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RESILIENCE-BASED ASSET MANAGEMENT FRAMEWORK AND ITS APPLICATION ON PAVEMENT NETWORKS

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Abstract: Infrastructure systems play a pivotal role in the development of economy and public services, which positively affects the quality of life of the communities. Accordingly, a growing need is required to support the ability of those systems to sustain extreme events and recover after, the later forms the general resilience concept. Nevertheless, resilience has been defined through many divergent interpretations according to both the method and domain of application. Thus, this paper introduces a resilience definition integrating both resilience and asset management concepts. It is important to mention that the average age of the core infrastructure in Canada (i.e. bridges, roads, water, wastewater, etc.) was about 14.7 years in year 2013, according to Canada infrastructure report 2016. Still, those infrastructure's resiliency is inferior due to the backlog in investment needs, aging, deterioration, severe weather conditions and previous disruption events effects. Accordingly, this paper aims at developing a resilience-based asset management framework for pavement networks maintenance and rehabilitation. This was carried out through development of five components; 1) a central database of asset inventory and network data, 2) a pavement condition and level of service (LOS) assessment model using asset-based resilience indicators, 3) a simulation model of the effect of Freeze-Thaw on pavement network using disruption-based indicators, and 4) financial and temporal models incorporating recovery-based indicators. This pavement resilience assessment framework is beneficial for asset management decision making where the intervention plans would not only target enhancing or restoring pavement condition or LOS, but also incorporate the implementation of proper recovery strategies for both regular and/or extreme events.

1 INTRODUCTION

During an infrastructure's life-cycle, aging and disruptive events strike causing significant deterioration in its functionality and hindering other interdependent assets functionality as well. Thus, a growing need is crucial to maintain the existing assets in satisfactory operational criteria during its life-cycle (Turnquist and Vugrin 2013). As in Canada, 62.6% of the roads are in good condition, nevertheless and with the current backlog in investment rates in road sector along with many other significant factors such as; aging, deterioration and severe weather condition, the current roads condition will diminish (FCM 2016). Such investment should involve a prioritization approach to satisfy limited budget and time constraints and achieve the overall effective resilience enhancement for the road network. Consequently, there has been a growing interest towards resilience, as it has been a dominant aspect in the recent conferences and research trends. Consequently, and to coop with budget limitations, a growing need arises to integrate both resilience and asset management concepts to help reduce the overall maintenance costs by integrating recovery into the regular intervention actions and achieve a better budget allocation based on the overall concepts' integration. For resilience, it has been widely investigated in respect to disaster management, nevertheless resilience assessment models were limited regarding taking the effect of regular and periodic disruptive events into consideration while assessing resilience (Baroud et al. 2015; Bocchini et al. 2013; Cimellaro et al. 2010; Gay and Sinha 2012; MacKenzie and Barker 2012; Ouyang et al. 2012; Vugrin et al. 2010). For the proposed integration concept, resilience is defined as "The ability of an asset or a system to maintain a minimum LOS after regular, periodic and extreme disruptive events during its life-cycle within time and cost limitations" (Mohammed et al. 2017).

Scholars provided several methodologies for resilience assessment. The majority studied resilience of an infrastructure in parallel to its interdependency with other interconnected networks (Baroud et al. 2015; MacKenzie and Barker 2012; Reed et al. 2009; Shah and Babiceanu 2015). Few investigated resilience for an asset as an isolated problem considering developing a more resilient isolated network would be of a great outcome on the return of other interconnected networks (Gay and Sinha 2012). Other scholars stressed that resilience should be a disruptive event related criterion for an asset where it shall fluctuate according to the expected events that may occur (Gay and Sinha 2012; Ouyang and Dueñas-Osorio 2012). Interdependency resilience assessment models using the well know known Input-output Model (IIM) and resilience assessment mathematical formulations were greatly used to capture an infrastructure resilience (Baroud et al. 2015; MacKenzie and Barker 2012; Reed et al. 2009; Shah and Babiceanu 2015). Risk analysis-based models were also widely used to assess resilience based on deriving the consequence of several disruptive events and the required recovery strategies (Cimellaro et al. 2014; Ikpong and Bagchi 2014; Ouyang et al. 2012; Ouyang and Wang 2015; Shah and Babiceanu 2015). Transportation networks had their share in both resilience definition and assessment originated from disaster management approach, neglecting other factors like aging (Herrera et al. 2017). Others considered resilience as structural design feature only emphasizing on the necessity of investment to increase an infrastructure's capacity, endure any extreme event, and recover with the least possible damage. In that context, scholars focused on pavement material and the possible techniques to enhance their resilience (Lu et al. 2017; Wang and Zhang 2016). The pre-existing pavement condition due to the natural deterioration process was also investigated in previous research along with multi-hazards scenarios effect to model pavement network performance and assess its resilience (Levenberg et al. 2016; Dehghani et al. 2014). Though there are multiple optimization models for selecting near optimal intervention plans for pavement networks (Abu-Samra 2015) limited research has been undertaken in the development of optimization models that aim at maximizing pavement resilience within the existing budgetary constraints

To conclude, resilience has been extensively investigated in relative to disaster management and as extreme hazard network feature, yet more research needs to be directed towards integrating both asset management and resilience concepts which is crucial to occur an optimized life-cycle intervention plans that satisfy budgetary constraints. Also, it is of great importance to develop an asset management framework that considers pavement resiliency and other regular and periodic events effect on resiliency. Even though, there exist multiple optimization models for selecting near optimal intervention plans for pavement networks, resilience-based decision making has not been thoroughly studied.

2 OBJECTIVES

This paper opts to provide an asset management framework for pavement network that reflects asset resiliency through two main asset features; pavement condition during its life-cycle under the effect of the extreme periodic events and their consequences, and maintenance and the associated recovery strategies required to reduce those consequences and the life-cycle deterioration. This is well-aligned with the asset management perception as a base for resilience assessment (Levenberg et al. 2016). In this context, the objectives of this paper are as follows; (1) identify main resilience indicators with respect to pavement network, and (2) develop resilience-based asset management framework for pavement network maintenance and rehabilitation.

3 METHODOLOGY

The main objective of this study aims to reduce maintenance and rehabilitation works cost for pavement networks. Authors believe that integrating resilience into asset management concept will combine and reduce the overall costs of M&R activities for pavement networks through maintaining appropriate network resilient state, based on authors' definition for resilience in asset management, while keeping pavement networks well maintained through their lifecycle. Three sequential phases are proposed to achieve research objectives; starting from resilience definition to determine the main resilience indicators, then going through defining the associated metrics related to pavements for each indicator and defining the corresponding model, and last defining the main disruption scenario and the associated constraints for intervention, maintenance and rehabilitation actions required to achieve the desired pavement network resiliency according to authors' proposed resilience definition. The main methodology framework is presented in Figure 1 and details of each model will be summarized in the following sections.

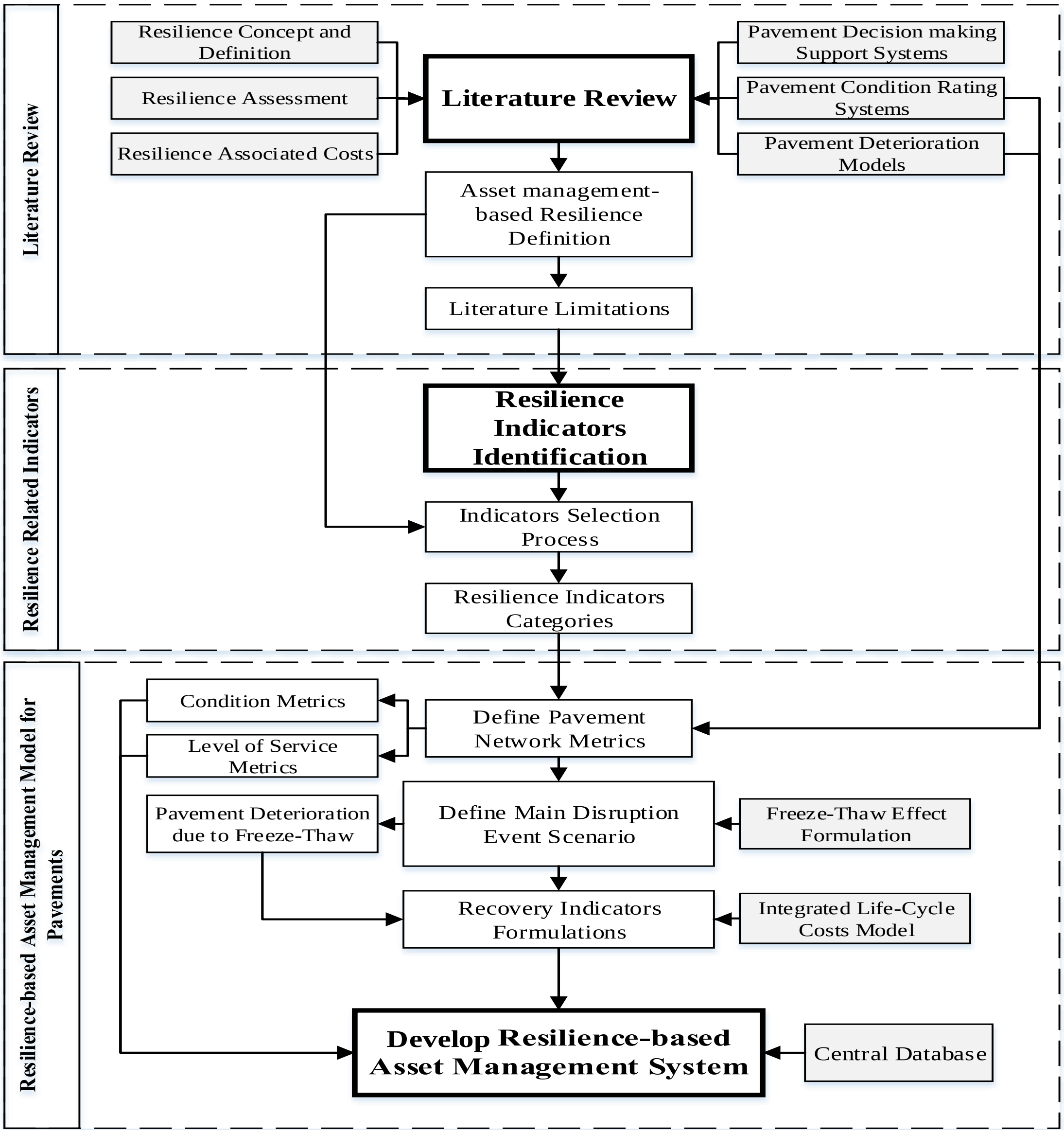

Figure 1: Resilience-based asset management methodology framework

3.1 Resilience Assessment Indicators

Resilience assessment indicators were identified through three phases as presented in Figure 2. Starting from database searching for infrastructure resilience indicators, then comes the filtration process for the collected indicators to match the targeted study objectives and based on resilience definition used in this study. Last, the selected indicators were classified into three categories; asset-based, disruption-based and recovery related indicators. Within each category, the relevant indicators were placed. To predict resilience, network condition was used while taking into consideration other types of factors such as; interdependency, asset criticality and the consequences and failure likelihood due to the various anticipated disruptive events (Gay and Sinha 2012; Ouyang and Dueñas-Osorio 2012; Bocchini et al. 2013). Other important resilience indicators that have a significant impact on an asset's resiliency are recovery time, cost and the availability of resources required to perform the recovery process when needed (Cimellaro et al. 2010; Gay and Sinha 2012). Accordingly, Asset condition, LOS and redundancy were taken into asset-based indicators category, while disruption type, likelihood and consequences of failure were considered as disruption-based indicators, and recovery time and cost constraints were considered as recovery indicators.

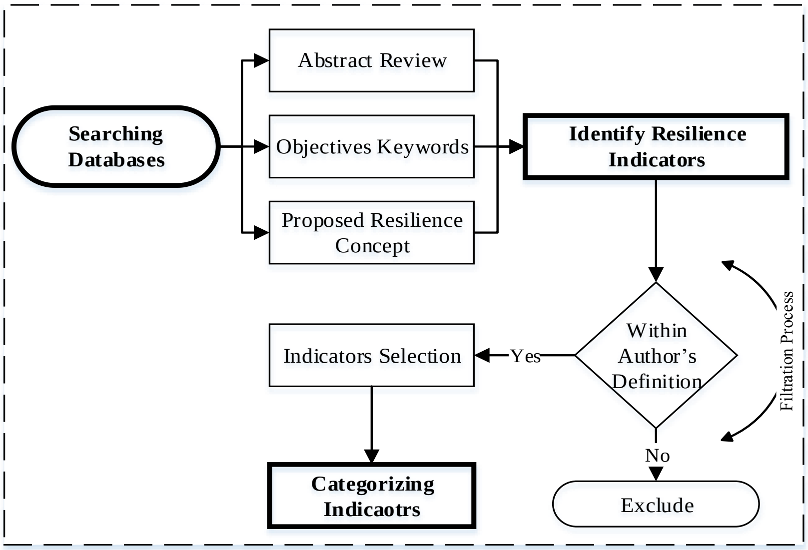

Figure 2: Resilience indicators identification process

Based on the identified indicators, Pavement Condition Index (PCI) was investigated in previous studies as an index that quantifies pavement condition while International Roughness Index (IRI) was introduced as measure for pavement LOS where it is usually calculated using instrumental field activities using laser mobile mounted devices. According to Federal Highway Administration, IRI's maximum threshold is 2.70 m/km for an acceptable road conditions while it is 1.50 m/km for a good road condition. One important consideration is predicting pavement condition through PCI during its life-cycle. Several deterioration models for PCI were introduced using regression models based on historical data analysis (Hamdi et al. 2012). Another used method to estimate the PCI is using ANN based on the results of the visual inspection of the different distresses existing on pavement (Shahnazari et al. 2012). Both models need great amount data yet, the second model needs extensive visual inspection reports to estimate PCI. After reviewing different models and based on the data available from the pavement network case study, Equation 1 was considered as the best fit for this study to model PCI deterioration, where the similar conditions to the pavement network case study existed to derive the regression relation for PCI deterioration with time (Hamdi et al. 2012). On the other hand, IRI can be derived from where quite few mathematical functions were derived between both indicators. Equation 2 presents the used formula that was used to predict LOS (Arhin et al. 2015). Redundancy was suggested to be denoted as a factor representing the degree of flexibility that exist in each pavement segment or each network element where; no clear approach and limited research is conducted to interoperate redundancy as resilience assessment indicator. For simplicity, network capacity criteria only will be used to estimate pavement corridors redundancy in future research stage and this matches with the authors scheme of processing the network as an isolated network.

[1] $PCI_i = 0.033i^2 - 2.688i + PCI_{in}$
where; PCI_i is the anticipated PCI at year i; i is the year counter (%) and PCI_{in} is the initial PCI (%).

[2] $\log(PCI) = 2 - 0.436\log(IRI)$

As stated earlier from previous researcher, resilience is considered disruption-event specific. Thus, Freeze-Thaw event was introduced as the main disruption event in parallel with the PCI deterioration resulting from the aging. Freeze-thaw cycles cause severe damage to pavement leading to accelerated deterioration in its performance and apparent reduction in its service life and decrease pavement resiliency in case of extreme events occurrence. Accordingly, maintenance and rehabilitation costs increase significantly to maintain the desired LOS. Equation 3 presents pavement reliability-based resilient deteriorating model under Freeze-Thaw cycles effect in cold regions. This formula presents the deterioration in resilient modulus for pavement, which denotes to the stiffness of the pavement layers to resist deformation from the applied stresses (Si et al. 2014). After intensive literature investigation, it was found that any degradation in the mechanical properties of the pavement layers, resulting from Freeze-Thaw effect, will directly cause additional distresses and accordingly drop the pavement condition (Doré et al. 2005; Ma et al. 2014; Si et al. 2014). Thus, it was assumed that the degradation in the resilience modulus, due to the Freeze-Thaw displayed in Equation 3, shall similarly occur to both the PCI and IRI.

[3] $RM = 625.33 + 151.92\, e^{-0.21X}$

where; $\boldsymbol{RM}$ is pavement resilience modulus after X Freeze-Thaw cycles; and X is the annual number of Freeze Thaw cycles. Equation 3 represents an exponential model for freeze-thaw cycles effect on the R.M of asphalt pavement. This model was verified and is believed to provide an excellent relationship between freeze-thaw effect and R.M (Ma et al. 2014).

Two important indicators play great role in disruption aftermath reduction. Accurate deterioration forecast, and life-cycle prediction models would be of a great asset to obtain a better maintenance and rehabilitation intervention/recovery plan while combining both usual and extreme disruption events. Pavement network damage pattern due to certain types of events would also be of a great use to develop the required intervention strategy (Lu et al. 2017). Accordingly, several questions arise; what are the available intervention actions available for post-disruption recovery, what is the effect of each action on pavement resilience and the corresponding costs for that action? And how long would it take to perform that action? Thus, four interventions were considered in this model as follows: (1) do nothing, (2) routine maintenance, (3) rehabilitation, (4) /reconstruction (Meneses and Ferreira 2015). Table 1 presents the unit cost and time for each intervention action, their application range, and their impacts on the PCI. Rehabilitation was divided into two categories to match the real practices when dealing with pavement maintenance and rehabilitation.

The mathematical formulation of the impact of the maintenance actions, aka decisions variables, and is displayed through equations 4 to 6. where; PCI_{ik} is the pavement condition index at year i for corridor k, PCI_{in} is the initial pavement condition, NCI_i is pavement network average condition at year i, and NCI is pavement network average condition.

[4] $PCI_{ik} = \begin{bmatrix} Do\ Nothing & 0.033i^2 - 2.688i + PCI_{in} \\ Overlay & (0.75)PCI_{in} \\ Deep\ Batching & (0.90)PCI_{in} \\ Reconstrcution & PCI_{in} \end{bmatrix}$

[5] $NCI_i = \sum_{\mathrm{i=1}}^{\mathrm{n}}[\mathrm{W_k} * PCI_{ik}]$

[6] $NCI = \overline{NCI_\iota}$

A financial model is developed to account for those costs and later implement and link it into the conditional if-then rules. The same goes to intervention time. The mathematical formulation for the model is presented through equations 7 to 9.

$$[7]\ RC_{ik} = [X_{ik} * RUC_x * L_k]$$

$$[8]\ NRC_i = \sum_{k=1}^{s}[RC_{ik}]$$

$$[9]\ NRC = \sum_{i=0}^{T}[NRC_i * (1+in)^I]$$

where; RC_{ik} is the rehabilitation/Recover cost of corridor k at year i, X_{ik} is a binary decision variable with “0” representing the “Do nothing” option and “1” representing the “Rehabilitation/Recovery” action, RUC_x is the recovery unit cost of decision variable X, L_k is corridor length, NRC_i is network recovery cost at year i, and NRC is the net present value of the cumulative network recovery costs over the study planning horizon T and in is the annual interest rate percentage. Annual recovery cost and time thresholds are assumed to be $35k and 1k man-hours.

Table 1: Intervention actions (Meneses and Ferreira 2015)

MAINTENANCE ACTION	NOTATION IN 2ND LEVEL DECISION VARIABLES	PCI APPLICATION RANGE (%)	IMPACT ON PCI (%)	RECOVERY TIME (HR/UNIT)	RECOVERY COST ($/UNIT)
ROUTINE MAINTENANCE (I.E. CRACK SEALING, ETC.)	-	-	-	0.30	10
REHABILITATION (OVERLAY)	1	65% - 100%	75%	0.45	15
REHABILITATION (DEEP PATCHING)	2	40% - 65%	90%	0.60	20
RECONSTRUCTION	3	0% - 40%	100%	1	30

3.2 Intervention Plan Modelling

The intervention plan modelling aims at defining the set of rules for applying the different maintenance and rehabilitation criteria. Metaheuristic rules were defined to select the intervention plan across the planning horizon. The metaheuristic rules were based on the PCI application ranges defined in Table 1. The model selected PCI application range for different maintenance actions as shown in Table 1. Furthermore, the number of overlays and deep patching activities was limited to 2 actions per corridor across the planning horizon to ensure that the corridor sub-surface layers are reconstructed after it passes its expected service life. Based on those rules, the model selected the intervention actions as will be discussed later in the upcoming section.

4 RESULTS AND ANALYSIS

For study horizon of 20 years, the proposed model was applied on a pilot case study, 3750m of residential pavement network stretch located in Kelowna city, British Columbia province, Canada (City of Kelowna 2016). Table 2 presents network data.

Table 2: Case study data

Corridor ID#	PCI (%)	IRI (in/mile)	Length (m)	Number of lanes	Section Area (m²)	Average Annual Daily Traffic (AADT)	Number of surrounding roads
1	96%	97.47	143	3	1,287	12,000	2
2	73%	137.01	146	4	1,752	8,000	2
3	79%	127.13	151	4	1,812	10,000	1
4	79%	127.13	275	2	1,650	11,000	3
5	66%	148.1	184	3	1,656	7,000	2
6	66%	148.1	278	4	3,336	9,500	3
7	94%	100.99	294	4	3,528	10,500	3
8	88%	111.42	158	2	948	8,500	4
9	94%	100.99	168	4	2,016	6,800	1
10	84%	118.59	187	4	2,244	7,500	3
11	44%	185.9	228	3	2,052	9,000	4
12	52%	172.9	134	4	1,608	6,000	4
13	73%	137.01	113	4	1,356	5,000	3
14	88%	111.42	154	4	1,848	11,000	4
15	44%	185.9	258	2	1,548	10,000	2
16	73%	137.01	124	3	1,116	6,000	2
17	59%	160.17	293	2	1,758	9,000	2
18	44%	185.9	103	2	618	12,000	4
19	73%	137.01	119	2	714	9,000	1
20	52%	172.9	231	4	2,772	8,000	4

The resulted intervention plan of the resilience assessment model is shown in Figure 3. It could be noticed that the reconstruction activities would be taking place early throughout the study planning horizon. This was anticipated due to the LOS and condition thresholds that were pre-set to satisfy the resilience definition conditions where; the PCI and IRI restrained the model from falling below their thresholds and thus forcing it to undertake early intervention actions. Moreover 61 minor rehabilitation actions and 17 major rehabilitation actions were planned throughout the planning horizon to maintain the pavement network resilience state. Nevertheless, incorporating more disruption events on pavement network, would generate diverse intervention plans with different required budget to keep the network resilient enough against those disruption events.

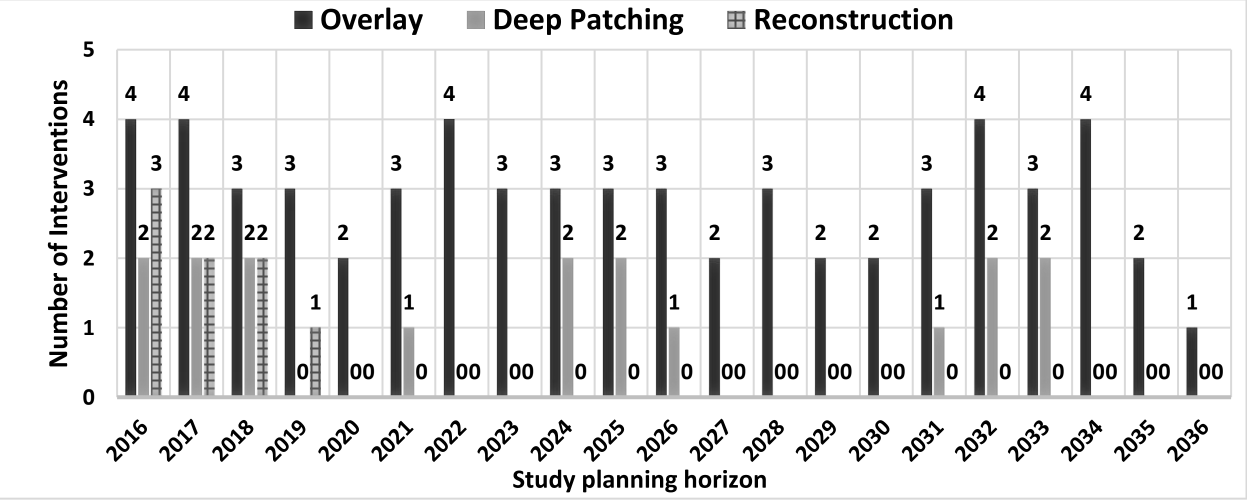

Figure 3: Optimized intervention plan layout for pavement network under study

5 KEY FINDINGS AND CONCLUSIONS

The key findings could be summarized as follows:

1. Identify key resilience indictors,
2. Develop resilience-based asset management framework based on the generated resilience definition, where intervention plans would not only be targeting enhancing or restoring pavement condition or LOS, but also incorporating the implementation of proper recovery strategies for both regular and/or extreme events into the intervention plan, while taking the regular deterioration and aging effects into account.

Introducing more disruptive events to the proposed model and developing an optimization model to achieve an optimized intervention plan is essential in next stage of research. Integrating both resilience and asset management concepts shows promising outcomes in terms of maintaining pavement resiliency and selecting a near optimal intervention plan that meets the municipality limitations in terms of condition, LOS, and cost. The proposed pavement resilience assessment framework is beneficial for asset management experts where; intervention plans would not only be targeting enhancing or restoring pavement condition or LOS, but also incorporating the implementation of proper recovery strategies for both regular and/or extreme events into the intervention plan, while taking the regular deterioration and aging effects into account. This would be beneficial to decision-makers as it would help optimize budget allocation for pavement maintenance and rehabilitation and enhance pavement resiliency instead of treating the regular and extreme events discretely without taking into consideration pavement condition and the effect of previous disruptions.

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