UNDERSTANDING THE EFFECT OF INTERDEPENDENCY AND VULNERABILITY ON THE PERFORMANCE OF CIVIL INFRASTRUCTURE

*A. Atef and O. Moselhi
Department of Building, Civil and Environmental Engineering
Concordia University
1455 de Maisonneuve Blvd. West
Montréal, Québec, Canada, H3G 1M8
*(*Corresponding author: a_atef@encs.concordia.ca)*

UNDERSTANDING THE EFFECT OF INTERDEPENDENCY AND VULNERABILITY ON THE PERFORMANCE OF CIVIL INFRASTRUCTURE

ABSTRACT

Vulnerability is a measure of the extent to which a community, structure, services or geographic area is likely to be damaged or disrupted by the impact of particular hazard. Current asset management practices focuses on studying factors that affect performance of isolated infrastructure networks and model a set of actions to control the expected performance of these networks. This approach ignores the underlying spatial and functional interdependencies among these infrastructure networks and their vulnerability. The purpose of this paper is to introduce a new method that recognizes the effect of spatial and functional interdependencies on vulnerability rating of water, sewer and road networks. The proposed method consists of: 1) risk assessment model, 2) interdependency assessment model and 3) vulnerability assessment model. The risk model is composed of two modules: 1) water and sewer risk module and 2) road infrastructure module. The water and sewer risk module will cluster these assets into three risk categories based on environmental, social, operational and economical factors. The road infrastructure module will cluster road assets into three risk categories by using rational factorial technique based on road type, serviceability index, traffic load, and freeze and thaw index. The interdependency model will deploy the risk ranking to perform geospatial analysis in ArcGIS which results in determining the interdependent layers of waters, sewers and roads. The vulnerability model will deploy fuzzy neural networks technique to determine the vulnerability rating based on spatial and functional interdependencies. The fuzzy neural networks are utilized to overcome the lack of historical data and incorporate experts' preferences for establishing the knowledge base for vulnerability assessment. The expected contribution of this framework is to aid decision makers in understanding the interdependencies between civil infrastructure assets and to which extent such interdependencies can compromise assets performance.

KEYWORDS

Vulnerability assessment, Interdependency assessment, ArcGIS, Fuzzy neural networks

INTRODUCTION

Asset management targets the sustainability of civil infrastructures throughout combining the economic and engineering principles to meet customers' preferences and avoid catastrophic failures. Generally, the asset engineers divide the civil infrastructure networks into isolated water, sewer and road networks. Subsequently, the performance and operation modeling of these systems is performed to support planning, maintenance from multiple view points, including infrastructure owners, investors, private and public users, and government entities. As such, the developed models focus on isolated analysis of infrastructure assets for specific domain (i.e. water, sewer, roadways…etc.) ignoring spatial and functional interdependencies. For example, consider a water pipeline attached to a bridge, a failure in that bridge will not affect only the adjacent road networks but the cascading consequences will prolong to the water pipeline networks. Additionally, a failure of a water asset may drop the performance of adjacent water assets and may lead to water outages that affect the customers' satisfaction. Therefore, due to spatial and functional interdependencies, failure in one asset may not only affect the functionality or structural resilience of its network but may likely also compromise the functionality or the structural resilience of other interdependent networks as well. The objective of this paper is to provide a framework that recognizes the effect of spatial and functional interdependency on water, sewer and road assets and their respective vulnerability.

The paper starts by presenting the current state of art of interdependency and vulnerability assessment models and highlights some of the current limitations in the literature. Subsequently, the proposed research methodology is presented to address some of the highlighted gaps in the literature. The research methodology consists of the three models; 1) risk assessment model, 2) interdependency assessment model and 3) vulnerability assessment model. The inputs, procedures and expected outputs of each models are discussed comprehensively for each model. The paper concludes with the expected contribution of the research methodology to the current asset management practice and also with the current limitation of the proposed research framework and expected future work.

LITERATURE REVIEW

Interdependency Assessment

Infrastructure systems interdependency is a growing area of study that incorporate the contributions of researchers from various engineering, mathematical and social science disciplines to better understand the behavior of interdependent infrastructures. It primarily focuses on aiding decision makers to achieve national security, economic prosperity, and the quality of life of today's societies (Gesara et al., 2010). Such economic and social prosperity is attained while heavily depending on the continuous and reliable operation of critical interdependent infrastructures. In recenet decade, researchers tried to unrestand and present classifcations for infrastructure interdepndencies that suites their domain of applications (Rinaldi et al., 2001; Lee et al., 2004; Dudenhoeffer et al., 2006) as shown in Table 1.

Table 1- Interdependencies classifications

Classification	Definition
Physical	The physical output of one infrastructure is the physical input to another infrastructure.
Cyber	Infrastructure is dependent on another infrastructure as they are connected via information links.
Geographical	Two infrastructures are dependent because of physical proximity.
Policy /procedural	Infrastructure state is dependent on another infrastructure state due to governmental policy or procedure.
Social	Infrastructure event may have influence on the community such as public opinion, public confidence and cultural issues.
Mutual	One infrastructure asset in an infrastructure group is depending on another infrastructures' functionalities
Shared	The same infrastructure is utilized in providing two or more services to a group of infrastructures
Exclusive	Two or more services can be provided by an infrastructure component at a time.

In this paper, civil infrastructures interdependencies are limited to spatial and functional interdependencies between water, sewer and road assets. The spatial and functional interdependencies definitions are close to geospatial and physical interdependencies definitions suggested by other authors in Table 1 with some modifications to suite the integrated asset management framework. Spatial interdependencies addresses whether an infrastructure's structural resilience or performance is threaten by being located in the same geospatial area as another asset. On the other hand, Functional interdependencies mean that an infrastructure's performance is limited by the structural resilience or performance of another asset.

Roughly, infrastructure interdependency modeling can be categorized into mathematical and simulation models. Mathematical models aim to abstract the network of these assets using graph theory and assess the interdependency using degree of vertices, average shortest path and clustering coefficient (Crucitti et al., 2003). Mathematical models can be used to assess the degree of inoperability of asset networks due to imposed action (Haimes & Jiang, 2001; Santos & Haimes, 2004). On the other hand, the simulation models can be utilized to simulate infrastructure networks throughout agent based modeling (ABM) (Dudenhoeffer et al., 2006) or system dynamic (SD) (Stapelberg, 2011) to encapsulate the interactions between various infrastructure networks, customers and decision makers.

Vulnerability Assessment

Vulnerability can be defined as the extent to which an infrastructure asset's performance is compromised due to performance interdependencies among the assets being considered. Hence, there are two types of vulnerabilities; 1) spatial vulnerability, 2) functional vulnerability. Spatial vulnerability represents the degree of susceptibility to structural failure as a result of being spatially interdependent with neighbouring assets. On the other hand, functional vulnerability represents the degree of susceptibility to functional failure as a result of being functionally interdependent with neighbouring assets. Vulnerability assessment is the process of identifying systems weaknesses due to specific events and assessing the extent of such weaknesses on systems performance or existence (Baker, 2003). Vulnerability assessment is carried out on two stages: 1) qualitative assessment which aims to identify the expected threats, 2) quantitative assessment which determines the likelihood and consequences for such identified threats on the system. Researchers tried to presents various methodologies for identifying system vulnerability which falls into two categories:

1- Objective scoring methods utilizing simple scoring method, multi-attribute utility theory and analytical hierarchy processes (Baker, 2003; Ezell, 2004, Karmakar et al., 2010).

2- Simulation methods utilizing agent based modeling or system dynamic simulation. (Eun et al., 2010; Ouyang et al., 2009).

Limitations in Current Literature

The main limitations of the methods described above are:

1- Overlooking infrastructure interdependencies: Infrastructure DSS for rehabilitation, maintenance and mitigation actions, are implemented ignoring the underlying spatial and functional interdependencies that exist between water, sewer and road networks (Moselhi et al., 2005).

2- Context and scope of interdependency models: Interdependency models were primarily concerned with the functional interdependency rather than the spatial interdependency for the domain of disaster management. In the context of disaster management, the decision maker should be able to restore the service in minimal time as possible to cope with community expectation. (Baker, 2003; Dudenhoeffer et al., 2006).

3- Scale of modeling: The size of networks to be represented is significant computational challenge. As the size of modeled network increases, the investigated scenarios space will necessary increases with complex, heterogeneous, interdependent infrastructure systems. (Rinaldi et al., 2001; Moselhi et al., 2005). Vulnerability models are implemented mainly to study the vulnerability in one network ignoring underlying interdependencies with other infrastructure networks (Ezell, 2004).

4- Research methods and data availability: Models are often limited by the amount and quality of information that infrastructure facility owners and managers are willing to share with public and private professional and academic entities, greatly reducing the generic applicability of the models and tools to be used in real-life scenarios (Earl et al., 2004).

RESEARCH METHODOLOGY

Risk Assessment Model

Water and Sewer Risk Module

Asset criticality, consequence of failure, plays an essential role in asset risk assessment frameworks. Asset criticality is utilized to express the economic, social and environmental implications of asset's failure to perform its intended function. Generally, the direct quantification of environmental and social costs of infrastructure asset failure are cumbersome and debatable. Therefore, asset managers commonly rely on a proxy for asset criticality by identifying attributes, risk variable, of the asset and surrounding environment that may explain possible failure consequences (*SOI Report, 2005*). For example, the classification of roadway and availability of alternative routes for the road are risk variables that can predict the social consequences of a pipe failure. The risk variable score (SRV) is defined based on consultation process with representative staff from the utility operator. Finally, a series of weights are utilized to identify an overall risk index for a risk category (e.g. economic, environmental, social risks, etc…). A sample of such risk identification and assessment for the City of Hamilton (Canada) was undertaken as part of the City's Water Main Management Framework project (*SOI Report, 2005*). For instance, environmental scores can range from 1 to 100 as shown in the **Table 2**. The risk category index is calculated as follows:

$$RCI_{i} = \sum_{j=1}^{NRV_{i}} WRV_{i,j} \times SRV_{i,j} \tag{1}$$

Where
RCI_i is Risk Category Index for category I, NRV_i is Number of Risk Variables in category i (for example there are 3 variables under the environmental risk category), $WRV_{i,j}$ is Weight of risk variable number j for category i , $SRV_{i,j}$ is Score of risk variable number j for category i.

Table 2- Risk scores, variables and scores for the environmental risk category

Index	Environmental			
Weight	0.25			
Category	Environmental Impact			
Weight	1.00			
Variables	Land use		Pipe Size	
Weight	0.2		0.4	
	Value	Score	Value	Score
	Park	1	0-300	10
	Residential	15	300-600	25
	Commercial	25	600-900	50
	Industrial dry customer	25	900	100
	Industrial wet customer	50		
	High Density	100		

As shown in Table 2, scores depend on the value of a risk variable (e.g. a 800mm pipe would score '50' in the pipe diameter risk variable). For all assets in the network an asset risk index (ARI) is calculated by combining all risk categories calculated in Equation 1 according to their respective weights. The ARI can be considered a subjective yet consistent rating of the overall asset criticality. To Calculate the Asset Risk Index (ARI) which is the total score for an individual asset taking into consideration all risk categories:

$$ARI = \sum_{i=1}^{NRC} RCI_i \times WRC_i \qquad (2)$$

Where

WRC_i: Weight of risk category I, NRC: Number of Risk Categories (in the preceding tables, there are four categories).

For the City of Hamilton, Canada, the model considered four major factors which are considered as intolerable events; operational, social, economic and operational. Aggregating these factors will cluster the assets into three main categories; high criticality (A), medium Criticality (B) and low Criticality (C). The asset risk index is subsequently used in the multi-objective optimization problem to calculate the overall network risk exposure due to delayed or inaccurate condition assessments. The output of this model is the clustering of water and sewer assets into three categories as shown in Table 3.

Table 3- Clustering scores for different assets

Cluster	Score
A: High criticality	ARI > 80
B: Medium criticality	10 < ARI < 80
C: Low criticality	ARI < 10

Road Risk Module

In this module, the road networks will be classified into various risk categories based on the: PSI (present serviceability index), distresses affecting the condition of the road, traffic load (ADT, annual daily traffic) according to (Robinson, 1998). This method is called the rational factorial rating method and the asset priority is determined by:

$$Y = 5.4 - 0.0263X_1 - 0.0132X_2 - 0.4\log X_3 + 0.749X_4 \qquad (3)$$

Where
X_1: rainfall. (5 to 40 in), X_2: Freeze and thaw, X_3: Traffic flow (AADT), X_4: Present Serviceability Index (PSI), X_5: Distress rating, Y Criticality: 10 for high critical assets- 1 to low critical assets.

After understanding the criticality of various assets, the interdependency module can aid in capturing the critical assets that are spatially and functionally interdependent.

Interdependency Assessment Model

The interdependency model is implemented to encapsulate:

1) The infrastructure assets that are spatially interdependent, co-located in the XYZ plans, using ArcGIS 10^{TM} geoprocessing toolbox.
2) The infrastructure assets that are functionally interdependent using an algorithm that will trace the impact of an asset failure on the network functionality.

Geoprocessing is a methodical execution of a sequence of operations on geographic data to create new information using two process; spatial analysis and automation. This can be utilized by taking two different datasets (i.e. waters and roads) and find a new single dataset with the intersected assets and their corresponding attributes. For spatial interdependency, selection queries using location attributes is used to select the intersected layers of water, sewer and roads. Subsequently, union module of the geoprocessing toolbox is deployed to formulate three new layers of the intersected assets (waters and sewers - roads and sewers - roads and waters) as shown in Figure 1. The outputs are new layers with new datasets that contain characteristics of the intersected assets. For instance, the new fields contain which roads and sewers are intersected, the soil type between them, the distance between the two assets…etc. Hence, these factors can be used for the vulnerability module to assess the extent of any asset failure on spatially interdependent assets.

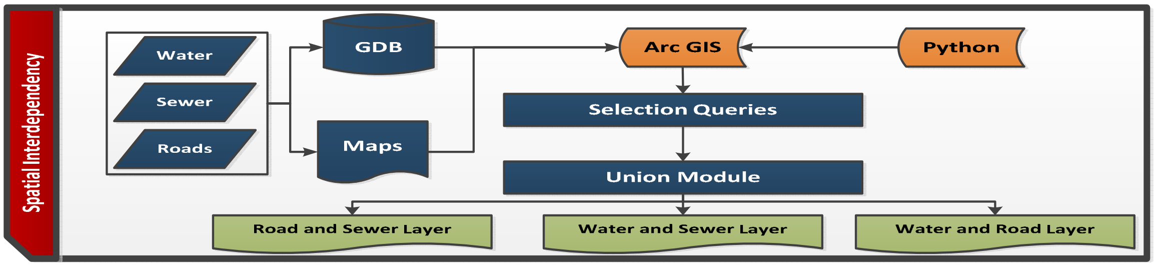

Figure 1- Spatial interdependency algorithm

Subsequently, the functional interdependency algorithm is utilized to determine to which extent an asset failure can affect other parts of the network. For example, the algorithm takes a water pipe and aggregates the number of pipes affected by such pipe failure, the number of affected customers, type of customers (commercial, industrial, domestic)…etc. as shown in Figure 2. These data are added to the geodatabase and are used in the functional vulnerability rating.

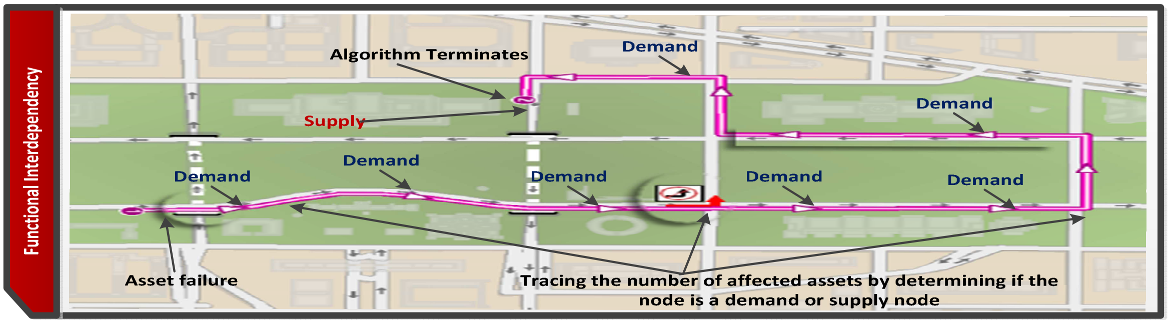

Figure 2- Functional interdependency algorithm

Vulnerability Assessment Model

A Fuzzy-neural model (FNN) will be utilized to rate the vulnerability of interdependent assets. FNN is suitable technique when there is a lack of historical data and interviews of experts can be used to overcome such limitation. In this model, questionnaires will be sent to experts and decision makers responsible for managing the water, sewer and road networks. These questionnaires will focus on three topics:

1. Eliciting the respondents about factors affecting spatial vulnerability of interdependent water, road and sewer networks. Respondents will be asked to determine the likely effect of factors like soil, buried depth, asset alignment on the spatial vulnerability between two assets. Also, respondents

will be asked to state any factors that can be added to that list with justification and its expected effect on the vulnerability rating as well.

2. Eliciting the respondents about factors affecting functional vulnerability of interdependent water, road and sewer networks. Respondents will be asked to determine the likely effect of factors like customer type, customer number, and number of affected assets due to that asset failure on the functional vulnerability between the asset and its network. Also, respondents will be asked to state any factors that can be added to that list with justification and its expected effect on the vulnerability rating as well.
3. Respondents will be given hypothetical scenarios and in these hypothetical scenarios they will be asked to determine the vulnerability rating of two interdependent assets based on number of factors. These will be used as a vehicle to perform two tasks: 1) Training the FNN model to find the best membership function that represents the considered factors and its effect on vulnerability. 2) Testing the model to verify and validate the generated output to overcome lack of historical data on the interaction between the three systems.

The output of the vulnerability model is displayed in three layers; representing the vulnerability rating of each water, road and sewer asset. The detailed process of vulnerability model is shown in Figure 3. The questionnaire will target a wide range of experts in the water, sewer and roads infrastructure management sector to formulate an expert system that can be adopted into the current context of asset management.

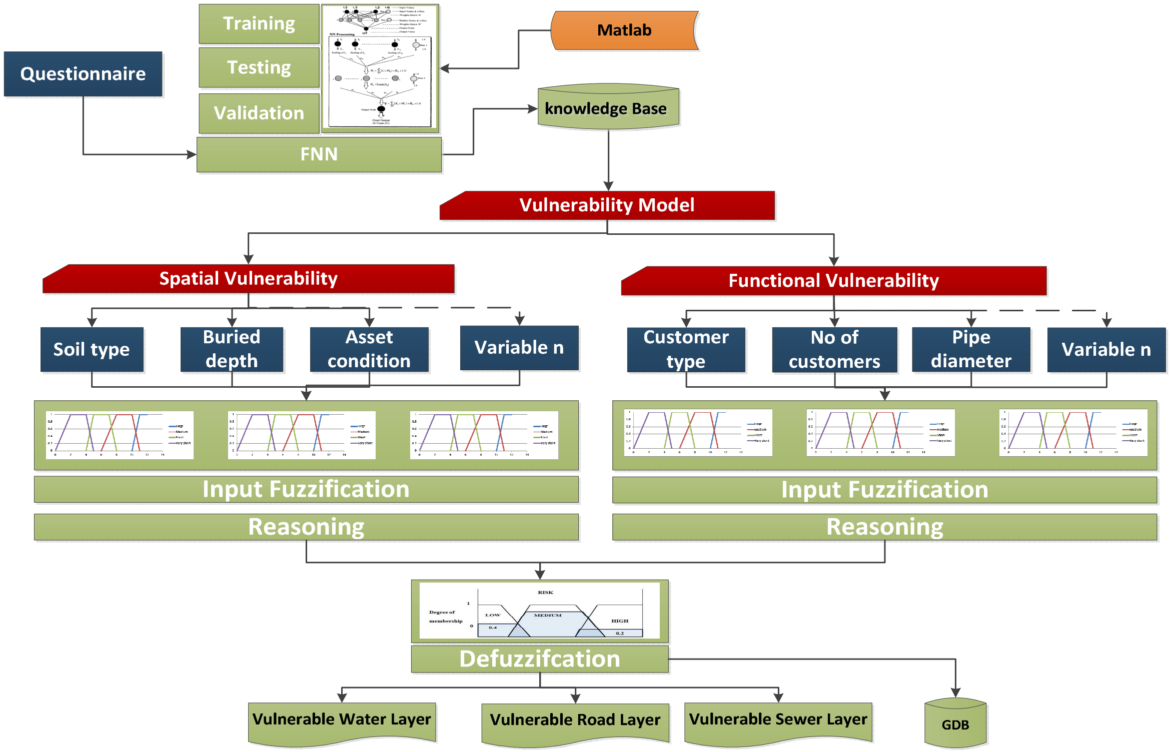

Figure 3- FNN model

CONCLUSIONS

This paper provides a framework to understand the vulnerability of civil infrastructure based on spatial and functional interdependencies. The framework started by clustering infrastructure networks into various asset criticalities hence the interdependency model encapsulates the spatially and functionally interdependent assets. Afterwards, the vulnerability module is utilized to rate the vulnerability of interdependent assets based on various factors rated by FNN based on experts interviews. Hence, decision makers can understand to which extend water, sewer or road asset can compromise the functionality of other assets utilizing fuzzy neural networks The data collection and experts interviews is still in progress. Value driven budget allocation model will be implemented to allocate budgetary resources based on customers' expectations and also maintain the vulnerability levels below certain threshold using multi-objective optimization.

REFERENCES

Baker, G. H. (2003). A Vulnerability Assessment Methodology for Critical Infrastructure Facilities. National Capital Region Critical Infrastructure Vulnerability, 1-50

Crucitti, P., Latora, V., Marchiori, M., & Rapisarda, A. (2003). Efficiency of scale-free networks: error and attack tolerance. Physica A: Statistical Mechanics and its Applications, 320, 622-642.

Dudenhoeffer, D., Permann, M., & Manic, M. (2006). CIMS: a framework for infrastructure interdependency modeling and analysis. Proceedings of the 2006 Winter Simulation Conference. Monterey, CA: IEEE.

Eun, H. O., Abhijeet, D., & Makarand, H. (2010). Vulnerability Assessment of Critical Infrastructure, Associated Industries, and Communities during Extreme Events. CONSTRUCTION RESEARCH CONGRESS 2010. Banaf: ASCE.

Ezell, B. (2004). “Quantifying Vulnerability to Critical Infrastructure Systems”. Ph.D. Dissertation, Department of Engineering Management, Old Dominion University.

Gesara, S. &. Dueñas-Osorio, L. (2010). Synthesis of Modeling and Simulation Methods on Critical Infrastructure Interdependencies. Sustainable and Resilient Critical Infrastructure Systems Simulation Modeling and *and* Intelligent Engineering (pp. 1-51). Berlin Heidelberg: Springer-Verlag.

Haimes, Y., & Jiang, P. (2001). Leontief-Based Model of Risk in Complex Interconnected Infrastructures. Journal of Infrastructure Systems, 7(1), 1-12.

Karmakar, S., Simonovic, S. P., Peck, A., & Black, J. (2010). An Information System for Risk-Vulnerability Assessment to Flood. Journal of Geographic Information System, 2, 129-146.

Lee, E. E., Mitchell, J. E., & Wallace, W. A. (2004). Assessing vulnerability of proposed designs for interdependent infrastructure systems. Proceedings of the 37th Annual Hawaii International Conference on (pp. 8-pp). IEEE.

Moselhi, O., Hammad, A., Alkass, S., Assi, C., Debbabi, M., & Haider, M. (June 2-4, 2005). Vulnerability assessment of civil infrastructure systems: a network approach. 1st CSCE Specialty Conference on Infrastructure Technologies, Management and Policy. Toronto, Ontario, Canada.

Ouyang, M., Hong, L., Maoa, Z.-J., Yu, M.-H., & Qi, F. (2009). A methodological approach to analyze vulnerability of interdependent infrastructures. Simulation Modelling Practice and Theory, 17 , 817–828.

Robinson ,R (1998). *Road Maintenance Management*. Birmingham: Macmillan, Vol. 1.

Rinaldi, S. M., Peerenboom, J. P., & Kelly, T. K. (2001). Identifying, understanding, and analyzing critical infrastructure interdependencies. IEEE Control Systems Magazine,, 21(6), 11-25.

Santos, J., & Haimes, Y. (2004). Modeling the demand reduction input-output (I-O) inoperability due to terrorism of interconnected infrastructures. 24(6), 1437–1451.

Stapelberg, R. F. (2011). Infrastructure Systems Interdependencies and Risk Informed Decision Making (RIDM): Impact Scenario Analysis of Infrastructure Risks Induced by Natural, Technological and Intentional Hazards. Journal of systemics, Cybernetics and Informatics, 9(5).

SOI Report (2005) City of Hamilton State of the Infrastructure Report. Available Online at http://www.myhamilton.ca/myhamilton/CityandGovernment/CityDepartments/PublicWorks/CapitalPlanning/Asset+Management/State+of+the+Infrastructure+Report.htm