck deterioration mechanism studied was chloride-induced corrosion of steel reinforcement. Chlorides are derived primarily from the application of roadway deicing salts. When the chlorides penetrate the concrete and reach a critical concentration, they cause the corrosion of reinforcing steel bars. Corrosion of reinforcing steel can lead to delamination and cracking of the concrete and is a main source of deck deterioration. The damage process is described in the flow chart of Figure A.1.

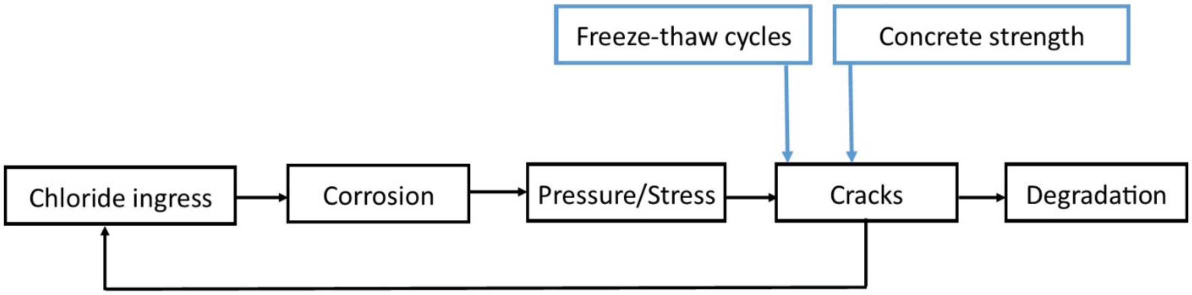

Figure A.1: Steps of chloride-induced degradation of concrete

Corrosion of reinforcing steel bars in concrete is an electrochemical reaction between the steel and its surrounding environment. The steel reinforcement is protected from corrosion by passivation. In a typical environment, the concrete pH ranges between 12.5 and 13.5. A protective oxide film is formed on the reinforcement surface during cement hydration and maintained by the high alkalinity of the concrete. This film acts as a barrier against corrosion and the steel exists in a passive condition.

In concrete bridge decks, chloride ions are derived from deicing salts used during winter maintenance operations and from exposure to sea water. The chloride ions penetrate the concrete and when their concentration at the rebar depth exceeds a critical threshold value, they break the passive film and active steel corrosion is initiated.

Chloride intrusion into concrete is a complex time-dependent process which is mainly controlled by the properties of the concrete cover. In this study, the model developed by Kassir and Ghosn (2002) was used to predict corrosion initiation time of reinforced concrete bridge decks knowing the concrete cover thickness and the diffusion coefficient of the concrete.

Bazant (1979) proposed a simplified mathematical model to calculate the time to corrosion cracking of concrete cover based on theoretical physical models. According to Bazant’s model, the time to cracking is a function of corrosion rate, cover depth, spacing, and certain mechanical properties of concrete such as tensile strength, modulus of elasticity, Poisson’s ratio and creep coefficient. Hu et al. (2013) also observed that for typical concrete decks it may take about 20 years for the cracks that initiate near the reinforced steel to propagate to the concrete surface. They propose that more exact determination of the time required for the crack propagation process be performed using fracture mechanics principles. Using the above listed models it is estimated that chloride-induced cracks will be observed on typical bridge decks after approximately 33 years of service and that within 40 years of service the damage may spread over 50% of the deck surface as observed in Figure A.2.

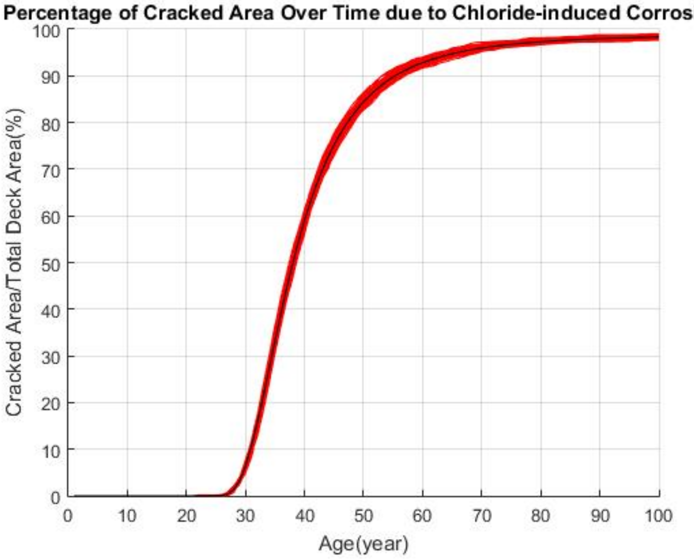

Figure A.2: Chloride-induced damage over time obtained with Monte-Carlo Simulation

Freeze-thaw Phenomenon

Damage of concrete due to freezing and thawing is a combination of different processes and several theories have been developed to explain the behavior of concrete in freeze-thaw environments. In this the model proposed by Barde (2009) is used to predict the service life of concrete in freeze thaw environments based on earlier work performed by Fagerlund (2004). Accordingly, service life can be divided into two parts: the time to initiate freeze-thaw damage ($Life_{init}$) and the time required for damage propagation ($Life_{sec}$). Following the approach used by Hu et al. (2013) which is based on the work of Barde (2009) a typical bridge deck located in Central New York State would have a probabilistic distribution of damage similar to that shown in Figure A.3. The results show that on the average, about 50% of a typical deck would be damaged after close to 40 years in service.

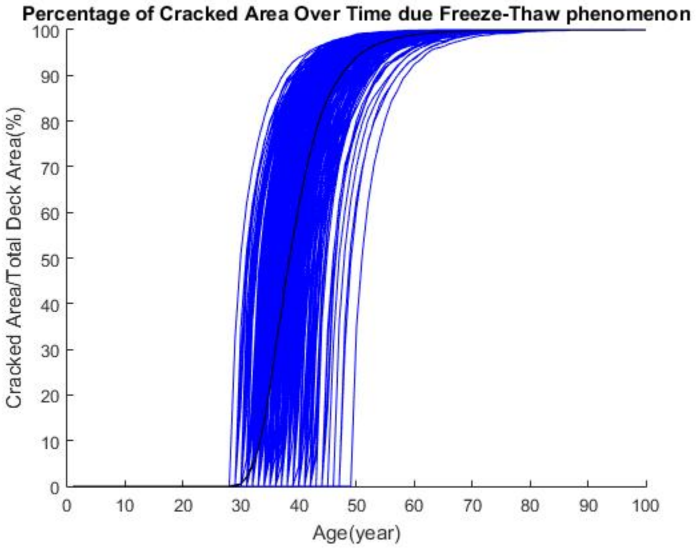

Figure A.3: Freeze-thaw induced damage over time obtained with Monte-Carlo Simulation

Fatigue Damage from Trucks

The service life of a bridge deck under the effect of vehicular traffic is affected by fatigue damage accumulation processes. The simplest approach of analyzing fatigue damage is to use appropriate S-N (stress versus number of loading cycles) curves assembled from data from a series of constant amplitude tests. The experimentally derived S-N curves can be used in conjunction with Miner's rule to predict the fatigue life of a bridge component that is subjected to service loads having a complicated time history Miner (1945). In this study, a load intensity versus number of loading cycles model developed by Perdikaris (1993) is used to study the time to fatigue failure of RC decks under rolling loads. The implementation of the analysis on a typical concrete bridge deck in New York produces the damage accumulation curve shown in Figure A.4. The curve shows that a typical bridge deck will be damaged at 60 % after 35 years of service life and complete damage in less than 60 years.

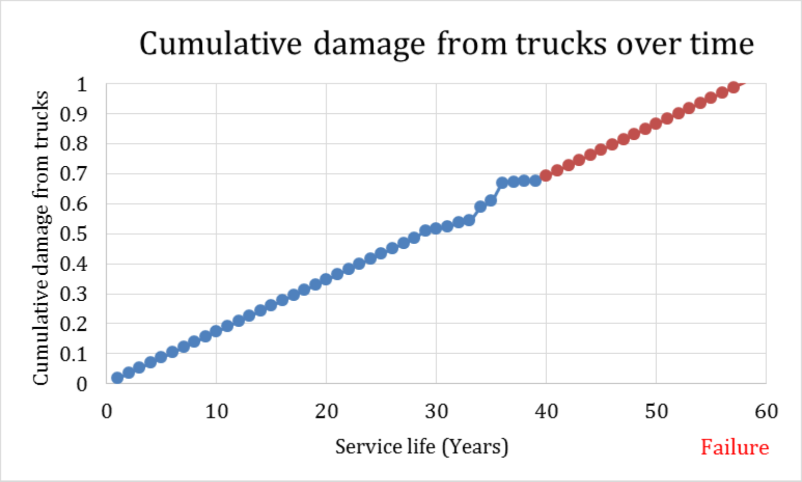

Figure A.4: Damage from trucks over time for the example bridge

Bridge Deck Condition Rating

The Federal Highway Administration (FHWA) makes available the results of annual reports on US bridge conditions through the National Bridge Inventory (NBI). The concrete deck condition rating used by the US Department of Transportation assigns a value that ranges between 0 and 9; 9 being the value assigned to a new deck and 0 being a value that indicates that the deck is in failed condition. The deck is considered to be in serious condition and must be rehabilitated if the rating reaches a value of 3. When the rating is equal to 6, the deck is found to have been exposed to an excessive number of open cracks but is still in satisfactory condition. These rating are usually assigned by trained bridge inspectors based on visual observations that are sometimes supplemented with nondestructive techniques. The NBI condition rating of all US bridges are available on the website of the US Department of Transportation (DOT) starting from the year 1992 up to 2015. It is interesting to observe that many analyses of the NBI data shows that the useful service life of typical bridge decks is on the order of 40 years. This service life is consistent with the results of the predictive models utilized for freeze-thaw damage and chloride-induced damage as performed in our study for a typical bridge deck. The NBI data for the typical bridge deck analyzed in this study show that some deck repairs were undertaken in the year 2001 and that during the last 13 years, the condition rating has fallen from 9 to 6 as shown in Figure A.5.

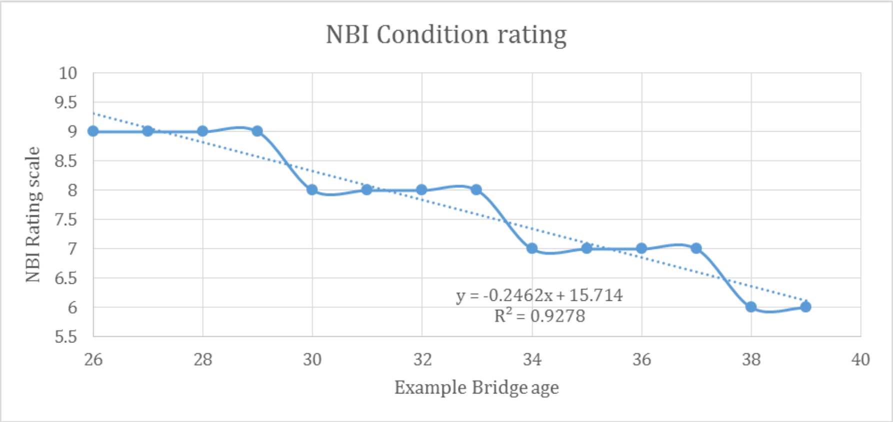

Figure A.5: NBI condition rating from 2001 and 2014 and linear regression

The deterioration rate observed in Figure A.5 is naturally related to the combination of various damage mechanisms including those of chloride-induced corrosion, freeze-thaw phenomenon and fatigue damage from repetitive truck loading cycles. The inversion of the curve would give an indication of the change in the percent of total deck damage over time as shown in Figure A.6 which compares the percent of total damage as estimated from the NBI condition rating to the analytical estimated damage obtained for each three factors studied; i.e. chloride-indicted corrosion, freeze-thaw and repetitive truck loads.

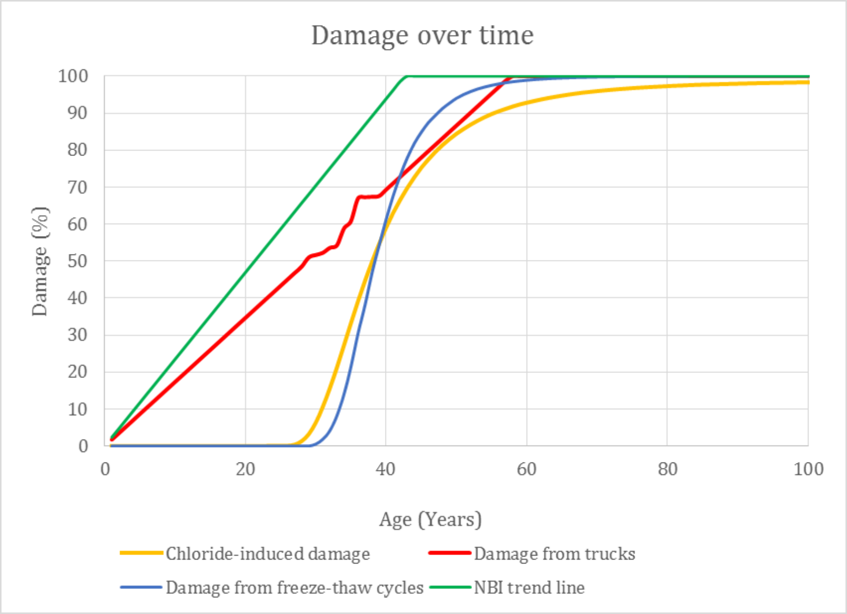

Figure A.6: Deterioration curves for the example bridge

To account for the fact that the actual observed damage to bridge decks is a combination of the three individually analyzed deterioration factors, a regression model is developed to obtain the best match between the observed percent of the total damage observed over time and the percent damage caused by each factor individually. A possible model may take the form:

$$D_{tot}(t) = A * D_{chloride}(t)^{\alpha} + B * D_{freeze-thaw}(t)^{\beta} + C * D_{trucks}(t)^{\gamma} + D \quad \text{Eq. (A.1)}$$

where D_{tot} is the total damage of the bridge deck, $D_{chloride}$ is the chloride-induced damage, $D_{freeze-thaw}$ is the damaged created by freeze-thaw phenomenon and D_{trucks} is the fatigue damage from trucks. A, B and C as well as α, β and γ are constants determined using regression fits as listed in Table A.1. Figure A.7 shows a plot of the total damage obtained from the regression formula and the percent of total damage line from NBI measurements over time.

A	**α**	**B**	**β**	**C**	**γ**
0.01073161	0.01453133	1.75005961	0.88286022	1.60928054	0.1721466

Table A.1: Coefficients of Eq. (1) based on multi-variable nonlinear regression

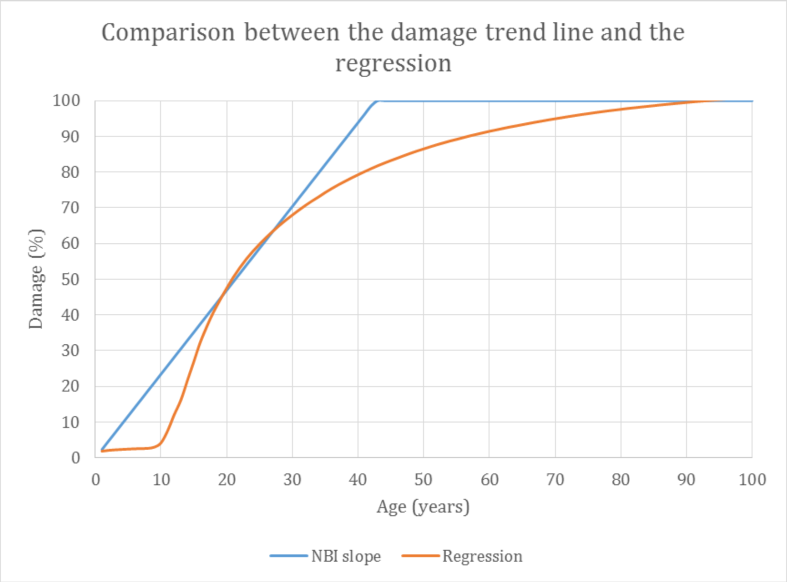

Figure A.7: Comparison of regression model and NBI percent of deck damage over time

Conclusion

A methodology was developed to link the main deteriorating factors of concrete bridge decks to changes in the condition rating of typical reinforced concrete bridge decks. For each factor of deterioration, a model was described for assessing and plotting the evolution of damage over the bridge deck service life. The models were implemented on a specific bridge in New York to obtain a numerical assessment of damage for a typical bridge. The actual bridge deck damage assessed by bridge inspectors as reported in the National Bridge Inventory (NBI) was compared to the results obtained from the models. A multiple nonlinear regression was performed in order to model the contribution of each deterioration factor to the overall deck deterioration phenomenon. It is interesting to observe that the analytical models showed a typical bridge deck service life close to 40 years which is what studies of NBI data shows to be a typical service life. Many assumptions were made to execute the calculations presented in this report as only a few required parameters can be easily gathered and the combined effect of different deterioration mechanisms are very difficult to model. Thus, at this stage, the calculations and numerical results obtained are only qualitative and should be revisited as more refined data is collected and after applying the models to a large sample of New York State bridges. Furthermore, the models analyzed pertain to typical reinforced concrete bridge decks and may not be applicable to orthotropic bridge decks that are typically used for long span bridges where the concrete layer is usually supported by a steel system which itself may undergo different deterioration mechanisms that affect the flexibility of the riding surface that could accelerate the deck's deterioration. For these reasons, it is suggested that in the reminder of the study, deck deterioration levels should be estimated based on inspection reports and NBI data rather than the analytical models investigated in this section of the report

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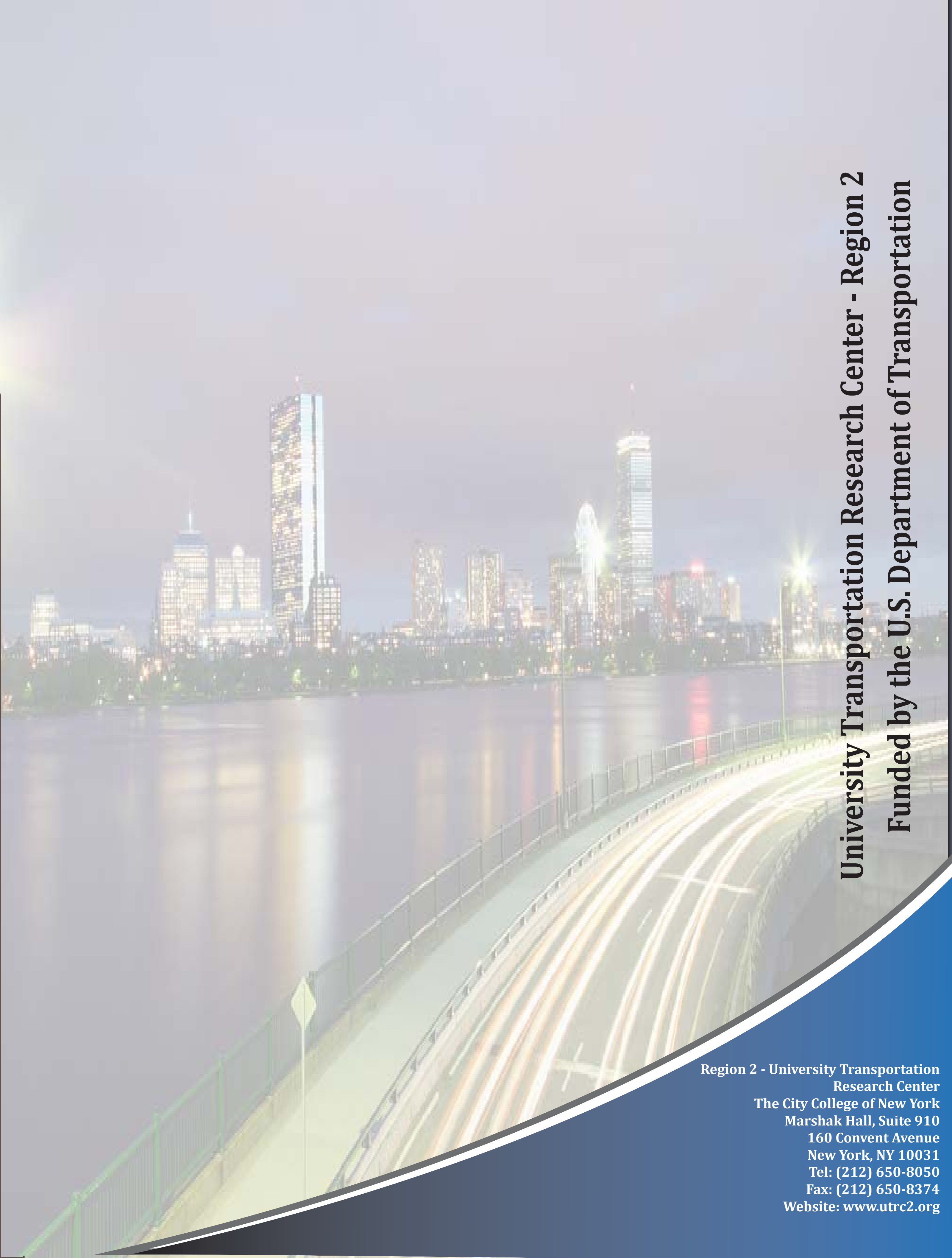

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