Effective, Comfortable, and Sustainable Railway Systems: Decision Models for Optimal Asset Management and Scenarios Analysis

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ABSTRACT

Effective, Comfortable, and Sustainable Railway Systems: Decision Models for Optimal Asset Management and Scenarios Analysis

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Millions of passengers worldwide rely on a fast, competitive, and reliable transit system for daily transportation. The American infrastructure report card 2017 assigned a level “D-” to the USA’s transit sector that means “poor” condition. The Canadian report card in 2016 assigned a grade of “Fair” to fixed assets (e.g. stations and tunnels) of the transport system; this indicates that such assets “require attention”. Meanwhile, 25% of such fixed assets were ranked in poor and very poor condition. In periods of 2016 – 2018, the *Société de Transport de Montréal* (STM) has invested the amount of C$2.2 billion, or 78% of its total capital expenditure for metro system maintenance and upgrading. Extensive deterioration of already aged metro systems in North America complicates managing the network while coping with the increased demand and the corresponding need to plan for capital upgrades with a restricted annual budget. Effective planning to rehabilitate existing assets and expand new ones while respecting constraints is key to the success of transit-oriented strategies. However, without a comprehensive multi-criteria decision-making procedure, it is impossible to achieve the optimal actions at the right time within the given budget. The main objective of this research is to develop a comprehensive model for managing urban railways, such as the metro, that supports strategic decisions to maintain the highest level of convenience, safety, comfort and reliability in the metropolitan area. To overcome the gaps found in the literature, these proposed steps should be used:

Step I: Developing an understanding of convenience with special concentration on the level of service from the passenger’s perspective. The idea is to model, quantitatively and practically,

aspects relevant to the user convenience for transit vehicle's comfort. **Step II**: Development of a decision-making model to mimic the operation of the transit systems capturing indirect impacts such as human development and sustainability. **Step III**: Development of an optimization model to analyze investment scenarios for the upgrade and expansion of the railway network, while up-keeping the existing operation at acceptable levels of service, guiding policies, and respecting budget limitation. This includes the relationships between the transit system and human development issues, addressing fighting poverty; supporting accessibility to health, education and job centers; and encouraging the modal shift away from the automobiles.

The proposed models could also be used by public transit systems such as Tramway, Bus Rapid Transit (BRT), Light Rail Transit (LRT), traditional buses and metro to guide planning for their maintenance, upgrade and expansion to achieve higher levels of convenience and reliability encouraging transit ridership.

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I would, also, like to thank the member of my committee, Dr. Zongzhi Li, Dr. Amin Hammad, Dr. Mazdak Nik-Bakht, and Dr. Sang Hyeok Han for their constructive inputs.

I dedicate this dissertation to my amazing wife, lovely princess, and new prince. This would not have been possible without their support and patient. Also, I would like to convey my appreciation to my parents for their endless love, support and prayers.

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CONTRIBUTION OF CO-AUTHORS

Mr. Feras Elsaid (MSc. a student at Concordia University, BCEE) had a contribution in chapter 4 in preparing human development assessment for case study section (extracting data from database and making shape files in ArcGIS software).

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LIST OF ABBREVIATIONS

ABM	Activity-Based Modelling
AHP	Analytic Hierarchy Process
ANP	Analytic Network Process
ATS	Automated Train Supervision
BIM	Building Information Model
BRT	Bus Rapid Transit
CDF	Cumulative Density Function
CIRC	Canadian infrastructure report card
CO_2	Carbon Dioxide
COF	Consequence of Failure
CR	Critical Index
CTA	Chicago Transit Authority
EMGTs	Equivalent Million Gross Tons
EP	Expansion Planning
EPA	Environmental Protection Agency
HDI	Human Development Index
HVAC	Heating, Ventilation, and Air Conditioning
IAMS	Infrastructure Asset Management System
IAQ	Indoor Air Quality
KPIs	Key Performance Indicators
LCC	Life-Cycle Costs
LOS	Level of Service
LRT	Light Rail Transit
LU	London underground
LUT	Land Use and Transport
NDE	Non-Destructive Evaluation

MAUT	Multi-Attribute Utility Theory
MARTA	Metropolitan Atlanta Rapid Transit Authority
MBTA	Massachusetts Bay Transportation Authority
MP	Maintenance Planning
MRR	Maintenance, Rehabilitation, and Replacement
MRRP	Maintenance, Rehabilitation, and Replacement Planning
MSRP	Model for Station Rehabilitation Planning
MTA-NYCT	Metropolitan Transportation Authority of New York City Transit
MTBF	Mean Time Between Failures
OHDI	Overall Human Development Index
OLOS	Overall Level of Service
POF	Probability of Failure
ppm	Parts Per Million
PT	Public Transit
RATP	*Régie Autonome des Transport Parisiens*
RH	Relative Humidity
SD	Standard Deviation
SDGs	Sustainable Development Goals
STM	*Société de Transport de Montréal*
SUPER	SUbway PERformance
TAM	Transportation Asset Management
TTC	Toronto Transit Commission
UN	United Nation
WA	Wait Assessment
WHO	World Health Organization

Chapter 1 : INTRODUCTION

1.1 BACKGROUND

Automobiles have been a synonym of transportation for decades. The need to shift from an automobile-centered paradigm to a transit-oriented and people-centered transportation has been more acknowledged recently by planners and politicians around the world (Cooley et al. 2016; LTA 2017). This is accomplished by strong support to non-motorized modes (DfT 2017a; *Ville de Montreal* 2017) and public transit (DfT 2017b), which is reflected through policies tested on variable demand modelling (DfT 2017c). Considerations of effective, comfortable, safe and sustainable urban railways then become a must to ensure that rail-transit can compete with automobiles and then achieve higher rates of ridership (ATC 2006). However, policy testing is faced with lack of frameworks to support the optimal selection and timing of strategies and the scheduling of improvements. Infrastructure Asset Management models seem like the natural fit to accomplish such goals.

1.1.1 Infrastructure Asset Management

The FCM and NRC (2003) defined asset management as "The combination of management, financial, economic, engineering, and operational and other practices applied to physical assets with the objective of providing the required level of service in the most cost-effective manner."

Management of infrastructure has not always been standard practice; however, since the 1980s there has been an increasing travel demand, accompanied by budget limitations, aging physical assets, and pressure to consider environmental sustainability. Under such context, progressive development of comprehensive Infrastructure Asset Management System (IAMS) has been observed. IAMS had become a crucial element of urbanization in coordinating the planning of maintenance, rehabilitation and the upgrading of assets and to enable the execution of all activities at an optimum level (Uddin et al. 2013).

The main goals in classic IAMS are listed below:

1) To reduce asset life cycle costs and increase the life span

2) To provide better and consistent levels of service for public

3) To improve safety, security, sustainability, and resilience

4) To allow for better decisions regarding resources allocation

5) To allow for more effective financial planning

6) To avoid problems, potential crisis, and risks.

These objectives are applicable to many civil infrastructure assets such as:

- Roads and Bridges;
- Water Distribution Networks;
- Wastewater Systems;
- Water Treatment Plants;
- Transit Systems;
- Ports;
- Buildings;
- Dams;
- Refineries;

1.1.2 Asset Management for Transportation Systems

Transportation asset management practices have been developed into a solid framework for optimizing the performance and cost effectiveness of transportation assets (AASHTO 2011). Transportation Asset Management across all transport systems concentrates on improving decisions to find the optimal solutions. Also, it examines scenarios of investment, timing, and methods to guarantee the use of available funds effectively. According to AASHTO (2011), there are three main goals for transportation asset management:

- "Keeping the infrastructure in as good or better condition than it is now.
- Developing and implementing a logical capital improvement plan.
- Containing the costs of planning, building, operating, and maintaining the facilities."

1.1.3 Sustainable Transportation System

According to United Nations (UN 2016b) "Sustainable transport is the provision of services and infrastructure for the mobility of people and goods advancing economic and social development to benefit today's and future generations in a manner that is safe, affordable, accessible, efficient, and resilient while minimizing carbon and other emissions and environmental impacts."

Sustainability and human development are hence new raised dimensions that shall be integrated with an asset management plan. It implies that the asset manager should study the effect of maintenance and replacement actions on the environment (Marzouk and Abdel Aty 2012). Therefore, the next generation of asset management models are expected to improve the level of service of non-motorized and transit modes (Ville de Montreal 2017) as well as sustainability and human development. Travel demand models, on the other hand, already have considered some of such issues (DfT 2017c).

1.2 PROBLEM STATEMENT

Worldwide millions of passengers expect fast, competitive, and reliable transit systems for daily transportation. However, extensive deterioration of already aged systems complicates the management of the network while coping with increased demand and the corresponding need to plan for capital upgrades with a restricted annual budget. The American infrastructure report card 2017 assigned a level “D-” to the USA’s transit sector, which means “poor” condition while those assets captured level “D” in 2009 and 2013 (ASCE 2009; ASCE 2013; ASCE 2017). Therefore, reports indicate that transportation system in the U.S. are not in an appropriate shape and since most of the transit infrastructure are facing deterioration caused by aging, worse and unsafe conditions would be predictable unless prepare actions are taken.

The Canadian infrastructure report card (CIRC 2016) assigned a grade of “Fair” to fixed transit assets (e.g. stations and tunnels) while 25% of those assets are ranked in poor and very poor condition (Figure 1-1). C$34.3 billion is needed for the replacement value of fixed transit assets while the average age of this group is 13 years.

Individual Building Type Ratings				
Transit Asset Type	Rating for All Transit Authorities	Rating for Small Transit Authorities (<50,000 pop.)	Rating for Medium Transit Authorities (50,000-400,000 pop.)	Rating for Large Transit Authorities (>400,000 pop.)
1. Vehicles (buses)	Very Good	Poor	Good	Very Good
2. Vehicles (railcars + ferries)	Good	N/A	N/A	Good
3. Technology	Very Good	Good	Very Good	Very Good
4. Fixed Assets	Fair	Fair	Fair	Fair

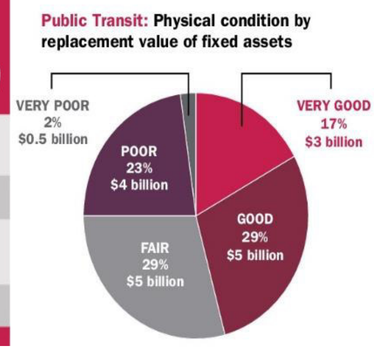

Figure 1-1, The Canadian infrastructure report card (Public Transit) (CIRC 2016)

The gouvernement du Québec planned to maintain a high, recurring level of investment to ensure the maintenance and development of public transit infrastructure. In this regard, the 2016 - 2026 Québec Infrastructure Plan has set aside almost C$7.1 billion for the bus, commuter train and metro networks (*Gouvernement du Québec* 2016). At the same time, the Québec infrastructure plan calls for, on the one hand, substantial investments in maintaining and rehabilitating the road network and, on the other hand, for its share in two major Québec public transit development projects: The Bus Rapid Transit between Québec and Lévis and the extension of the Montréal metro's blue line, and more than C$10 billion will be invested in public transit in Québec over the coming years for those 3 projects (*Gouvernement du Québec* 2017).

Although it was planned to expand the Montreal metro Blue line in a few years ago still, it is not part of the network due to budget limitations. From 2016 – 2018, the *Société de Transport de Montréal* (STM) is investing CAD$2.2 billion, or 78% of its total capital expenditure for maintenance and upgrading of the Metro system (STM 2015). Montreal Metro passed 50-year-old and faces an increase in demand of 27% for the year 2020 in comparison to 2010 (STM 2012). The system is periodically maintained, and repairs are common to upkeep it in good levels of operational convenience. Three lines: Blue, Orange, and Yellow, are planned to be extended and the impacts of this extension should be addressed in capital investments and policies for the following years. Therefore, in such a situation (Montreal metro system) and many similar metropolitans, these tactical questions should be answered well:

1) Which asset (stations, tunnels, or cars), when and how to be replaced or renovated first in order to improve overall levels of service, safety, and comfort in the whole network?

2) How transit maintenance and rehabilitation investments could be optimized to support the socio-economic development and sustainability through reducing poverty; support accessibility to health, education, and job centers; and encourage the modal shift away from the automobiles?

3) How demand, service upgrades, and network expansion impacts could be captured in the asset management model for existing and future systems?

1.3 RESEARCH MOTIVATION AND OBJECTIVES

Effective planning to maintain, rehabilitate, upgrade and expand transit networks is key to the success of transit-oriented strategies. However, without a comprehensive multi-criteria decision-making procedure, it is impossible to achieve optimal actions at the right time within the available budget. This situation brings to matters the need to count with a comprehensive decision support model that can simulate and optimize dynamically the operation of the entire system.

The main objective of this research is to develop a comprehensive model for managing urban railway systems that support strategic decisions to maintain the highest level of convenience, safety, comfort, and sustainability in the movement of passengers in a metropolitan area. The models should capture the impacts of service expansion through the opening of more corridors. This is key to guide policies and planning and for this reason, models will include the relationships between the transit system and human development indicators locally available to reduce poverty; support accessibility to health, education, and job centers; and encourage the modal shift away from the automobiles.

1.4 RESEARCH SCOPE AND TASKS

The scope of this research is limited to applications in urban railway asset management. The case studies are all taken from urban railway systems to demonstrate the applicability in practice. The present thesis pursues the above-mentioned objectives within developing three models:

Model I: Performance assessment model.

This model fills in literature gaps of performance assessment for urban railway systems and quantitatively measures aspects relevant to the user's comfort while riding the vehicles. The outputs could further be utilized in the decision-making and asset management process to retrofit and correct deficiencies related to inadequate levels of air quality, thermal comfort, vibration, lighting, and excessive noise, which affect the convenience of using urban rail transit. Generally, many factors affect riders' comfort; however, in this research, these five mentioned attributes are considered and others such as space, crowding, cleaning, and issues related to disability are excluded.

The main tasks are:

- To cover missed elements in transit system planning and decision-making (level of comfort from a rider perspective).
- To develop a quantitative and people-centered assessment model for the level of comfort in urban railway vehicles.

Model II: Sustainable asset management model.

This model covers current and future needs respecting human development and sustainability issues to advance classical asset management platforms addressing novel raised concerns through the below tasks:

- To develop a human development assessment model for urban railways.
- To propose a decision-making model that supports its implementation as guided by human development factors.

Model III: Network-level asset management model for urban railway.

Finally, covering lack of decision-making (optimization) models for urban railway infrastructure, the last model proposes decision-making platforms for optimal asset management and policy analysis in the network level to bring safe, effective, comfort and sustainable urban railways. Thus, the main purpose of this model is the development of a comprehensive decision support system that connects the performance assessment platform with an optimization model capable of analyzing investment scenarios for the upgrade and expansion of the network, while up-keeping the existing operation of transit systems at acceptable levels of performance. The main tasks are:

- To identify ridership (usage rate) changes and its impact on asset management in urban railway.
- To propose a network level decision-making model for urban railway systems, which plans for maintenance and renovation as well as upgrading and expansion addressing identified gaps.

1.5 THESIS LAYOUT

This thesis is presented in six chapters as follows (Figure 1-2). The work described in Chapters 2, 3, 4 and 5 have been written as self-contained papers and as such, each chapter has its own abstract and introduction; however, a comprehensive reference list is prepared at the end of this thesis.

Chapter 2 presents a full literature review for urban railway (focusing on the metro systems) asset management models and studies. Main limitations are identified and discussed respecting current and future concerns. Also, evidence from the literature is used to identify critical components and develop a general platform for the implementation of a comprehensive transit asset management for urban railways. This effort is published by the journal of Transport Reviews:

Mohammadi, A., Amador-Jimenez, L., and Nasiri, F. (2018). Review of asset management for metro systems: challenges and opportunities. Transport Reviews, 1-18.

Chapter 3 covers the first model in the methodology, which develops an assessment platform for railway vehicles. This study proposes an approach to quantitatively measure railway riders' comfort and safety (i.e. aspects related to comfort) in terms of humidity, temperature, vibration, the concentration of CO_2, noise, and lighting level. This effort is under review by the journal of sustainable cities and society since September 2018:

Mohammadi, A., Amador, L., and Nasiri, F. (2019). A Multi-Criteria Assessment of the Passengers' Level of Comfort in Urban Railway Rolling Stocks. Journal of sustainable cities and society (SCS_2018_1816).

Chapter 4 shows that transit asset management platforms could be used to improve the sustainability of nations. Several types of research pointed out to the role of the transit system in human development and sustainability; however, none of them gives a decision-making tool to governments and municipalities for objectively distributing the budget among alternatives that respond to the various dimensions behind human development and sustainability. This chapter is published by the international journal of sustainable transportation:

Mohammadi, A., Elsaid, F., and Amador-Jiminez, L. (2018). Optimizing transit maintenance and rehabilitation to support human development and sustainability: A case study of Costa Rica's railroad network. International Journal of Sustainable Transportation, 1-14.

Chapter 5 fills the main identified gap in the literature regarding, which is lack of a comprehensive and efficient decision-making (optimization) model for maintenance, renovation and upgrading of urban railway systems. Developed models in chapters 3 and 4 can also be used in developing this model in order to address literature gaps, transit agency concerns, and society needs. This chapter is written in a paper format and is under review by the journal of construction engineering and management (ASCE).

Mohammadi, A., Amador, L., and Nasiri, F. (2019). Reliable, effective and sustainable urban railways, a model for optimal asset management, Journal of construction engineering and management (ASCE)(Under submission process).

Chapter 6 in this thesis summarizes research contributions, limitations and future works.

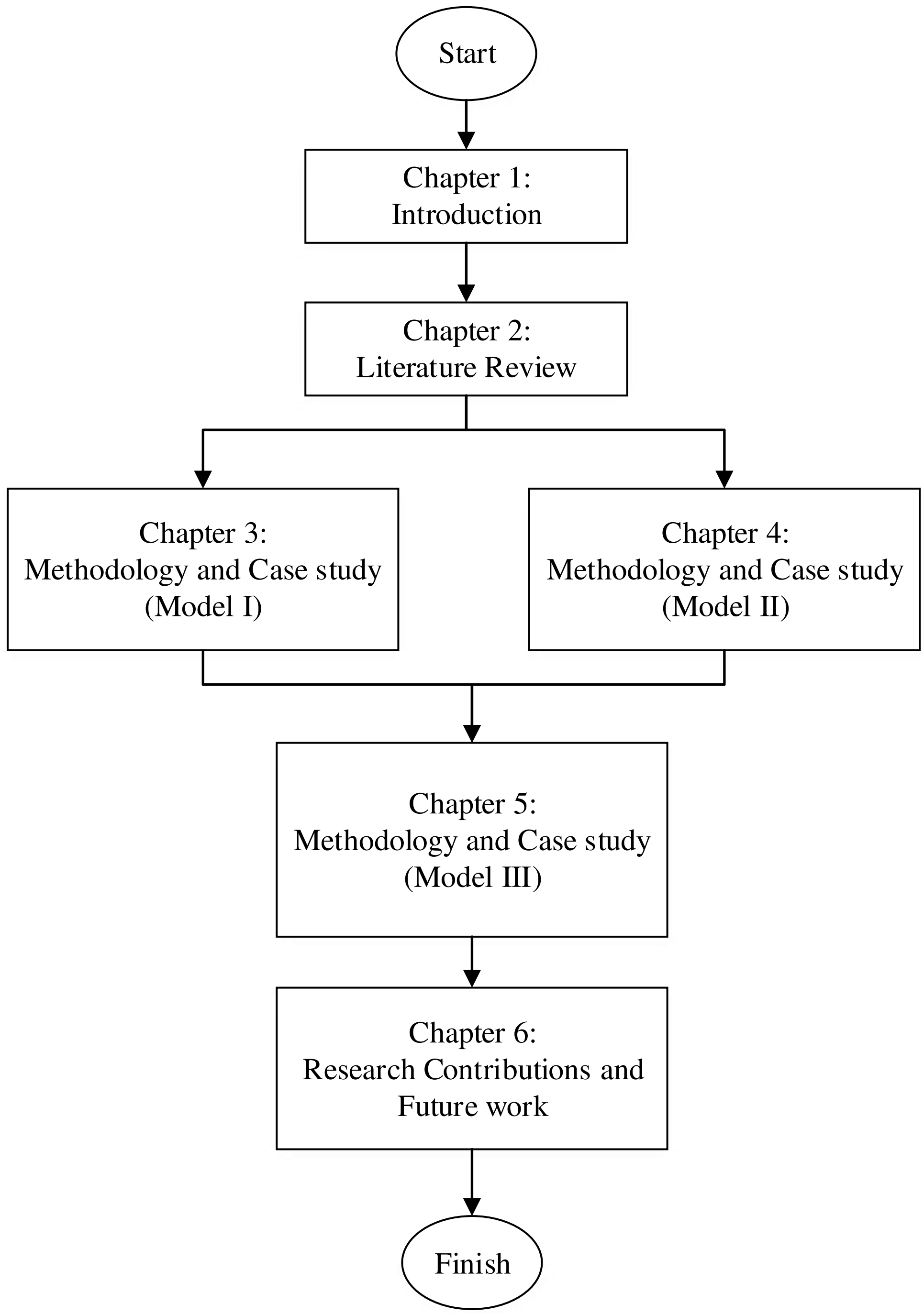

Figure 1-2, Thesis layout

Chapter 2 : BACKGROUND REVIEW AND SYNTHESIS OF LITERATURE

REVIEW OF ASSET MANAGEMENT FOR METRO SYSTEMS: CHALLENGES AND OPPORTUNITIES

This chapter provides a full review of proposed asset management platforms in the literature or implemented by transit agencies for urban railway systems by focusing on the metro systems. This manuscript has been published by the journal of Transport Reviews:

Mohammadi, A., Amador-Jimenez, L., and Nasiri, F. (2018). Review of asset management for metro systems: challenges and opportunities. Transport Reviews, 1-18.

Abstract: Metro systems play a crucial role in the movement of millions of passengers worldwide as commuters rely on a fast, reliable, and convenient underground railway for their daily transportation. However, in many cases, the quality of the service that can be delivered, including performance, attractiveness, and customer satisfaction, are constrained by poorly maintained infrastructure. Meanwhile, effective planning to maintain, rehabilitate, replace and expand existing systems must respect technical, social, political, financial, and management constraints. There is a lack of a comprehensive framework for managing metro assets. This is mainly due to the multiplicity of components; the complexity of their interdependencies; common lack of historical data and performance indicators; and unavailability of a unified framework that integrates forecasts of future demand with decision-making systems. The main objective of this research is to review available studies and models for underground rail systems, identify the main strategic-operational planning gaps, and propose critical tasks for a comprehensive asset management framework. The platform developed in this research is suitable for further studies in urban railways such as Rail Rapid Transit (underground and surface), Light Rail Transit, and suburban trains as well as other modes of transport (e.g. traditional buses, Bus-Rapid-Transit).

2.1 INTRODUCTION

Infrastructure Asset Management Systems (IAMS) were established in the 1980s in response to a growing stock of aging physical assets and increasing service demand, which contrast with a backdrop of funding cuts and more stringent environmental regulations. IAMS contribute to ensuring a systematic-coordinated planning and management of maintenance, rehabilitation, and upgrading. It enables an efficient use of available budgets while maximizing the performance and provision of infrastructure services (Uddin et al. 2013).

Nowadays, several infrastructure asset management guidelines exist (AASHTO 2011; BSI 2014; NAMS 2015; FCM and NRC 2003). However, these guidelines only provide a general view of the steps and required elements to develop an asset management system. To improve the implementation of these guidelines for a specific infrastructure, it is required to: 1) identify a set of performance indicators, its assets, and components; 2) conduct a periodic assessment of these indicators to acquire a good knowledge of the impact of planned interventions and upgrades; 3) develop performance prediction models that could forecast future levels of these indicators, which might be various by nature of infrastructure or involved assets; 4) design a decision-making system to schedule the reinvestment (e.g. maintenance, rehabilitation, and replacement). The interventions should be coordinated to address conflicts in scheduling and use of limited resources.

In the case of transportation infrastructure, several additional factors must be taken into account to develop a comprehensive management system with respect to the needs of agencies addressing the complexity of the system, funding requirements, demand changes and assets aging. The expectations of the users including service demand, comfort, safety, and convenience, should also be addressed. The management of urban railway assets is a complex process; as there are different types of facilities (rail cars, stations, tunnels, etc.) with many sub-components geographically dispersed across the network. Metro systems are heterogeneous in both function and deterioration aspects, and due to interdependencies between facilities, rehabilitation of one facility could affect the efficiency and the proper functioning of other facilities (Furuya and Madanat 2013). This leads to the need to use a multi-facility multi-criterion assessment and decision-making approach when it comes to the management of the underground rail systems.

As with any other public infrastructure, it is common to encounter extensive deterioration of already aged transit assets, which further complicates the rehabilitation planning efforts. In North America, there are cases of metro systems surpassing their functional service life and the American Infrastructure Report Card assigned a level of D- to the transit system, which is less than the previously reported level, and means "poor" condition (ASCE 2017). It is also common to see budget limitations with funds only enough to conduct palliative solutions, and underfunding preventive maintenance and rehabilitation accelerates aging. U.S. transit system is suffering from $90 billion rehabilitation backlog while 45% of American households are still outside the proximal access buffer to transit systems and many have inadequate service levels (ASCE 2013; ASCE 2017). Rail-based systems carry just over a third of all transit trips (35%) in the U.S.; however, have the greatest maintenance needs of all transit modes. In addition, these systems have larger than normal, average replacement needs (i.e., annual costs required to maintain a state of good repair) requiring $8 billion as compared with an average of $6 billion across all other transit modes (ASCE 2013).

Also, an adequate share of travellers could maintain ridership in transit systems to provide financial viability to the expansion of the network (Figueroa and Rodríguez 2013; Miranda et al. 2012; Batarce et al. 2016). In Canada, the *Société de Transport de Montréal* (Montreal Transit Society)

STM has targeted an increase of 27% for 2020 in comparison to 2010. According to the (STM 2012), it has been observed that in many cases improving quality, comfort, and safety can convince commuters to abandon the use of the automobile. However, this requires periodic reinvestment to upkeep the fixed infrastructure and rolling stock in the urban railway.

Although infrastructure management models are common among researchers, especially for pavements, bridges and water networks, there is a lack of a comprehensive framework for urban railways due to the multiplicity of components; the complexity of their interdependencies; common lack of historical data and performance indicators; and unavailability of a unified framework that integrates forecasts of future demand with decision-making systems. The aim of this study is to review management platform for metro systems including decision support models for preventive maintenance and rehabilitation proposed in the literature or implemented by transit agencies and identify their gaps and challenges. The evidence from the literature is used to identify critical tasks in order to develop a framework for the implementation of a comprehensive asset management for underground railways (Figure 2-1). Such framework provides an appropriate foundation for future studies in urban railways such as Rail Rapid Transit (underground and surface), Light Rail Transit, and suburban trains as well as other modes of transport (e.g. traditional buses, Bus-Rapid-Transit). Also, this study attempts to relate demand prediction models such as Activity-Based Modelling (ABM) to Transportation Asset Management (TAM) to improve transportation planning and decision-making.

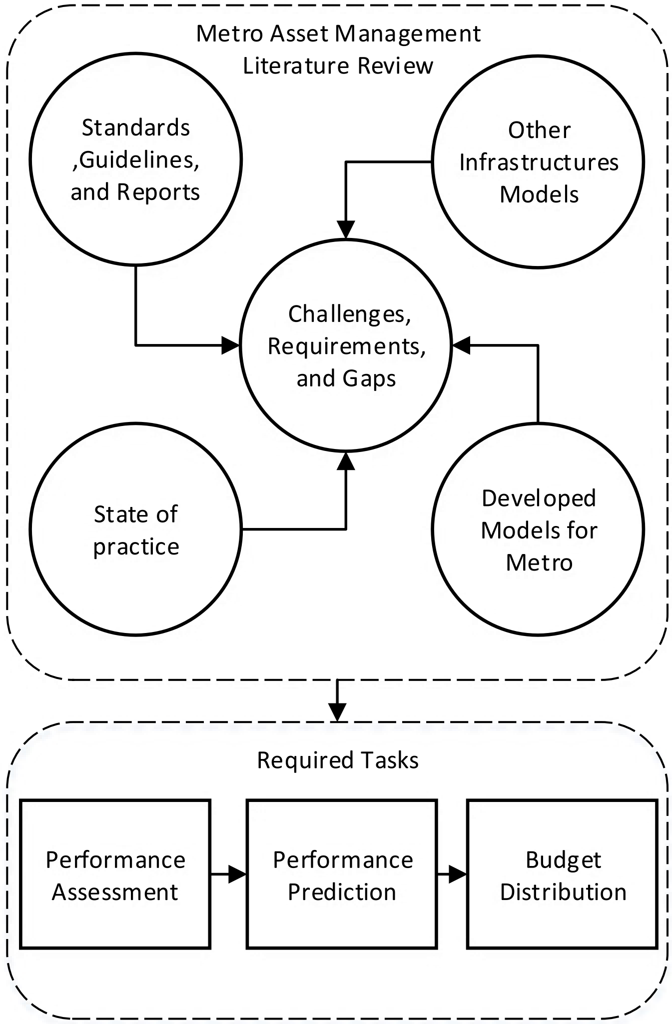

Figure 2-1, Metro asset management literature review methodology

2.2 LITERATURE REVIEW

In this section, the state of literature and practice are reviewed side by side respecting identified required tasks. Highlights and challenges for developed frameworks are also summarized in Tables 2-1 and 2-2. In the early 1980s, the *Régie Autonome des Transport Parisiens* (RATP) implemented a decision-making framework for planning the renovation of metro stations in Paris (Roy et al. 1986). The objective of this model was to rank 224 stations in terms of the need for renovation. For this purpose, multiple criteria were considered building environment (e.g. low-income area), platform users (e.g. a number of passengers), performance (e.g. level of discomfort), and maintenance (e.g. ongoing renovation). The Elimination and Choice Expressing Reality (ELECTRE III) technique (Roy 1978) was used to integrate these assessment criteria and establish a ranking index for the stations. However, this outranking approach was utilized only for year-by-year prioritization of station renovations while the long-term and dynamic nature of assets deterioration (and the corresponding maintenance needs) was not considered.

In the late 1990s, Hastak and Abu-Mallouh (2001) developed a Model for Station Rehabilitation Planning (MSRP) in order to prioritize metro stations for rehabilitation. The main objective was to optimize budget allocation while achieving a given performance threshold. The proposed model was based on the requirements of the Metropolitan Transportation Authority of New York City Transit (MTA-NYCT). First, two groups of functional and socio-political criteria and corresponding sub-criteria were identified. The Analytic Hierarchy Process (AHP) (Saaty 1980) decision-making tool was used to establish the weights for these criteria and sub-criteria. In the next level, for each functional or socio-political criteria, rehabilitation costs were estimated (including partial and full rehabilitation), and in the third and fourth levels, resource allocation was done based on available budget and upper-lower threshold limits. Priority was given to stations with a low performance (less than the lower threshold) to receive a full rehabilitation. Then an integer programming was used to distribute the remaining budget among stations based on their score values. Stations in moderate performance (between an upper and lower threshold) received a partial rehabilitation. The model gave priority to functional criteria ignoring long-term asset deteriorations. Also, it assigned the remaining budget based on only weights of criteria, rather than overall scores, thus failing to guarantee an optimized approach. Furthermore, the use of AHP for weighting fails to account for interdependencies among the criteria.

A model presented by Kepaptsoglou et al. (2013) used a similar approach by developing a hierarchical decision-making structure using AHP. The model calculated a condition index for Athens metro system. Four major criteria and 13 sub-criteria were selected for evaluating the performance of stations, and fuzzy aggregation was used to combine criteria scores. Another model was proposed by Semaan and Zayed (2009), which developed a metro station diagnosis index to assess functional criteria of stations based on PROMETHEE method (Brans et al. 1986). An integrated condition assessment index for the station and tunnel was developed and tested for Athens metro (Gkountis and Zayed 2015). The indicators included in the study were chosen based on defects in different structural, electrical, and mechanical components. In order to account for interdependencies among components, an Analytic Network Process (ANP) (Saaty 2001) was used to calculate component importance weights. Furthermore, to account for the uncertainties in the condition assessment, triangular fuzzy scores for each condition state were considered. To integrate these scores, a customized TOPSIS approach (Hwang and Yoon, 1981) was adopted. The focus of the above studies was on performance-based condition, while all customer and agency's concerns were not addressed, and ranking alternatives (e.g. station or tunnel) could not ensure optimum long-term planning. In addition, the assessment of cars as a main component in the transit system was not addressed.

A network level index that considers the structural performance of metro concrete elements was developed by Semaan (2011). Hierarchy networks for lines including stations, tunnels, and auxiliary structures were identified. Visual inspection scores were collected based on different concrete crack types and conditions. Assets deterioration was considered; however, assumed that asset service life was known and followed a Weibull distribution. A similar approach was proposed by Nishimura et al. (2015) for the Tokyo metro. The model used data available from a long-term concrete inspection program for tunnels. Each tunnel segment (in 5-meter spans) was classified based on 6 deterioration grades according to concrete hammering tests and visual inspections, and tunnel-line overall condition was evaluated by averaging values along the metro line. A Markov chain process was then designed to predict deterioration rates. Eight (8) repair scenarios were considered for a case study network of tunnels, and benefit/cost ratio analysis was done. Some studies have suggested the use of several Non-Destructive Evaluation (NDE) methods including spectral analysis of surface waves, impact echo, ground-penetrating radar, and impulse response for condition assessment of metro systems (Delatte et al. 2003; Dawood et al. 2017). Taguchi et al. (2016) applied a mathematical modelling based on observed deformation and quantified structural health grades in Tokyo metro tunnels. Such methods can detect water leakage, corrosion, and cracks in metro tunnels and complement visual inspections. All these studies assessed structural aspects of metro systems, while safety, security, and Level of Service (LOS) on Key Performance Indicators (KPIs) are influenced by other non-included sub-components such as electrical, and mechanical.

A linear programming model was implemented by Farran and Zayed (2009) to minimize the Life-Cycle Costs (LCC) for rehabilitating of concrete slabs in Montreal metro while complying with an acceptable level of performance. A Markov chain process was adopted for deterioration prediction with customized transition matrices prepared for the replacement, repair, preventive maintenance, and do-nothing actions. This model could only give general recommendations for the best time of implementing maintenance actions. Also, the performance was incorporated into this model as a constraint without encouraging improvements in performance beyond a satisfactory target. More non-physical indicators of economical (such as transit agency profit), and sociological (such as wait time) were selected for metro system performance assessment (Reddy et al. 2010; and Levine et al. 2013); however, these models could not address comprehensively customer satisfaction and agencies concerns. Reddy et al. (2010) used the benchmarking technique to compare New York City metro system with four Southeast Asian rail systems. A bigger benchmarking program has been developed since 1982 by the CoMET community including 34 metro systems around the world (CoMET and Nova 2018). To improve performance and productivity, this group designed a system of KPIs.

The Regional Transportation Authority (RTA) of Chicago developed a model (Gallucci et al., 2012) categorizing its assets into five functional groups: (1) track and structures; (2) electrical and metro equipment; (3) signals, communications, and fare collection; (4) stations, garages, and facilities; (5) rolling stock. Asset condition was determined based on the age, using a ranking system from level 5 (excellent) to level 1 (beyond use). Then, the replacement cost for assets that have reached the end of the lifespan, as well as maintenance costs for the rest, were estimated for a 10-year period. The state-of-good-repair level in terms of asset performance or remaining useful service life was not defined, and age was the sole indicator of assets condition, which might not detect other issues responsible for deterioration such as changes in traffic flow (Amador-Jiménez and Mrawira 2011).

A Building Information Model (BIM) was employed to assess the metro system by Marzouk and Abdel Aty (2012); however, BIM only maps available data on components, history, and inspection results. This model uses wireless sensors to collect environmental conditions and passengers' data at stations.

Metro car maintenance planning was studied for Guangzhou City in China (Ding et al. 2013). Maintenance plan was defined through procedures to maximize the train working days and reduce the reserved spare train. The Mean Time Between Failures (MTBF) was used to assess cars and a

Weibull distribution was recommended for the prediction of the operation life and Rough Sets Theory (Pawlak 1982) applied for allocation of resources. The results from this study could be used for equipment maintenance planning in metro systems; however, many elements are facing lack of historical data to be able to develop a Weibull distribution and the optimization model is not able to optimally distribute funding for the metro network including its components and sub-components.

A global risk-based assessment framework for metro structural sub-components was proposed by Abouhamad (2014) and the model was implemented on the Montreal metro system. This model presented three indicators for the Probability of Failure (POF), the Consequence of Failure (COF), and a Critical Index (CR). Through the integration of these indices, a risk index was calculated for defined segments. A POF was estimated based on the SUbway PERformance (SUPER) model (Semaan 2011) methodology. The COF was expressed in terms of social, financial, and operational impacts. CR was calculated by integrating station size, location, and nature of use criteria. A fuzzy ANP technique was adopted to establish the weights for COF, and CR. While other principal elements of mechanical, electrical, or rolling stocks were not covered, stations and tunnels were considered to operate separately for estimating COF; however, a failing tunnel, or a problematic station could disrupt the functioning of other segments or lines. In summary, Table 2-1 classifies the reviewed literature on metro asset management with taxonomy details for the employed methods.

Table 2-1, A taxonomy of transit asset management literature

Developer	Performance Indicators	Data Collection	Covered Tasks			Case Study	Model Validation
			Performance Assessment	Performance Prediction	Budget Distribution		
Roy et al. (1986)	Social, traffic, performance & maintenance plan	RATP staff	ELECTRE III	-	Ranking	Hypothetical example	-
Hastak and Abu-Mallouh (2001)	Functional & socio-political	Questionnaire survey & personnel interviews	AHP	-	Ranking & Integer programming	Hypothetical example	-
Delatte et al. (2003)	Concrete cracks in tunnels	Benchmarking	-	-	-	Five Japanese companies in metro inspection	-
Farran andZayed (2009)	-	Personal judgment & inspection report	Condition scale from 1 to 5	Markov chain	Linear programming	STM stations (concrete slabs)	-
Semaan and Zayed (2009)	4 functional criteria including 12 sub-criteria	24 Questionnaires, interviews, inspection & reports	AHP, PROMETHEE & MAUT	-	Ranking	Seven stations in STM network	Two STM experts
Reddy et al. (2010)	Productivity (density & utilization); profitability (return on investment); & performance (timeliness, reliability & troubleshooting)	Benchmarking	-	-	-	New York City metro & four southeast Asian rail transit systems	-
Semaan (2011)	Concrete crack	Visual inspection reports & 32 questionnaires	AHP& MAUT	Weibull distribution based on assumed life spans	Ranking	Two stations, one tunnel & auxiliary structures in STM	Empirical validation
Gallucci et al. (2012)	Asset age	Chicago transit system	Scoring (1-5) based on asset age	Based on asset age	Ranking	Chicago transit system	-
Marzouk and Abdel Aty (2012)	Asset managers & users' criteria	BIM (sensors & web-based users' feedback)	-	-	-	-	-

Developer	Performance Indicators	Data Collection	Covered Tasks			Case Study	Model Validation
			Performance Assessment	Performance Prediction	Budget Distribution		
Levine et al. (2013)	Wait time in station	Surveyors & an Automated Train Supervision (ATS) system	Wait Assessment (WA)	-	-	New York City metro	-
Ding et al. (2013)	Failure indicators	Vehicular sensors & observations	Reliability analysis	Weibull distribution	Rough Set Theory	Guangzhou City	-
Kepaptsoglou et al. (2013)	Overall rate of sub-elements	Athens metro experts (group decision)	Fuzzy AHP	-	Ranking	22 Athens metro stations	-
Gkountis and Zayed (2015)	Defect-based for different structural, electrical &mechanical hierarchy components	23 on-line surveys	AHP, ANP &TOPSIS	Weibull distribution	Ranking	Three metro stations in the Athens metro system	Comparing model results with a benchmark case study
Abouhamad (2014)	POF based on (Semaan &Zayed,2009) for structural elements; consequence of failure (COF) index based on social, financial, operational criteria groups; & size, location, & nature of use for station criticality index.	Historical data, experts' judgment & 16 questionnaires	Fuzzy ANP	Weibull distribution based (Semaan and Zayed, 2009)	Genetic Algorithm	6 segments (station tunnel, auxiliary structure) in STM	Expert's judgment
Nishimura et al. (2015)	Concrete defects	Inspection report	-	Markov chain	Cost-Benefit	Tokyo metro tunnels	-
Taguchi et al. (2016)	Structural deformation	Inspection report	Bayesian, Markov chain & Monte Carlo	-	-	Tokyo metro tunnels	-
Dawood et al. (2017)	Concrete elements defects (Moisture)	Inspection	-	-	-	STM	Statistical measures

Many transport planners and decision-makers, particularly in developed countries, are facing a situation in which a large portion of their vehicles and fixed assets, are either approaching the end of their useful life or have already exceeded it. Meanwhile, this situation is against a backdrop of budget backlogs, which limits investments in maintenance, rehabilitation, and renewal of transit systems. In this situation, proper asset management practices would be crucial to address mentioned issues, as well as system complexity and ridership, grow, while many transit agencies in U.S. neglect conducting a regular asset performance assessment (ASCE 2013). Table 2-2 illustrates the assessment criteria and decision-making approaches of some major transit urban railway systems in North America and Europe.

A major limitation of existing practical approaches is the lack of quantification of the impacts and implications of underinvestment in maintenance and rehabilitation. This is key to guide the expansion of the network and frequency of service operations. Existing models help describe how much investment is needed; however, do not provide an estimation of investment consequences (positive and negative) over the service life of the transit systems. Without such information, it is difficult to prioritize rehabilitation and replacement alternatives (Cohen and Barr 2012). Also, in the majority of the proposed frameworks, customer satisfaction and comfort are neglected.

In addition, the long-term impacts of decisions made at different points of time (in particular on asset deterioration) are often not investigated. Finally, agencies aim at evaluating a limited number of alternative asset management plans. In this sense, employing an asset optimization model provides an opportunity to account for an infinite number of alternatives while respecting technical, economic, social, and environmental objectives and constraints.

Table 2-2, Asset management models used by transit agencies

Agency	Major Performance Indicators	Budget Distribution
Toronto Transit Commission (TTC 2015); (Federal Transit Administration) (FTA, 2010)	Five key indicator groups include safety and security; customer (journeys, satisfaction, environment, and service performance); people; assets (vehicle and equipment reliability); and financial.	Each sub-indicator is periodically measured and compared with a target (Benchmarking).
STM (Abouhamad 2014)	Station age and expert judgment.	Ranking stations based on age and expert opinion only without an actual evaluation of the condition.
Massachusetts Bay Transportation Authority (MBTA) (Eric 2011)	Six criteria of health; age; legal commitment; cost/benefit; operational and environmental impacts are assessed and weighted for each alternative based on asset manager's preferences.	Defining alternatives for rehabilitation-replacement projects and ranking them with respect to a set of criteria as well as the budget constraint.
Metropolitan Atlanta Rapid Transit Authority (MARTA) (David et al. 2011)	Assessments based on condition ratings, life cycle priority, estimated useful life, in-service date, and installation/purchase costs.	Conditions of assets are obtained through sampling from preventive maintenance and inspection. Next, they are ranked for replacement.
Chicago Transit Authority (CTA) (FTA 2010)	Key measures include on-time performance, miles between in-service failures; defect rates for vehicles, the extent of slow orders for the track, and station/vehicle cleanliness.	A five-point scale, similar to Transit Economic Requirements Model (TERM) presented by FTA, is used for characterizing physical conditions of CTA's assets.
London underground (LU) (Cohen and Barr 2012) (Transport for London 2017)	Key measure groups of availability (perform reliably in case of delay, interruptions, and facilities); capability (capacity of the assets to accommodate higher volumes of passengers); ambience (reflects the quality of the traveling environment); and customer satisfaction.	Development of an annual asset management plan including condition performance measurement and optimizing available funding based on the objective of minimizing customer delays.
MTA-NYCT (Cohen and Barr 2012)	On-time performance; metro wait assessment, elevator and escalator availability; mean distance between failures; customer injury rate; and accidents rate.	After collecting data from operations, customer feedbacks, NYCT executives, and stakeholders, candidate projects are identified.

2.3 METRO ASSET MANAGEMENT FRAMEWORK

In this section, a framework for designing a comprehensive asset management for metro systems is developed. It includes reinvestment for Maintenance, Rehabilitation, and Replacement Planning

(MRRP) for metro systems (Figure 2-2) and excluding routine maintenance implemented by agencies. It covers three main tasks of performance measurement, performance prediction, and budget distribution and optimization, reflecting on the state of the art in the methodologies proposed in each of these areas. In the following sections, more details about these areas and related methodologies are provided.

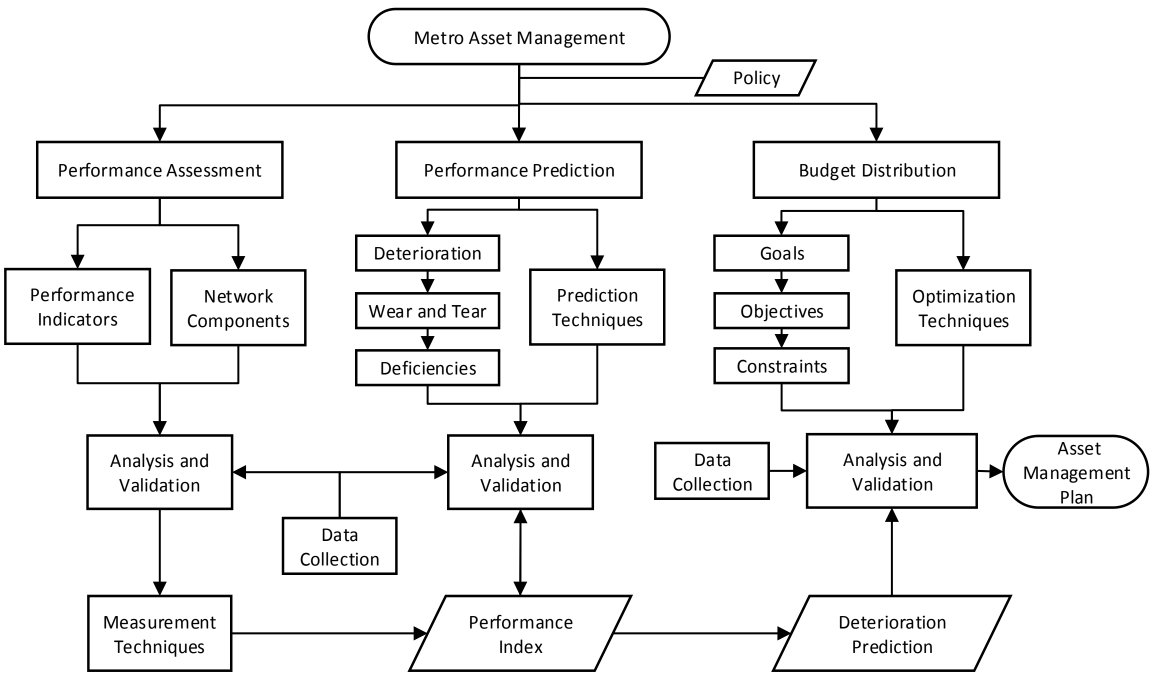

Figure 2-2, Developed framework for metro asset management

2.3.1 Performance assessment

The National Research Council (1995) identified costs, benefits (social and economic), reliability, and environmental consequences, as widely recognized aspects related to performance measurement. However, it admitted the fact that there is not a widely accepted list of elements that could comprehensively describe infrastructure performance. In the case of metro systems, the rationale behind performance measurement is to model all performance aspects related to both the agency and the user's perspective; including the station, tunnels and the rolling stock. Such a measurement must be capable of supporting a multidimensional understanding of LOS before aggregating or combining the related indicators. Performance measurement for metro systems should include the components of stations, cars, and tunnels, as well as, the user needs commonly represented by convenience and comfort in addition to travel time, transfer time, and the system service reliability. A set of performance indicators must be developed and assessed based on current technologies and appropriate targets where preference is given to quantitative elements that can be measured, compared, traced and updated regularly reflecting requirements of safety, reliability, performance, sustainability, and user convenience and comfort.

Figure 2-3 presents KPIs based on the literature that could be used in performance measurement of metro assets. According to the agency's policy and stakeholders' preferences, three different groups of indicators namely technical, economical, and sociological could be used for network performance assessment. Technical indicators cover asset conditions, reliability, and efficiency. The economic indicators refer to asset business condition in terms of cost and revenue. Finally, transit systems could be evaluated based on customers' perspectives and satisfaction capturing the social performance (Balzer and Schorn 2015).

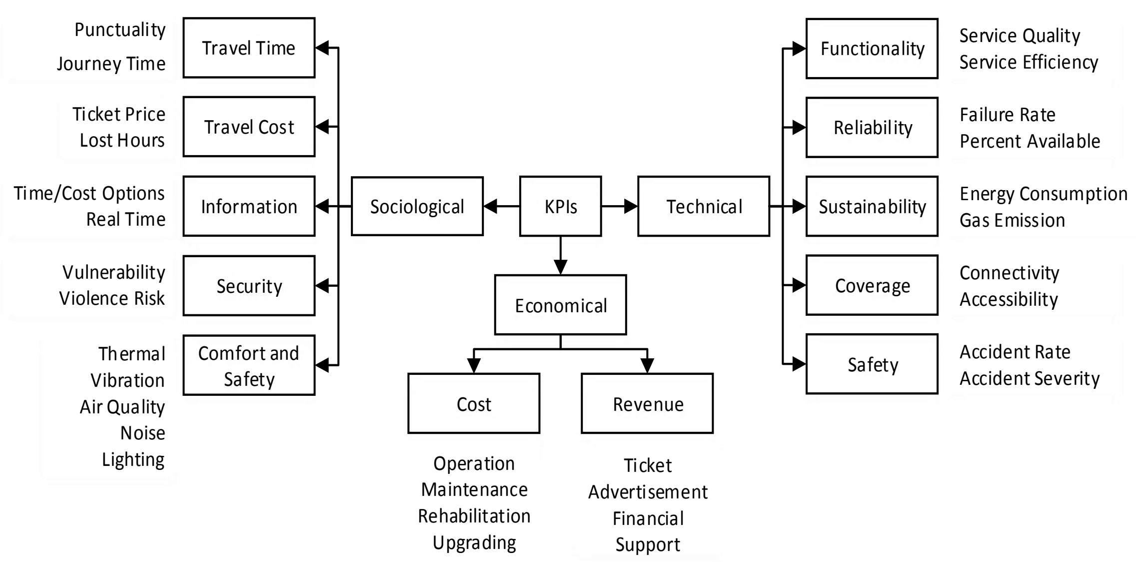

Figure 2-3, KPIs for metro transit systems.

Underground railway systems have many components and sub-components of dissimilar nature and behaviour, distinguishing them from typical infrastructure, such as pavement or pipeline, which consists of fewer components. In this sense, performance measurement should follow a hierarchical framework based on categories for each line and could be broken down into components of stations, tunnels, and cars. Figure 2-4 shows two ways of constructing such a hierarchy for a sample metro network. From a functional perspective, the system could be mapped based on functional types grouped into stations, tunnels, and cars. This approach gives an opportunity to make and follow decisions for each different-nature component separately. From a network segmentation perspective, each station and connecting tunnels are defined as one segment to be coordinated in terms of maintenance, rehabilitation, and renewal plans (Figure 2-4). Also, station criticality in the network could be addressed by this hierarchy. Each functional unit could be further divided into sub-components and elements for more refined assessment as illustrated in Figure 2-5. The choice of the hierarchy dictates the way performances are combined to form an aggregated index for the network level.

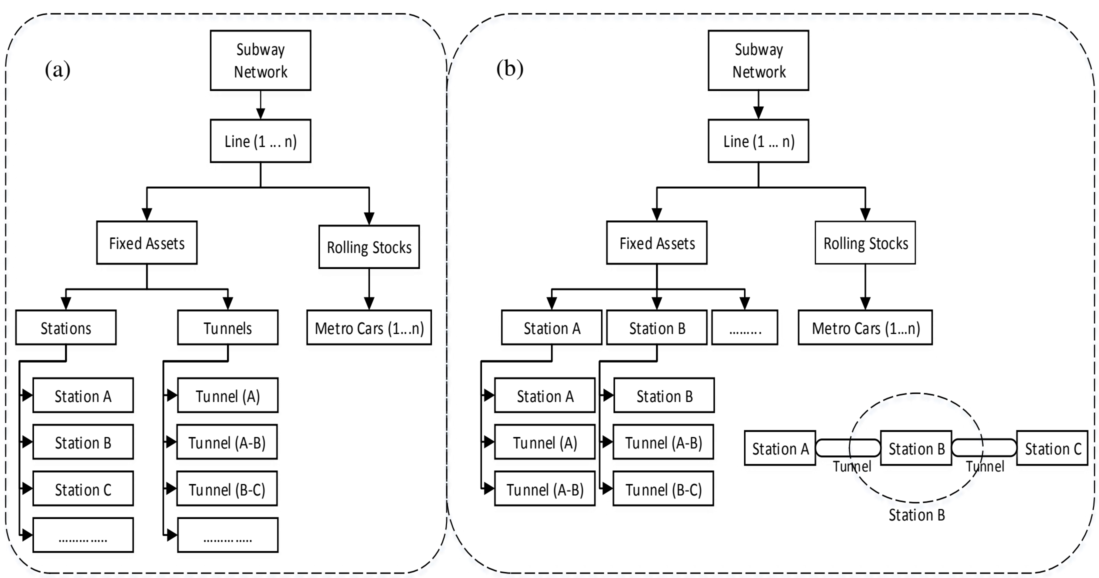

Figure 2-4, Hierarchical mapping of the metro network based on (a) functional units and (b) network segments.

As seen in Figure 2-5, performance measurement starts at the element level (e.g. elevator for mechanical sub-component). Based on defined indicators (Figure 2-3) and the scoring system of the transit agency, assessment scores are integrated to the upper levels in the hierarchy network (Figure 2-4) to address metro network performance. Several techniques such as AHP, ANP, and TOPSIS could be used for performance integration.

2.3.2 Performance prediction

Performance forecasting models are developed to estimate future LOS for components of the system expressed by their corresponding performance indicators. These estimates are used to plan for timely interventions (maintenance, rehabilitation, and replacement) in the future, ensuring a reliable and convenient system operation.

Due to data availability and system simplicity, other infrastructure systems such as pavement and pipeline count with many previously proposed deterioration modellings; however, different approaches should be selected to improve already developed models for metro system deterioration. For instance, customized building performance prediction models (Edirisinghe et al. 2015) could be used for modelling stations. AASHTO (2011) defines two general approaches for performance prediction: deterministic, and stochastic.

Deterministic is the most often used model for performance prediction commonly developed to forecast the deterioration rate of the physical condition in assets. Schram (2008) found that 91% of Canadian and American transit agencies used empirical models for pavement deterioration with mechanistic or mechanistic-empirical models that contain cause and effect equations. Their application to metro systems are faced with lack of historical data and weakness in application to a complex system with many components, sub-components, and indicators (Grussing et al. 2016).

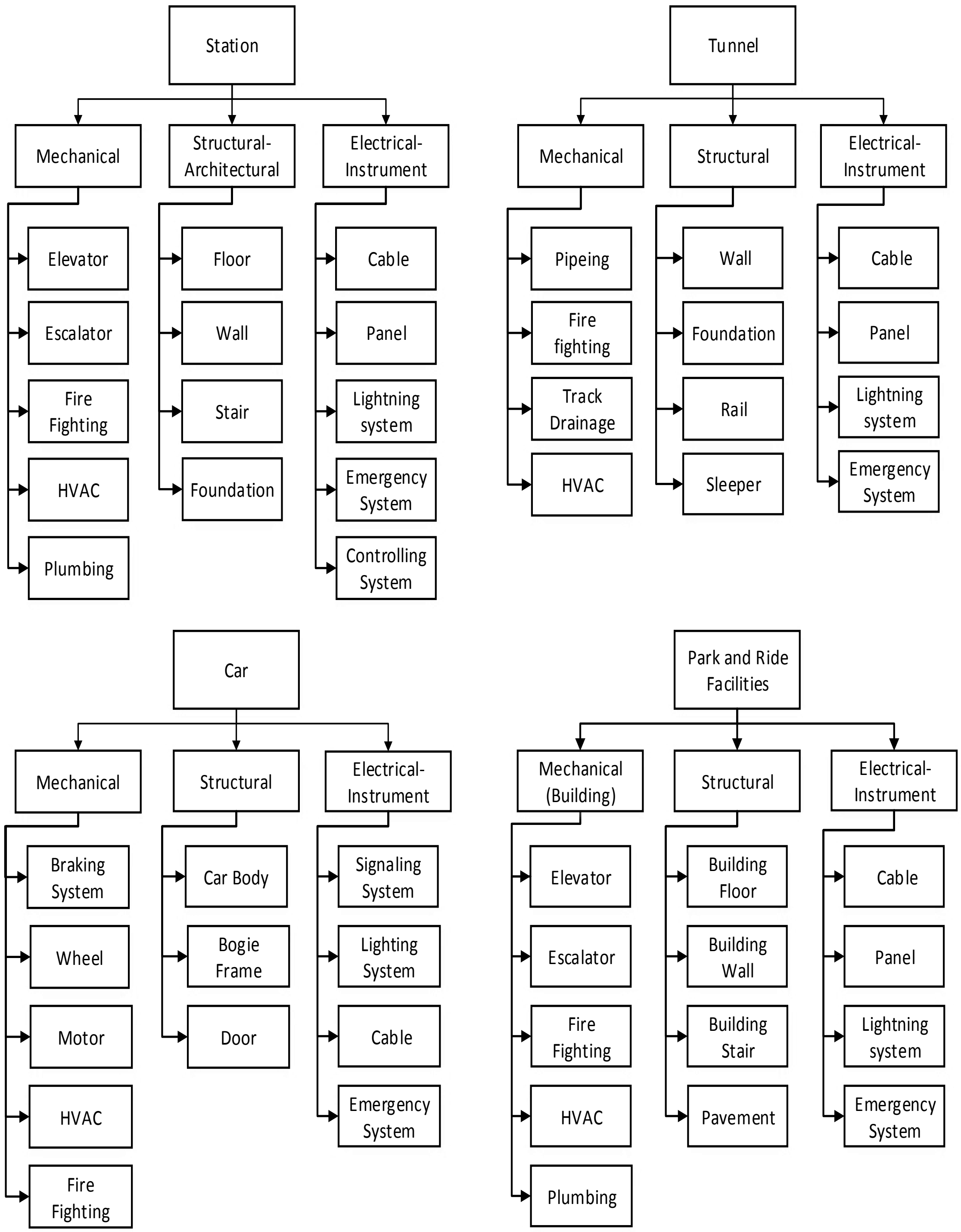

Figure 2-5, Sub-components and elements of typical metro components mapped based on the functional units.

Stochastic approaches such as Markov chain model address uncertainty in the deterioration processes (Thomas and Sobanjo 2016); however, requiring longitudinal (time-series) data for the prediction of the transition matrix (Baik et al. 2006) making it difficult to be prepared for a metro system. In such case, expert judgments could be utilized to fill data gaps and develop the transition matrix for the Markov model. Another programming-base prediction models such as artificial neural network have been applied to less complex assets (El-Abbasy et al. 2014); however, in addition to the limited transparency of such black-box approaches, still large amount of data needs to be collected for training and calibrating the model (Abra 2012).

It should be mentioned that some indicators tend to be static (inadequate signage, the absence of benches or safety hardware, defective noise isolation) reflecting that only an intervention needs to be corrected. Other elements tend to change across time and hence are of dynamic nature (wear, tear, and deterioration of the assets). Additionally, some indicators are linked to demand (number of users) and the capacity of the system such as those related to frequency and availability of the transit service. Others are independent of the number of users (such as lighting systems) and defined based on codes and standards.

2.3.3 Budget allocation and optimization

An optimization model allocates funds from the annual budget among reinvestment alternatives (e.g. maintenance, rehabilitation, and replacement) in order to assure the safety and secure movement of travellers, and the highest LOS. Traditional methods such as ranking (worst-first), which are commonly used (Tables 1 and 2), no longer work due to budget gaps, the number of alternatives and system complexity. Thus, optimization model plays a critical role in ensuring that acceptable levels of service and optimum planning are achieved. It selects the appropriate investments throughout the network resulting in an improved system performance. In this way, agencies can ensure the provision of a convenient transit system (i.e. comfortable and reliable), which can be expanded in line with the increasing demand for services.

Several studies have proposed in other infrastructure to find optimal solutions for capital investment to support year by year maintenance plans that could be applied to urban railway systems. Generally speaking, planning consists of three stages: strategic, tactical and operational, which could be developed based on agency policy, goals and metropolitan size (Figure 2-6). The state of the art in decision support systems indicates that binary dynamic programming model could be utilized for a long-term planning horizon with a hierarchical structure that transfers long-term scheduled interventions into tactical plans (medium term) through a bipartite matching or a greedy algorithm (Amador and Magnuson 2011). This produces coordinated interventions within a given space-time proximity window and connects to a final allocation model that produces operational plans for transit agencies while linear programming is a common approach for short-term modelling. Budget allocation could also be included heuristic algorithms to arrive at optimal asset management solutions using evolutionary methods such as Genetic Algorithm, simulated annealing, Ant colony, etc. (Atef et al. 2012; Torres-Machí et al. 2013).

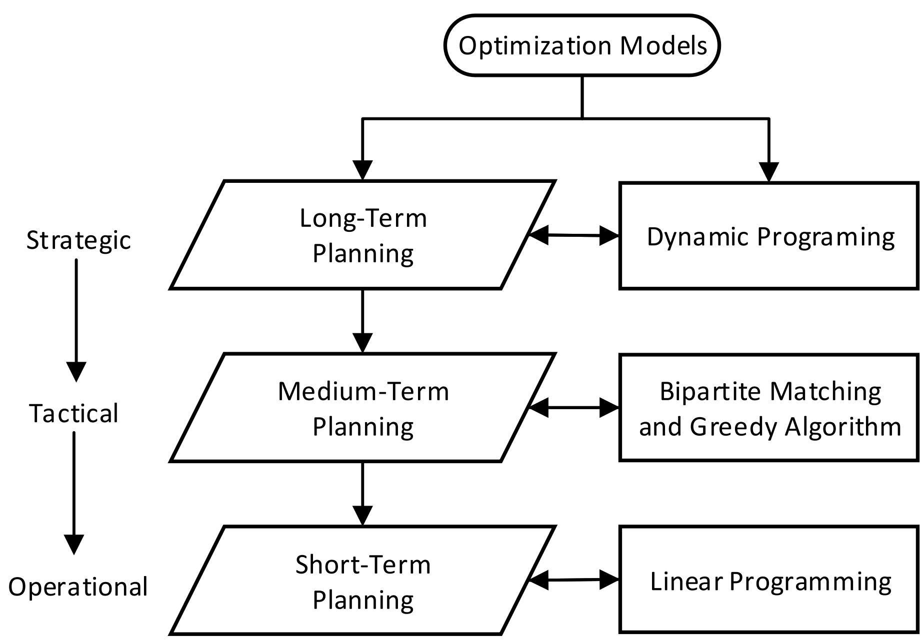

Figure 2-6, Optimization models for budget distribution in transport asset management.

2.4 METRO ASSET MANAGEMENT AND DEMAND (USAGE)

The role of demand (usage) and expansion projects in long-term planning and future decision-making is often neglected in TAM studies. There are mutual relations among asset performance, ridership, and rate of deterioration where increased usage of the network could be achieved by high LOS on KPIs such as travel time, travel costs, safety, comfort, accessibility, and reliability. Meanwhile, network expansion not only extends the reach and coverage of the system but can possibly affect travellers' daily activities. Extending the rail lines and stations could result in increased mobility and added accessibility to regions previously secluded. For this reason, possibly increasing ridership should be considered in strategic, tactical, and operational management plans in order to address performance and deterioration impacts and promote transit. Thus, ABM or Land Use and Transport (LUT) outputs in the existing networks could impact on TAM strategies, at the same time, network performance and LOS can alter ABM and LUT outputs since it might encourage more commuters to abandon private automobiles and use public transit. Urban railway asset management model, as a multi-criterion assessment framework, should be capable of addressing impacts of changing usage and upgrading in decisions to achieve more realistic and cost-effective plans. For this purpose, major planning frameworks of TAM, LUT, and ABM are tied together through asset performance and deterioration in Figure 2-7.

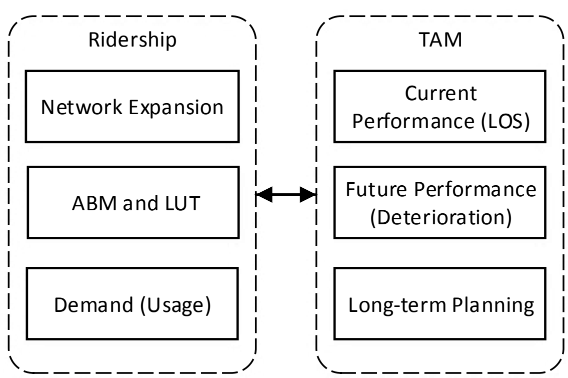

Figure 2-7, Linking Ridership and TAM.

2.5 CONCLUSION

Despite the historical fact that infrastructure management research has been well-established particularly in the case of pavement, bridge and water network management, there is a lack of asset management framework for urban railway systems. This is mainly due to the multiplicity of components; the complexity of their interdependencies; common lack of historical data and performance indicators; and unavailability of a unified framework that integrates forecasts of future demand with decision-making systems. Literature shows that there are only a limited number of studies that target underground transit asset management, with limitations that restrict their applicability. Most of the studies focus only on one part of the network such as stations or tunnels. The transit cars as one of the main components of urban railway systems are often ignored. Prioritization of maintenance and rehabilitation alternatives usually has been done based on asset age, or current condition, and other key factors in deterioration processes are missed. The budget allocation using optimization approaches are widely neglected and worst-first scenarios are commonly used. This paper elaborated that there is a critical need for the development of a comprehensive management model that is capable of integrating all components of metro systems. This model should consider current and future ridership and its consequences in congestion, safety, and deterioration of the network, its vehicles, and stations. The framework developed in this research is suitable for further studies in urban railways such as Rail Rapid Transit (underground and surface), Light Rail Transit, and suburban trains as well as other modes of transport (e.g., traditional buses, Bus-Rapid-Transit) while addressing both customers' and agencies' concerns and expectations.

Chapter 3 : METHODOLOGY (MODEL I)

A MULTI-CRITERIA ASSESSMENT OF THE PASSENGERS' LEVEL OF COMFORT IN URBAN RAILWAY ROLLING STOCKS

This chapter covers the first model in the methodology and an assessment platform for railway vehicles is proposed. This study provides an approach to quantitatively measure railway riders' comfort and safety (i.e. aspects related to comfort) in terms of humidity, temperature, vibration, the concentration of CO_2, noise, and lighting level. This effort is under review by the journal of sustainable cities and society:

Mohammadi, A., Amador, L., and Nasiri, F. (2019). A Multi-Criteria Assessment of the Passengers' Level of Comfort in Urban Railway Rolling Stocks. Journal of sustainable cities and society (SCS_2018_1816).

Abstract-Transit agencies around the world concentrate their efforts to satisfy most commuters and convince them to abandon the use of the private car in daily trips. Travel time and cost have been widely investigated as travelers' satisfaction factors, while human aspects such as comfort are mostly neglected. Management of urban transit systems should ensure a convenient transit service with adequate levels of ride and quality (time and cost) as well as users' comfort, health and safety to achieve sustainable societies. This study proposes an approach to quantitatively measure railway riders' comfort in terms of humidity, temperature, vibration, the concentration of CO_2, noise, and lighting. Such indexes can be used to direct the allocation of investments for improvement of comfort in urban transit infrastructures as well as capture reality in demand prediction modeling. A case study of several lines in Montreal metro network is presented to illustrate the applicability and usefulness of the proposed approach. The newer trains on Montreal's Metro are an improvement over older trains when it comes to rider comfort; however, they could still be better, especially when it comes to sound levels, while old cars need improvement in most factors such as noise and thermal condition.

3.1 INTRODUCTION

Governments and cities are increasingly promoting Public Transit (PT); however, convincing commuters to abandon the use of the private automobile in exchange for public transport in order to have sustainable cities is highly depending on the convenience of public transport. In North America, in many megacities (e.g. New York, Chicago, and Toronto), private transit has higher portions than public systems in daily journeys (Singapore L.T. Authority 2011). This is partly caused by an undesirable level of service in public transport. Level of "D-" was assigned to transit sector by American infrastructure report card 2017, which reflects such "Poor" condition (ASCE 2017).

Urban railways play a crucial role in daily movements of commuters and passengers. A greater degree of passengers' satisfaction, and subsequently, a higher likelihood of using public transport would be achievable by providing a better service quality in public transportation (Cats et al. 2015). Therefore, customers' expectations and concerns particularly in rolling stock, where customers spend most of their travel time, need to be monitored and analyzed by public transit agencies. Performance conditions for railway cars could be assessed according to several corresponding aspects such as technical (i.e. sustainability and reliability), and social (i.e. safety, health and comfort), reflecting customers' points of view (Balzer and Schorn 2015). A comfortable ambiance results in improving the performance of the drivers, and consequently, the safety of users (Da Silva 2002).

Although advanced models in transit asset management and planning could address socio-environmental concerns (through incorporating proper indicators); classical models of railway assessment concentrate mainly on travel time, cost, and loss of customers' productivity in hours or availability of physical assets (e.g. escalators and lifts), disregarding users' level of comfort and possible non-driving activities related to work or leisure during travel time. However, in well-organized agencies, other aspects of customer satisfaction and comfort are critical elements of performance assessment (Transport for London 2017). At the same time, for a socially desirable and environmentally sustainable transport system that respects travelers' preferences, demand forecasting models should help in enhancing our understanding of the preferences that drive the individual's choice of transport modes (Vredin Johansson et al. 2005).

To assess the impacts of the level of comfort in transit asset management and demand forecasting, a comprehensive model is required that quantifies all critical factors affecting the users' comfort in order to estimate an overall index for their level of comfort. The main objective of this study is to establish an assessment model for railway cars oriented to the customers' points of view on comfort and safety. A number of indices for railroad travelers' comfort and health are identified incorporating factors as diverse as humidity, temperature, vibration, the concentration of CO_2, noise, and lighting levels inside the vehicles. In doing so, a set of thresholds defined according to public health and comfort standards, are considered. Each index reflects the performance of railway trains assets as well as tracks and tunnels. These indices could be used as a basis for asset management decision-making and for optimum budget allocation in maintenance and rehabilitation plans. Also, comfort assessment could be used in the analysis of transit modal choices in addition to cost and travel time criteria. The proposed approach is applicable to railway systems (underground and surface) and other transit modes such as Bus-Rapid-Transit (BRT) or Tramways.

3.2 LITERATURE REVIEW

Mohammadi et al. (2018) reviewed metro asset management models and concluded that the railway cars, one of the main components of metro systems, are often ignored in the developed assessment models. Meanwhile, several studies discussed the role of vehicles comfort in public transit attractiveness and effectiveness (Wan et al. 2016). A public transit service study conducted by the Chicago Transit Authority showed that comfort improvement has significant impacts on customer satisfaction (Foote 2004). A study conducted by Scherer (2010) found that the qualitative factors of reliability and ride comfort result in rider preference for light rail trains versus bus. Wen et al. (2011) found that to experience better service including onboard comfort, bus travelers were willing to pay more. Chee and Fernandez (2013) indicated that 70.49% of commuters believe in the essentiality of the comfort in transport, preferring private cars.

In the meantime, researchers use discrete choice models to forecast the impact of transport policies and strategies on the transportation demand. These models consider socio-economic characteristics and a number of travel attributes (such as time, distance, and fees) (Idris et al. 2014) as well as household socio-demographic factors such as gender, income, car ownership, and employment status (Eluru et al. 2012). Ben-Akiva and Morikawa (2002) showed that travel comfort, safety, and security are as important as travel time and cost in ridership attractiveness and mode choices. According to the STM (2012), it has been observed that improving quality, comfort, and safety are the main factors in convincing the travelers to use public transit.

The above-mentioned studies have shown that while the level of comfort could impact travelers' satisfaction and demand for public transport, people's preferences in choosing the train over buses, or metro over automobiles is subjective. As such, there is a need to models that can quantify the perceived comfort of travelers across different modes of transportation, in order to better understand the individual's choices when it comes to public transport.

Passengers' level of comfort could depend on several physical and psychological factors of thermal, movement, air quality, auditory, and visual conditions experienced during a journey. A study by Wardman and Whelman (2001) showed that passengers prefer to spend money for higher ambiance, seating comfort, and ride quality. Schwanitz et al. (2013) identified that the most contributing attributes in comfort of travelers on trains are the odour, air quality, air ventilation and temperature. Castellanos and Fruett (2014) highlighted acceleration in public transportation as an influencing factor on comfort. Some literature has concentrated in evaluating those factors related to vehicle comfort and health in terms of Thermal (Croitoru et al. 2015; Haller 2004; Danca et al. 2016; Abbaspour et al. 2008; Simion 2016), Noise (Patania et al. 2013; Pahalavithana and Sonnadara 2009; Paulraj 2010; hardy 2000), and Vibration (Barone et al. 2016; Tung et al. 2011), and Air quality (Li 2007).

However, these studies often concentrated on one factor without quantifying the level of comfort such that to be able to link it to resource allocation decisions in maintenance, rehabilitation, and upgrade of infrastructure or to travel demand forecasting. Da Silva (2002) investigated thermal conditions, sound, vibration and air quality in automobiles using laboratory methods to present some techniques in the measurement of comfort parameters. Nordin et al. (2016) suggested several indicators and ranked various types of trains employed in a metro network from a comfort perspective. However, they have not considered passengers' preferences among these criteria and the level of comfort was not ultimately quantified. A recent framework developed by Amador-Jimenez and Christopher (2016) incorporates three factors (vibration, sound, and air quality) to assess users' level of comfort in transit systems using a set of numerical indices. However, this model did not consider thermal comfort and lighting levels among the assessed criteria. In addition, they used a set of maximum health threshold values to calculate the comfort indexes. This implies a focus on safety and neglects human preferences, interpretation, and perception as relating to the comfort. Also, the proposed assessment process does not account for multiplicity and diversity of transport modes.

In the sense of the existing literature, it can be concluded that there is a gap as relating to developing and using a comprehensive comfort assessment model for railway vehicles from passengers' perspectives linking them to asset conditions, travel demand forecasts, and resource allocation decisions.

3.3 METHODOLOGY

Comfort; safety and security; surrounding; and convenience are among the aspects influencing passengers' satisfaction. These criteria are mutually interrelated as a lack of comfort could result in health and safety risks while a less clean and convenient environment leads to discomfort and dissatisfaction. As a physiological and psychological phenomenon, comfort could impact the commuter's satisfaction, concentration, and ability to develop productive activities while riding a transit vehicle. Various factors related to the type of activity and the physical surroundings (including people, furnishings, and adjacent spaces) could impact the riders comfort level. In this study, comfort is defined according to five factors of thermal, air quality, noise, vibration and visual comfort (Figure 3-1). As mentioned before, such an assessment model could be used for mode-choice analysis and asset management purposes.

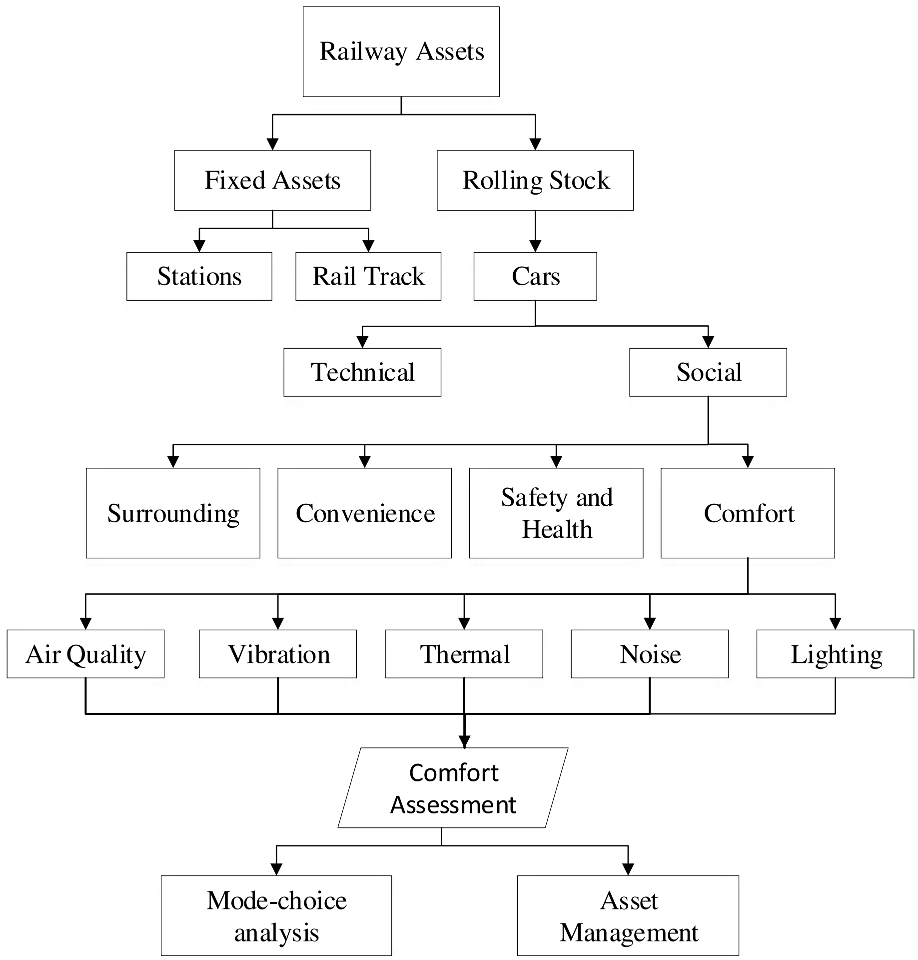

Figure 3-1, Railway vehicles performance assessment and passengers' perspectives

3.3.1 Comfort assessment and asset management

Comfort indices could be used by asset managers to assess the entire network accordingly and objectively distribute budgets for maintenance, rehabilitation and replacement actions leading to improvement of comfort levels (Table 3-1).

Table 3-1, Comfort factors and their corresponding assets.

Comfort factor	Corresponding assets
Vibration	Braking system, wheels, damping system and tracks
Thermal	Heating, Ventilation, and Air Conditioning (HVAC) system
Noise	Insulation system (including doors and windows)
Lighting	Lighting and caballing systems
Air Quality	HVAC system

3.3.2 Comfort assessment and mode-choice analysis

Commuters' perception about service quality influences their choice of transit mode. The main service quality aspects of a public transit system include proper scheduling, reliability, coverage, access to information, comfort, and safety (Eboli and Mazzulla 2009).

The mode-choice analysis is an integral part of travel-demand forecasting (Martin and McGuckin 1998). Traditionally, cost and time have been the two principal attributes considered in the mode-choice analysis. These attributes can be easily quantified and incorporated into econometrics models to establish travel forecasting models. However, qualitative attributes of safety, flexibility, comfort, and convenience are also influencing the individual's decision-making about the choice of travel modes (Zheng et al. 2016).

In this sense, the level of comfort should be part of an integrated public transport modelling and decision-making process. Demand forecasting frameworks should incorporate travelers' level of comfort and safety in terms of humidity, temperature, vibration, CO_2, noise, and lighting inside the vehicles to reflect upon the commuters' perspective and preferences. Figure 3-2 presents an expanded demand forecast modeling framework that includes comfort criteria.

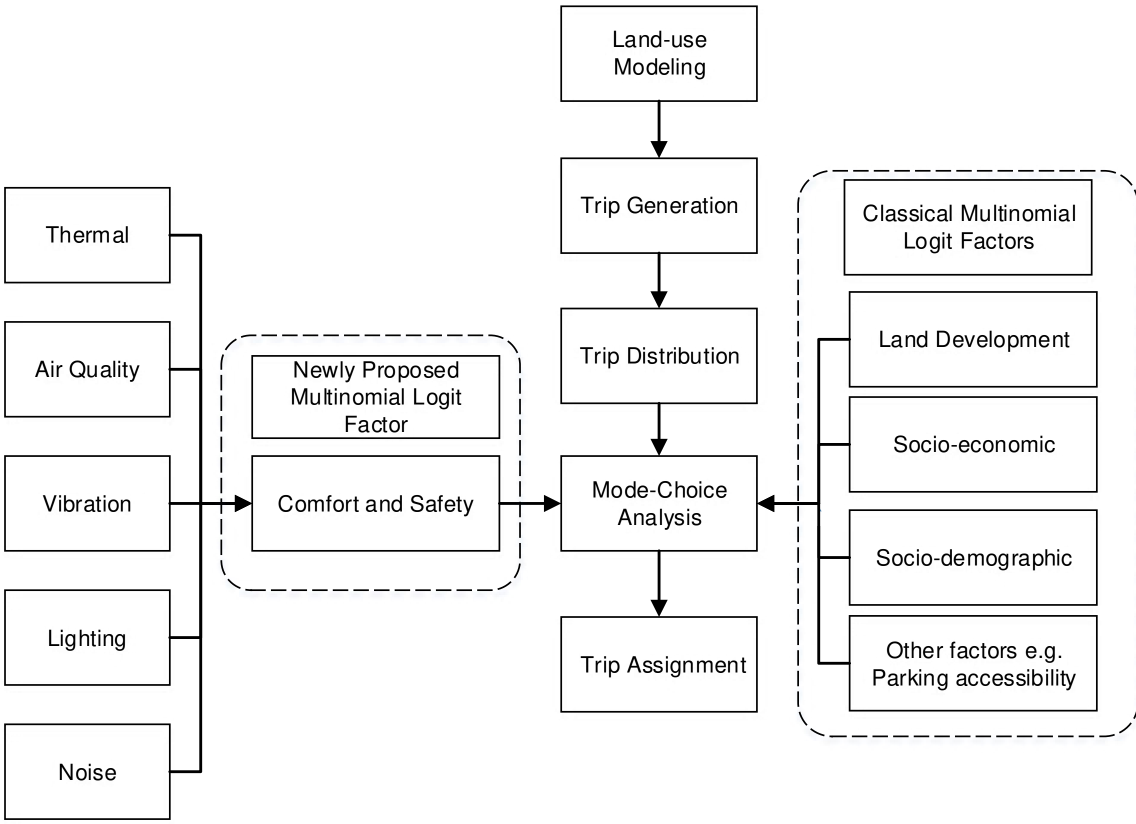

Figure 3-2, Addressing level of comfort in mode-choice analysis and demand modeling

Disaggregate discrete choice models developed based on individual preferences are often used to address the limitations and challenges in predicting the commuter's behavior towards travel choices (Vuchic 2007). These types of models calculate a maximum likelihood for each travel choice based on a trip utility function (Equation 3-1), which is a weighted function comprised of travel time and cost, and other influencing factors:

$$U_i = \alpha + \beta X_i + \gamma Y_i + \delta Z_i \;\; \forall \; i=2 \text{ to } n \qquad (3\text{-}1)$$

Where U_i is modal choice utility for mode i, α is a constant and β, γ, δ are regression coefficients for the cost, time, and comfort respectively. X, Y, and Z are associated utility for the cost, time, and comfort for modal choice i. Modal choices probability could be estimated based on Equations 2-3 and 3-3 for each journey option as follows:

$$P_i = \frac{e^{U_i}}{\sum_{i=1}^{n} e^{U_i}} \quad (3\text{-}2)$$

Where $0 \leq P_i \leq 1$ and $\sum_{i=1}^{n} P_i = 1$ (3-3)

3.3.3 Comfort assessment indexes

Figure 3-3 presents a framework for developing a performance assessment model for railway vehicles. Personal comfort levels during a transit journey could be incorporated in this model accounting for thermal control; seating, and riding comfort (that could include the severity of acceleration and braking); noise; as well as light and air quality inside the vehicles. As the perception of comfort is different from rider to rider (depending on age, gender, fitness, and other socioeconomic characteristics), there is no ideal comfort level that could fully satisfy everyone. In this sense, some studies suggest that attaining about 80% satisfaction from the riders is considered a good performance (TSI 2016). Also, the interdependency among the influencing factors on comfort should be assessed carefully, where non-motion factors such as acoustic noise level, visual stimuli, temperature, and humidity, interact with vibration changing the passenger's perception about comfort (ISO 2631-4 2001).

Comfort expectations and annoyance tolerance are quite different in transportation vehicles as compared to commercial or residential buildings (ISO 2631-1 1997; ASHRAE 2015). Several issues such as exposure time, type of activity, and a rider's choice of clothing creates the need to develop specific comfort and discomfort thresholds and ride quality in transit systems. The railway trip could consist of very short to long journeys. As such, this study classifies the travels into two categories of A: the suburban trip (average of 3 hours travels time) and B: the urban trip (average of half an hour travel time).

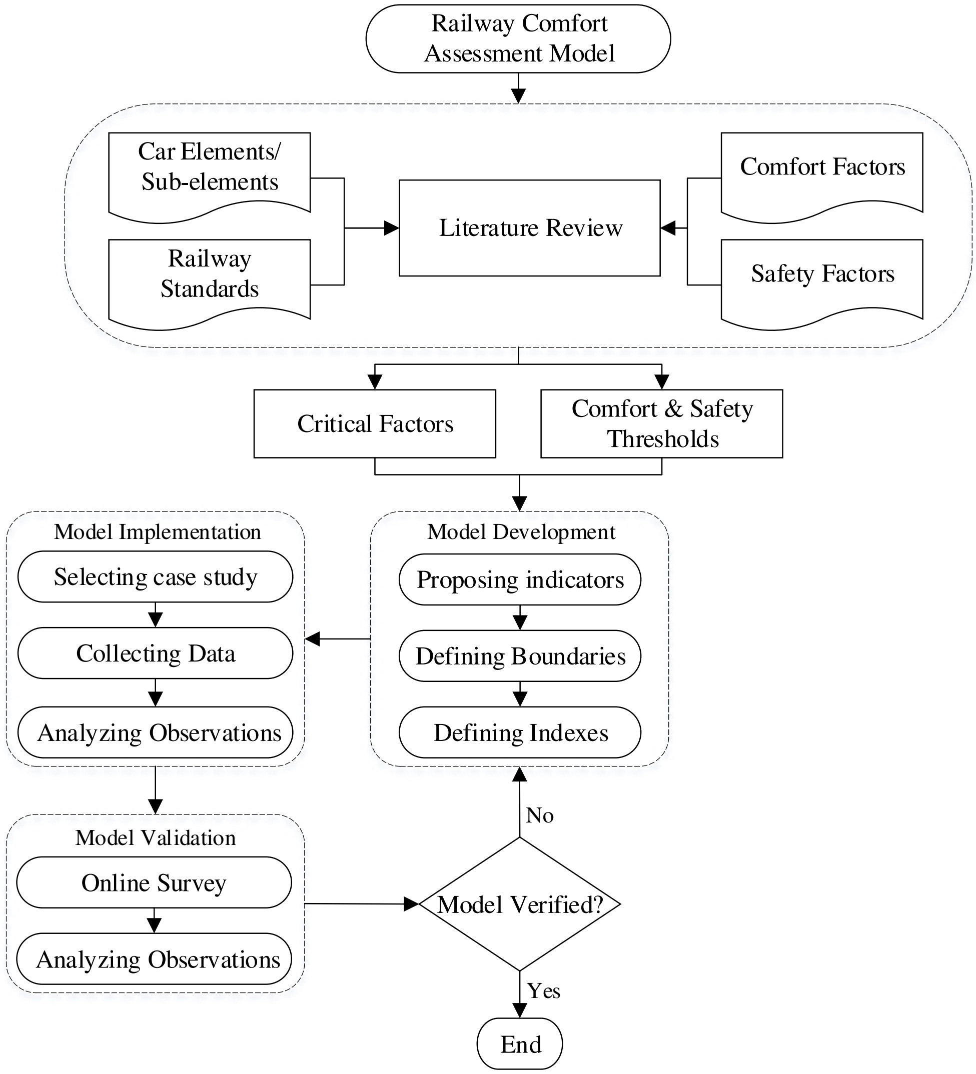

Figure 3-3, Railway comfort assessment framework development

Thermal Comfort

Thermal comfort accounts for environmental conditions in which a user expresses satisfaction (ASHRAE 2013). It relates to several factors ranging from weather conditions to level of physical activity and clothing. Furthermore, the thermal sensation perceived, and environmental conditions required for comfort can be different for different people (Simion 2016). However, in this case, as ASHRAE 55 (2010) recommended, thermal comfort usually refers to a zone, for which, an 80% of sedentary or slightly active persons accept its thermal conditions as comfortable. Among different controllable indicators, temperature and Relative Humidity (RH) have the most significant contribution to the experience of comfort. ASHRAE's standards define a separate comfort "zone" for winter and summer; respecting the level of clothing, where most occupants are likely to feel comfortable. The requirement of ASHRAE 55-2010 can be customized for transportation systems in two main perspectives: passengers clothing-level in winter and travel duration. In comparison with building occupants, the travelers use different clothing levels in winter inside transit vehicles (ASHRAE, 2015). Therefore, EN 14750-1 (2006) recommended colder boundaries (19-22 degrees Celsius ($°C$)) for railway vehicles in winter to set a preferable comfort zone inside of transit cars.

In addition, high humidity supports bacterial growth. Thus, ASHRAE 55-2010 recommends that humidity ratio should be maintained below 0.012. A specific lower level of humidity has not been recommended in both standards of ASHRAE (2015) and EN 14750-1 (2006). Charles et al. (2005) recommended a minimum RH of 30% to control dry conditions and the resulting health problems (such as skin irritation) in transit systems. This boundary could be ignored for relatively short travels.

In the sense of the above discussion, Figures 3-4 and 3-5 are presented to coordinate summer and winter thermal comfort levels (through appropriate Indices), with respect to the above-mentioned temperature and humidity thresholds.

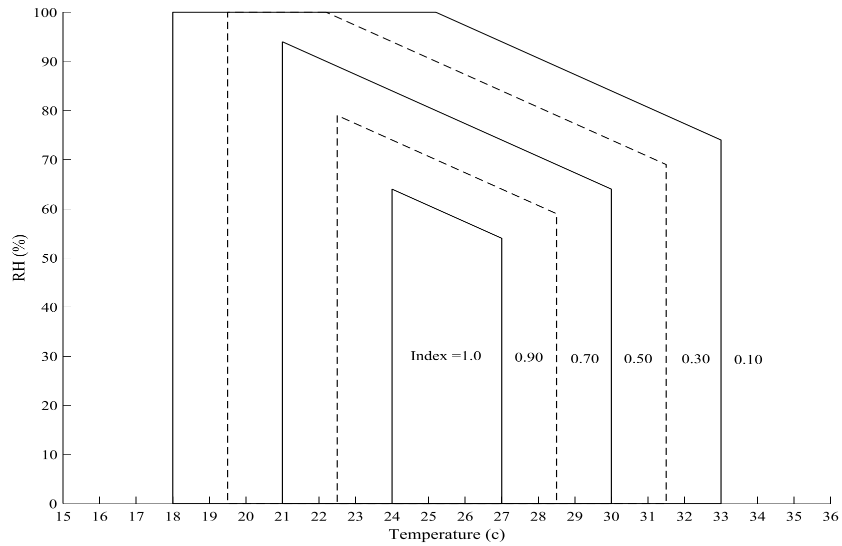

Figure 3-4, Thermal comfort index for summer (Category A)

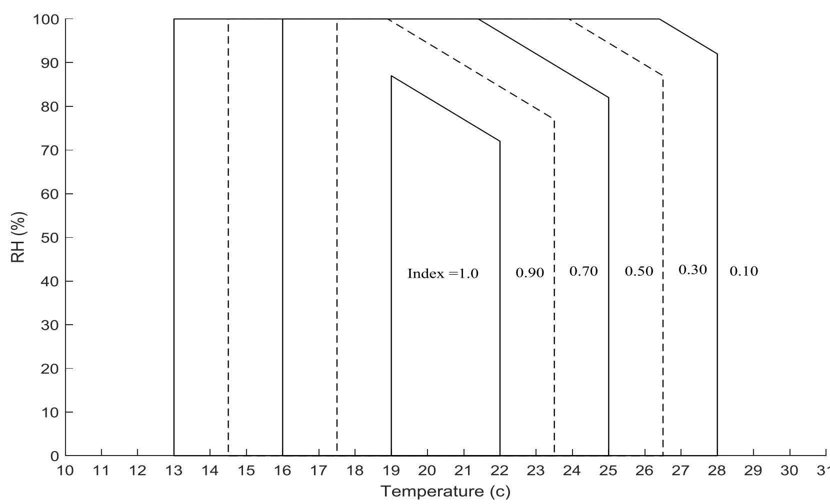

Figure 3-5, Thermal comfort index for winter (Category A)

The second criteria that could impact thermal comfort zones in transit vehicles (in comparison with buildings) is travel duration. Since rail journey is not long, particularly in case of urban railway, EN 14750-1 categorizes railway trips into two groups: less or higher than 20 minutes and assigns

1 °C flexibility for minimum temperature in winter and 3 °C for maximum temperature in summer. Following this standard, 10% flexibility could be considered for maximum RH in the summer. Therefore, a similar approach is considered for short urban railway trips with an average travel time around half an hour to address the impact of exposure time (Category B).

Vibration

Vibrations are associated with different responses and sensations in commuters' subject to environmental conditions and commuters' characteristics (Barone et al. 2016). As such, many factors contribute to determining the degree to which discomfort may be noted or tolerated. Direction, frequency, magnitude, and duration are the main factors contributing to vibration discomfort (Griffin 1990). According to ISO 2631-1 (1997), an index for the level of vibration can be determined by the root-mean-square (r.m.s) of the instantaneous vibration corresponding to the exposure time (Equation 3-4). BS 6841 (1987) and ISO 2631-4 (2001) standards for comfort, use frequency-weighted accelerations to establish a measure for the response from the human body. These standards apply a vertical *(W_b)* and lateral-longitudinal (W_d) weighting system to index acceleration. On that basis, the overall vibration could be estimated through Equation 3-4:

$$a_v = \sqrt[2]{(k_x\, a_{wx})^2 + (k_y\, a_{wy})^2 + (k_z\, a_{wz})^2} \tag{3-4}$$

Where a_{wx}, a_{wy}, and a_{wz} are the frequency-weighted *r.m.s.* acceleration in (m/s^2) along x, y and z directions, and k_x, k_y, and k_z are multiplying factors with respect to the orthogonal x, y, and z-axis, respectively. ISO 2631-1 (1997) suggests multiplying factors of k_x =1.0, k_y =1.0, and k_z = 1.0 for seated passengers respecting comfort issues.

A customized Vibration Index (V_I) is presented in Equation 3-5 for whole body vibration based on ISO 2631-1(1997) recommendations as a function of measured acceleration in rail transit vehicles. Also, the effect of exposure time on vibration comfort in transit vehicles has not yet been investigated (ISO 2631-4 2001), therefore, a same group of indexes is defined for both category A and category B.

$$V_I(A\&B) = \begin{cases} 1.00 & \mathrm{a_v}\ (\mathrm{m}/\mathrm{s}^2) \leq 0.315 & \text{Extremely Comfortable} \\ 0.90 & 0.315 < \mathrm{a_v}\ (\mathrm{m}/\mathrm{s}^2) \leq 0.500 & \text{Very Comfortable} \\ 0.70 & 0.500 < \mathrm{a_v}\ (\mathrm{m}/\mathrm{s}^2) \leq 0.750 & \text{Comfortable} \\ 0.50 & 0.750 < \mathrm{a_v}\ (\mathrm{m}/\mathrm{s}^2) \leq 1.000 & \text{Fair} \\ 0.30 & 1.000 < \mathrm{a_v}\ (\mathrm{m}/\mathrm{s}^2) \leq 1.250 & \text{Uncomfortable} \\ 0.10 & 1.250 < \mathrm{a_v}\ (\mathrm{m}/\mathrm{s}^2) \leq 2.000 & \text{Very uncomfortable} \\ 0.00 & 2.000 < \mathrm{a_v}\ (\mathrm{m}/\mathrm{s}^2) & \text{Extremely uncomfortable} \end{cases} \tag{3-5}$$

Discomfort could be underestimated by using an average r.m.s value as passenger's comfort could be influenced by peak values of acceleration (ISO 2631-1 1997). Therefore, railway companies use statistical methods to take into account variation in vibration (ISO 10056 2001).

Auditory Comfort

The sound could be described and assessed qualitatively and quantitatively. Loudness can be assessed qualitatively based on people's experience and perception of noise. It can also be measured quantitatively in decibels. Noise exposure is a function of two main factors: (1) the frequency-weighted exposure level, measured in A-weighted decibels (*dBA*), and (2) the exposure duration. For hearing loss protection, the World Health Organization (WHO) (Berglund 1999) and U.S. Environmental Protection Agency (EPA) (1974) recommended a maximum daily equivalent A-Weighted sound level of 70 *dB* for 24 hours, and with the same energy contained, a level of 75 *dB* for 8 hours. The same trend could be used to find maximum health thresholds for shorter exposure time such as 3 hours (80 *dB*) and 30 minutes (90 *dB*) (Neitzel 2009). Nagano and Horikoshi (2001) and Yang and Kang (2005) concluded that a sound threshold for the human comfort of less than 50 (*dBA*) satisfies most individuals. Based on such thresholds, Equations 3-6 and 3-7 correspond to the Noise Index (N_I) according to the equivalent continuous A-weighted sound pressure level (LAeq (*dB*)) to comfort levels for categories A and B, respectively.

$$N_I(A) = \begin{cases} 1.00 & LAeq(dB) \leq 50 \\ 0.90 & 50 < LAeq\ (dB) \leq 60 \\ 0.70 & 60 < LAeq\ (dB) \leq 65 \\ 0.50 & 65 < LAeq\ (dB) \leq 70 \\ 0.30 & 70 < LAeq\ (dB) \leq 75 \\ 0.10 & 75 < LAeq\ (dB) \leq 80 \\ 0.00 & 80 < LAeq\ (dB) \end{cases} \tag{3-6}$$

$$N_I(B) = \begin{cases} 1.00 & LAeq\ (dB) \leq 60 \\ 0.90 & 60 < LAeq\ (dB) \leq 70 \\ 0.70 & 70 < LAeq\ (dB) \leq 75 \\ 0.50 & 75 < LAeq\ (dB) \leq 80 \\ 0.30 & 80 < LAeq\ (dB) \leq 85 \\ 0.10 & 85 < LAeq\ (dB) \leq 90 \\ 0.00 & 90 < LAeq\ (dB) \end{cases} \tag{3-7}$$

Visual Comfort

Visual comfort mainly comes from light levels, contrast, and glare. Guidelines and standards such as (ISO 8995 2002; DiLaura et al. 2011; and NSW 2014) recommend a minimum level of 300 *lux* for common seating areas for reading purposes, and 75 *lux* as a minimum lighting level for passengers safety and health (EN 13272 2012). Equation 3-8 and 3-9 provide a Lighting Index (L_I) as a function of (*lux*) level for categories A and B, respectively:

$$L_I(A) = \begin{cases} 1.00 & lux \geq 300 \\ 0.90 & 300 > lux \geq 250 \\ 0.70 & 250 > lux \geq 200 \\ 0.50 & 200 > lux \geq 150 \\ 0.30 & 150 > lux \geq 75 \\ 0.10 & lux < 75 \end{cases} \tag{3-8}$$

$$L_I(B) = \begin{cases} 1.00 & lux \geq 250 \\ 0.90 & 250 > lux \geq 200 \\ 0.70 & 200 > lux \geq 150 \\ 0.50 & 150 > lux \geq 100 \\ 0.30 & 100 > lux \geq 75 \\ 0.10 & lux < 75 \end{cases} \tag{3-9}$$

Air quality

Indoor Air Quality (IAQ) could be impacted by different factors including type and concentration of pollutants in the air, outdoor conditions, and indoor cleanness. A commonly used indicator for IAQ is the level of Carbon Dioxide (CO_2) present in a given space. A CO_2 level assessment in the cabins of Seoul metropolitan metro showed that there is a high correlation between the CO_2 levels and the number of passengers, which could reach up to 4000 Parts Per Million (*ppm*) in rush hours (Kwon 2010). ASHRAE Standard 62 (2001) recommends that indoor levels of CO_2 should not exceed 700 *ppm* above the outdoor ambient air, which means typically a level between 300 and 400 *ppm*. CO_2 levels beyond 1000 *ppm* correspond to an unsatisfactory human experience and higher health risks.

IRC (2005) showed that for a range of 470 to 1100 *ppm*, there was a direct relationship between CO_2 concentration and human satisfaction; in cases when CO_2 concentrations were less than 650 *ppm* more people expressed satisfaction. Satish et al. (2012) assessed direct effects of increased CO_2 on decision making capability of twenty-two participants for a 2.5 hours exposure time. Moderate and statistically significant decrements in six of nine scales of decision-making performance were observed between 600 *ppm* and 1,000 *ppm* CO_2 levels. Equations 3-10 and 3-11 present an indoor Air Quality Index (A_I) using CO_2 levels (*ppm*) considering the above-mentioned thresholds for each category:

$$A_I(A) = \begin{cases} 1.00 & CO_2(ppm) \leq 600 \\ 0.90 & 600 < CO_2(ppm) \leq 700 \\ 0.70 & 700 < CO_2(ppm) \leq 800 \\ 0.50 & 800 < CO_2(ppm) \leq 900 \\ 0.30 & 900 < CO_2(ppm) \leq 1000 \\ 0.10 & CO_2(ppm) > 1000 \end{cases} \tag{3-10}$$

$$A_I(B) = \begin{cases} 1.00 & CO_2(ppm) \leq 1000 \\ 0.90 & 1000 < CO_2(ppm) \leq 1100 \\ 0.70 & 1100 < CO_2(ppm) \leq 1200 \\ 0.50 & 1200 < CO_2(ppm) \leq 1300 \\ 0.30 & 1300 < CO_2(ppm) \leq 1400 \\ 0.10 & CO_2(ppm) > 1400 \end{cases} \tag{3-11}$$

Overall condition index

Overall Index (O_I) of comfort for each journey could be estimated based on a weighted geometric average of the above-mentioned indices (Equation 3-12). In comparison to an additive weighting approach, the geometric average has the advantage of highlighting the extreme discomfort conditions.

$$O_I = \left[\prod_{j=1}^{J} (I_j)^{\alpha_j}\right]^{1/\sum_{j=1}^{J} \alpha_j} \tag{3-12}$$

where α_j is the weight corresponding to comfort index j that reflects criticality of each comfort factor. However, similar to American or Canadian infrastructure report cards (ASCE 2017; CIRC 2016), this study proposes a qualitative grading system based on the overall comfort index particularly for communication with non-technical stakeholders (Equation 3-13).

$$O_I = \begin{cases} Very\ comfortable & Index \geq 0.90 \\ Comfortable & 0.90 > Index \geq 0.70 \\ Fair & 0.70 > Index \geq 0.50 \\ Uncomfortable & 0.50 > Index \geq 0.30 \\ Very\ uncomfortable & 0.30 > Index \end{cases} \tag{3-13}$$

3.4 CASE STUDY AND DATA COLLECTION

The metro system in Montreal city is selected as a case study. The *Société de Transport de Montréa* (Montreal Society of Transportation) (STM) recently celebrated its 50th anniversary (Figure 3-6 and Table 3-2). The network includes 4 lines: Green, Orange, Blue, and Yellow with 68 stations (73 platforms). It is one of the busiest metro networks in North America with over 430 million trips per year in 2017 (STM 2019). STM has started to replace the old MR-63 cars, which date back to 1966 by new MPM-10 (named AZUR) mostly in the Orange line and recently in the green line. New cars are benefited from acoustic environment, innovative lighting, and pneumatic suspension system to present more comfortable environment (STM 2017). The Yellow line connects only two stations to the network and has a low rate of ridership; therefore, data were not collected for this line. Below is an overview of the main routes (Green, Orange, and Blue) in this network.

Figure 3-6, Montreal metro system map (STM 2019)

Table 3-2, Overview of Montreal metro system

Line	Green	Blue	Yellow	Orange
Length (km)	22.1	9.7	4.25	30
Number of Platforms	27	12	3	31
Ridership (Entries)	99,551,806	25,410,817	9,517,996	114,728,719

3.4.1 Green Line

This line has started in 1966 with 10 stations connecting Montreal city west to east. Later, at the end of 1980, the blue line was extended to 27 stations (platforms) from *Angrignon* to *Honoré-Beaugrand*. MR-63 cars are still operational in this line since 1966; however, by extension of this line, the MR-73 type has been added.

3.4.2 Orange line

The longest line in Montreal with 31 stations and the highest rate of ridership was initially launched in 1966 with 15 stations. It was extended on two occasions in 1980 and 2007 and now connects north-west (*Côte-Vertu*) to north-east (*Montmorency*) crossing the downtown. Currently, two different types of cars -old (MR-73) and new (MPM-10)- are working in this line simultaneously. That creates the possibility to verify the proposed model by comparing comfort factor observations for these vehicles.

3.4.3 Blue Line

The blue line was put into service from 1986 to 1988 and this west (*Snowdon*) to east (*Saint-Michel*) line, covers north areas in the city and has two connections to the orange line. MR-73 cars are used to transfer passengers in this line, which has 12 stations (STM 2017).

3.4.4 Data collection methods

In our case study, RH (%), temperature (°*C*), acceleration (m/s^2), noise (LAeq (*dB*)), CO_2 (*ppm*) and lighting (*lux*) are measured for the above three lines and for both new and old cars during winter and summer seasons. Accelerations are collected using a smartphone (iPhone 6). The use of a smartphone as a tool to collect vibration data is a promising alternative because of its low cost and easy to use features (Douangphachanh 2013; Scholotjes 2014). Acceleration in three dimensions of x, y and z is measured by Graphical app (Vernier, 2017), which observes 50 times per second. As per ISO 2631-4 (2001) recommendations for fixed-guideway transit systems, measurement at the seat/body interface was selected for collecting acceleration signals. Frequency-weighted acceleration was estimated by running MATLAB script (Irvine, 2013) based on ISO 2631. On that basis, measured vibration values are characterized in reference to 95 percent of the weighted r.m.s for 5-second time intervals. As mean measured signals are removed in process of estimating frequency-weighted acceleration, therefore any phone noise is removed from data. Data collection for thermal, lighting, noise and CO_2 levels are done using NODE+ (Variableinc 2017) -with a rate of one observation per second-and also Casella (Casella 2017), and Vaisala (Vaisala 2017) devices. Data were collected at various dates of the year as well as different times of the day in the year 2017.

3.5 RESULT AND DISCUSSION

The main findings of this study could be summarized as follows with respect to targeted comfort factors:

3.5.1 Vibration comfort

Figure 3-7 presents the 95 percent of the total weighted r.m.s acceleration signals of an old car in Green line (*Angrignon* to *Honoré-Beaugrand*) for 5-second time intervals. As presented in this figure, a similar repeated trend is followed in this journey, which shows changing acceleration between every two stations and is directly influenced by the speed of metro car. Therefore, when metro is passing the city center (i.e. at times between 15 and 20 min), where stations are closer, and as such, metro cars cannot reach a higher speed, we could observe lower acceleration values. Figure 3-8 shows the fluctuation of corresponding vibration index during this journey, showing a more desirable vibration index for the downtown area.

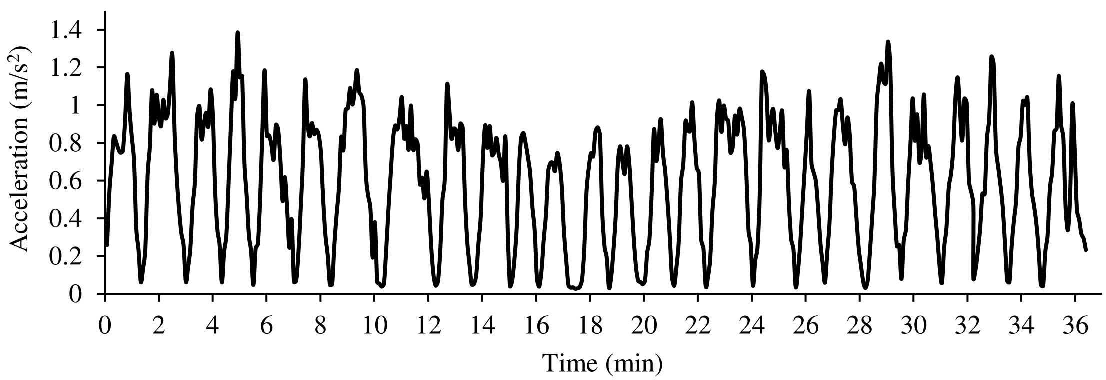

Figure 3-7, One sample total frequency-weighted acceleration in Green line

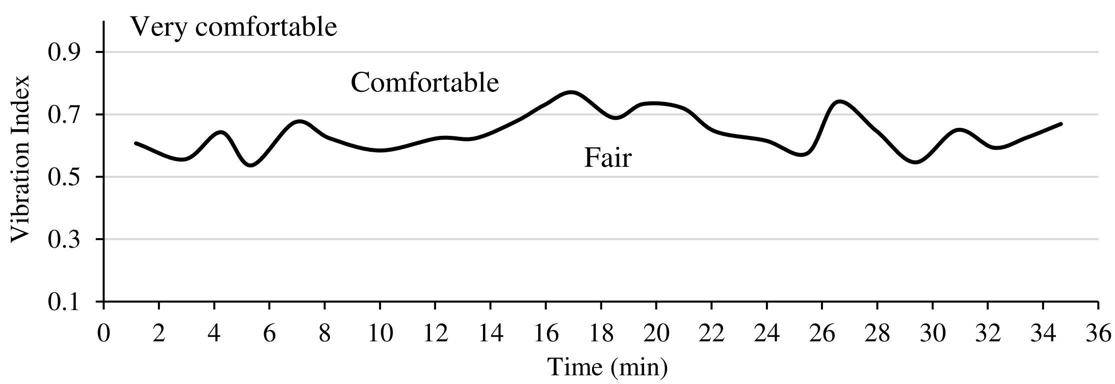

Figure 3-8, Vibration index for same sample journey in Figure 3-7

Figure 3-9 compares vibration indices for representative old and new cars operating in the Orange line (*Montmorency* to *Côte-Vertu*). It can be observed that the new car exhibits better comfort condition throughout this line. In this figure similar fluctuation has been observed for both car types. Considering the distance between stations, one can conclude that the fluctuations are mostly resulted from variations in car speed. Therefore, an inspection team could examine the track by running the car at constant speed to find the track condition and in the next step, inspect the vehicles to assess the performance of each car or wagon in terms of vibration.

Figure 3-10 shows the vibration index trends for another sample (*Snowdon* to *Saint-Michel*) in Blue line. Similar levels of vibration index are observed for this line comparing Green line; however, a slightly higher level of comfort could be observed in this sample journey.

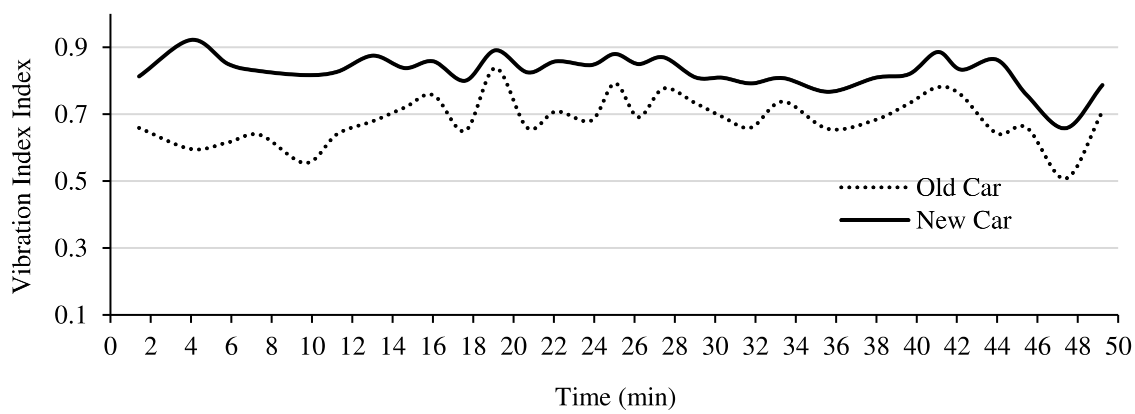

Figure 3-9, Comparing vibration index for one sample of old and new cars in Orange line

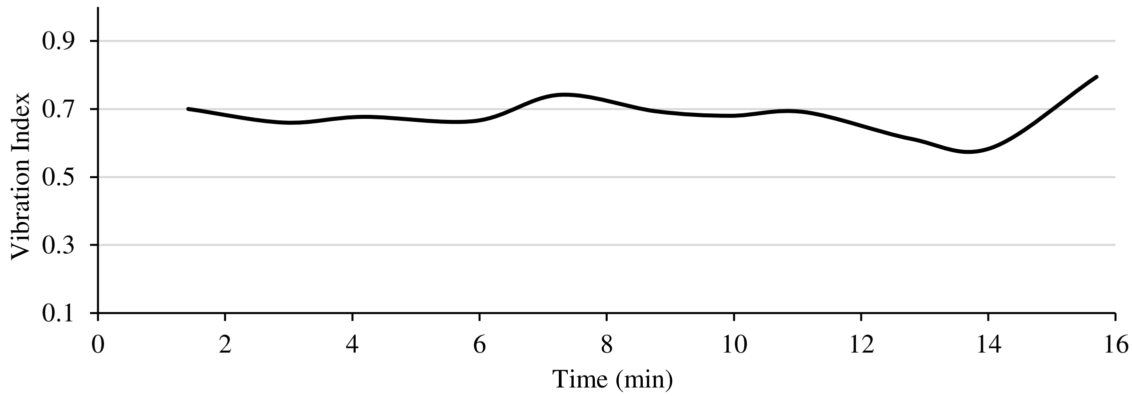

Figure 3-10, One sample vibration index in Blue line

3.5.2 Thermal Comfort

Figure 3-11 presents thermal (temperature and RH) observations for one sample journey in the Green line, in the path towards downtown (*Angrignon* to *McGill*) in winter. RH (%) fluctuations are associated with the metro-car movement inside the tunnel as well as stops at the stations. In the beginning, the tunnels are closer to the surface and hence colder; however, the temperature increases in the subsequent deeper tunnels and this contributes to dropping of the comfort index values (Figure 3-12).

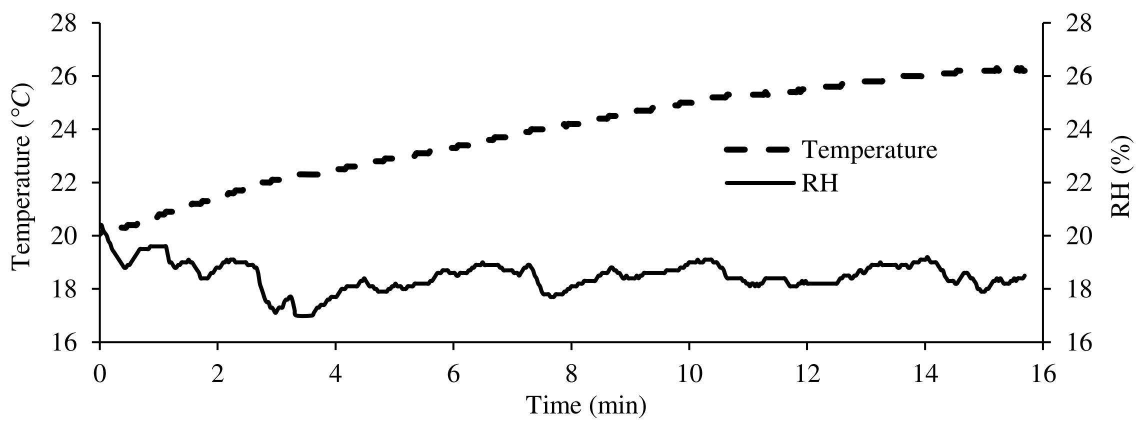

Figure 3-11, One sample temperature (°C) and RH (%) measurement in Green line

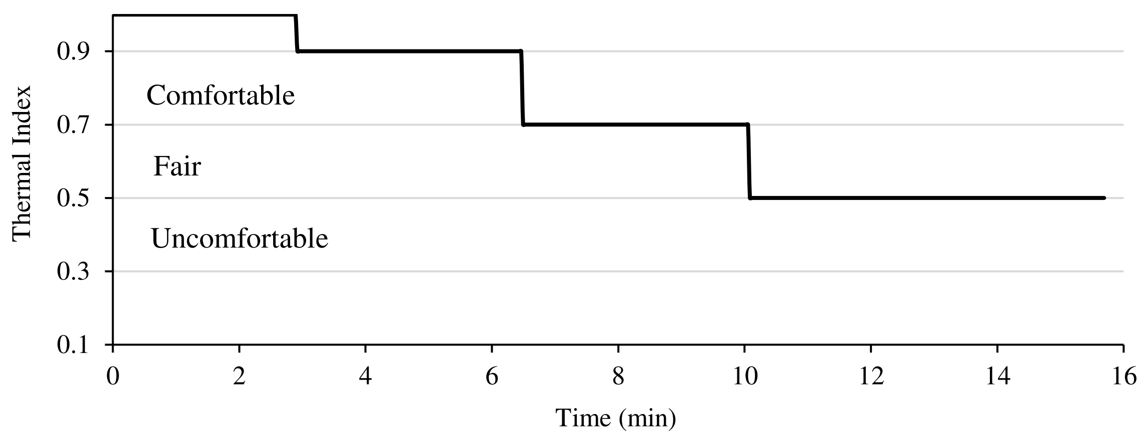

Figure 3-12, Thermal comfort index for same sample journey in Figure 3-11

Another sample journey is selected in Orange line from downtown heading to north-east (*Bonaventure* to *Montmorency*) to further compare old and new cars (Figure 3-13). This sample shows that the old cars have a more uncomfortable thermal condition. Despite improvements, the new cars still present an uncomfortable environment in most situations. There is no separation between wagons in new cars, which allows the air to flow through the vehicles. This contributes to commuters feeling more comfortable in warm weather inside metro vehicles in winter. This is in line with Srivajana (2003) study that showed the fact that in hot and humid climates, higher air velocity is preferable; however, it has not been measured in this study.

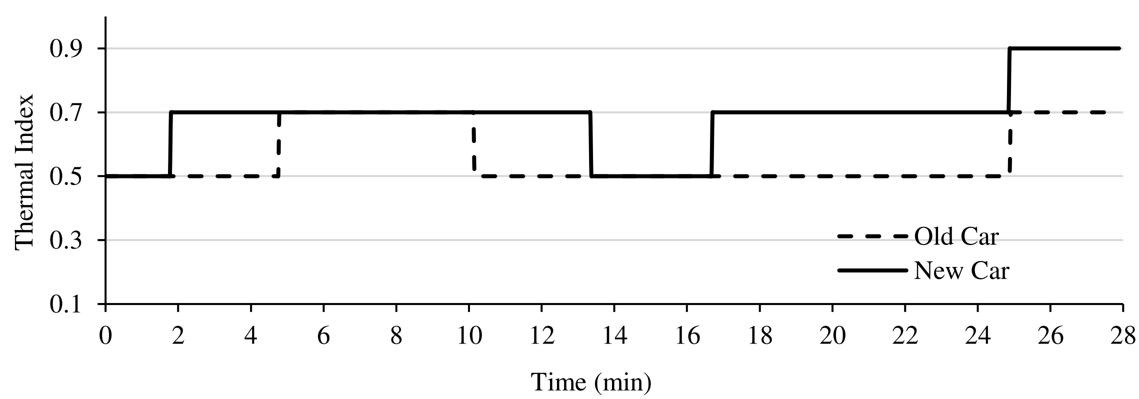

Figure 3-13, Winter comfort index for one sample of old and new cars in Orange line

3.5.3 Lighting, noise, and air quality level

Old cars were found to suffer from low levels of lighting. Measurements showed that there is less than 200 *lux* inside the old vehicles in all routes. The new cars are very bright and easily satisfy the 300-*lux* threshold. LAeq in old and new cars are 75-80 and less than 75 *dB*, respectively. Lower levels of noise can be observed in the downtown area, as cars run slower due to shorter distances between the stations. There is a correlation between crowding and air quality (CO_2), however, even during the rush hour, the level of CO_2 concentration is less than 600 *ppm.* This shows that in comparison with many other metro systems, passengers experience a lower level of density, and thus, higher levels of comfort.

3.5.4 Overall comfort

In this section, lines and cars are compared in terms of different comfort factors to establish an overall level of comfort. For each factor, several observations have been collected in all lines. As such, an average index can be calculated as summarized in Table 3. The results reveal that old cars in the Blue and Green lines have almost similar levels of vibration, while old cars in the Orange line present the lowest level of comfort. In Orange line, higher accelerations for this car type could be resulted depending on vehicle or track conditions. For new cars, the vibration index drops to 0.835. In this case, it could be concluded that track condition has impacted the level of vibration comfort. Two significantly varied levels of thermal comfort in winter and summer were observed. Results for summer show that a higher comfort level can be observed for most of the journeys, while in winter, cars are often overheated and thus uncomfortable. This condition is exacerbated by Montreal's city weather condition, which is very cold in winter and moderate in summer. During winter due to the level of clothing, a lower temperature is preferable, while in most journeys the monitored temperature was higher than 25°C.

Table 3-3, Comfort assessment summary results for Montreal metro

Line	Green	Blue	Orange (Old Car)	Orange (New Car)
Vibration (*v*)	0.67	0.69	0.61	0.83
Thermal Winter (*t*)	0.46	0.43	0.60	0.64
Thermal Summer (*t*)	0.97	0.97	0.99	0.99
Noise (*n*)	0.60	0.60	0.57	0.70
Lighting (*l*)	0.60	0.51	0.63	1.00
Air Quality (*a*)	1.00	1.00	1.00	1.00

Observations also show that new cars are not associated with a high level of noise comfort and only a slight difference was observed between old and new cars. As seen in the above, the old cars could not provide comfortable levels of lighting, while new cars provide a more comfortable environment for reading. As it was discussed earlier, air quality is not a critical concern for the level of comfort in this case study.

Basically, it is not easy to establish a weighting system to combine comfort indices and arrive at an overall comfort index (O_I) as the passengers' preferences could vary greatly subject to age, gender, travel distance, etc. Thus, a sensitivity analysis is conducted to elaborate further on the impact of different weighting approaches that can be adopted for calculation of O_I. This has been done for a sample winter journey in the Orange line (*Montmorency to Cote-Vertu*) aboard the old car (Figure 3-14). As it can be seen from Figure 3-14, weighting scenarios could change the value of O_I in this sample journey and using equal weights led to highest overall comfort levels.

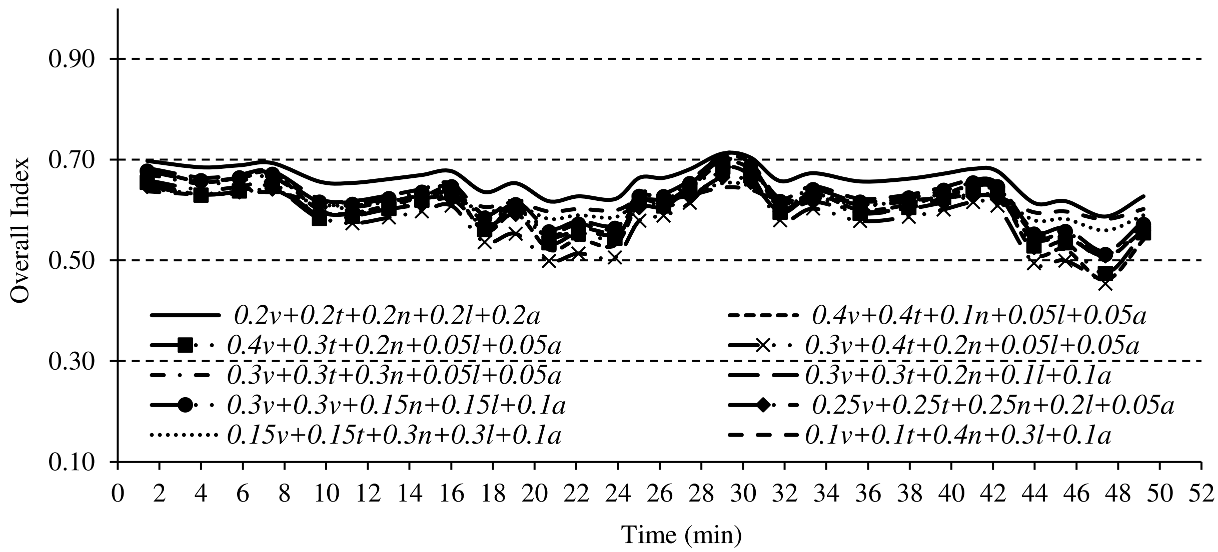

Figure 3-14, Sensitivity analysis for weighting comfort factors

3.6 MODEL VALIDATION

As the model was used to compare new and old cars with respect to different factors; a questionnaire was also designed to conduct a survey of Montreal metro passengers for verification purposes. Commuters in the Orange and Green lines were asked to evaluate old and new cars in terms of comfort factors in five qualitative levels from very comfortable to very uncomfortable. 230 and 263 surveys were collected for old and new cars, respectively. To verify the model outputs and compare them with the outcomes of the survey, scores of 0.90, 0.70, 0.50, 0.3, and 0.10 were assigned respectively to very comfortable, comfortable, fair, uncomfortable, and very uncomfortable qualitative judgment to convert survey responses to numerical values.

To reflect on the relationship between the age of respondents and the comfort preference, the survey targeted two groups of passengers; less and more than 40 years old. It is revealed that 71.4% of participants were less than 40 Years (Y). Almost equal Males (M) (52%) and Females (F) (48%) participated in this survey. However, the survey results show that females assigned lower thermal comfort index to old cars. Youngers mostly complained about noise in both old and new cars, which comes from their higher sensitivity to sound level. Also, impact of noise while listening to music, a popular choice in urban journeys, is another reason for this feedback. Surprisingly, metro riders ranked air quality in uncomfortable levels in old cars while almost same scores are observed for thermal and air quality in both car types. Although it was clarified that thermal reflects temperature-humidity and air quality means fresh air, it possibly comes from mixing these two factors by interviewers (Table 3-4).

Furthermore, when passengers asked to select the most important comfort factor, the thermal and air quality factors were given the highest weight. Further, comparing males and females' preference shows that females ranked thermal and air quality factors much more than males, while vibration has the highest rank for male (Table 3-4).

Table 3-4, Online survey feedback summery

Comfort Factor	Old Cars					New Cars			W (%)				
	< 40	> 40	Ave.	M	F	< 40	> 40	Ave.	M	F	< 40	> 40	Ave.
Vibration (v)	0.49	0.53	0.51	0.50	0.50	0.75	0.78	0.76	26.13	15.79	21.18	14.08	17.63
Thermal (t)	0.45	0.46	0.46	0.49	0.42	0.71	0.74	0.72	21.62	30.70	27.06	33.80	30.43
Noise (n)	0.39	0.46	0.42	0.41	0.41	0.64	0.71	0.68	17.12	15.79	19.41	14.08	16.75
Lighting (l)	0.52	0.54	0.53	0.51	0.53	0.79	0.77	0.78	6.31	7.02	5.29	7.04	6.17
Air Quality (a)	0.43	0.44	0.44	0.45	0.42	0.69	0.72	0.70	28.83	30.70	27.06	30.99	29.02

By considering a 95% confidence level and a 3% margin of error (α), the maximum observed Standard Deviation (SD) (δ) (i.e. 0.214) for lighting index in old cars, and using Equation 13, the

N (sample size) would be estimated at 195 samples, which is less than the number of collected survey responses:

$$N = (\frac{1.96}{\alpha} \times \delta)^2 \tag{3-14}$$

Table 3-5 provides a comparison of survey and model results for old and new cars. Since 100% satisfaction is not achievable, in the most comfort factors, the model estimated higher index as was expected. The survey was done in winter; therefore, thermal comfort assessment for this season is compared with feedback. Thermal factor in new cars should be increased considering airspeed as was discussed earlier and that probably caused higher grades for air quality in the new cars. However, a more accurate judgment could be done in future have both summer and winter survey feedbacks and considering airspeed. Although a higher standard level of lighting (300 *lux*) is prepared in all new cars, still some commuters are not fully satisfied. Only CO_2 is measured in this research for air quality assessment; however, in future studies, more indicators could be assessed.

Comfortability and uncomfortably in one or more factors could influence others due to mutual relations and it could be seen in this table that similar scores are assigned for all factors in each type of car by commuters. In new cars, riders experience the more comfortable environment in most factors and the mutual relation among factors possibly resulted in scoring higher noise level by commuters. The overall level of comfort is estimated based two weighting systems; equal weights and survey-based weights as reflected in Table 3-5.

Table 3-5, Comparing model and survey outputs (comfort indexes)

Comfort Factor	Old Cars		New Cars	
	Model	Survey	Model	Survey
Vibration (*v*)	0.66	0.51	0.83	0.76
Thermal (*t*)	0.50	0.46	0.64	0.72
Noise (*n*)	0.59	0.42	0.70	0.68
Lighting (*l*)	0.58	0.53	1.00	0.78
Air Quality (*a*)	1.00	0.44	1.00	0.70
Overall (Average)	0.64	0.47	0.82	0.73
Weighted Overall (Survey feedback)	0.66	0.46	0.80	0.72

3.7 CONCLUSION

A railway vehicle assessment model was proposed in this study to measure metro car performance from a passenger's comfort perspective. This framework could enable transit agencies to quantitatively assess the level of comfort incorporating five critical factors of thermal, vibration, noise, lighting and air quality. Applying the model to Montreal metro system confirmed that old cars bring a "Fair" level of comfort for different factors in comparison with new cars, which prepare "Comfortable" environment. Vibration is mostly influenced by car speed; however, new cars braking, and damping systems could control vibration more efficiently. The thermal assessment indicates that higher levels of clothing and overheated environment inside vehicles create less comfortable conditions for riders in winter in all car types. Although, the new cars noise level is graded higher in comparison to old cars; however, as a brand-new vehicles insulation system should work more efficiently. A direct correlation between crowding and air quality (CO_2) was observed. However, passengers generally experience a low level of density and CO_2 in Montreal metro system compared to other major metro systems. A survey of a large sample of passengers provided a verification of the results from the model and revealed the interdependency among comfort factors. Overall, the passengers considered the thermal and air quality as the most important comfort factors in Montreal metro cars, while they are not satisfied by old cars and assigned a comfortable rank to new ones.

The findings of the above assessment could provide feedback and insight for decision-making as relating to budget allocations for maintenance and rehabilitation of both cars and track assets. Also, comfort measurements could be applied to the transit modal choices analysis to promote public transport. The proposed model is applicable to railway systems (underground and surface) and could be extended for applications in other transit systems such as bus-rapid or Tramways.

Chapter 4 : METHODOLOGY (MODEL II)

OPTIMIZING TRANSIT MAINTENANCE AND REHABILITATION TO SUPPORT HUMAN DEVELOPMENT AND SUSTAINABILITY: A CASE STUDY OF COSTA RICA'S RAILROAD NETWORK

This chapter presents a decision-making model to governments and municipalities for objectively distributing the maintenance and upgrading budget among urban railway alternatives that respond to the improving level of service as well as various dimensions behind human development and sustainability. This chapter is published by International journal of sustainable transportation:

Mohammadi, A., Elsaid, F., & Amador-Jiminez, L. (2018). Optimizing transit maintenance and rehabilitation to support human development and sustainability: A case study of Costa Rica's railroad network. International Journal of Sustainable Transportation, 1-14.

Abstract: Public transportation plays a critical role in improving human development and consequently the 17 Sustainable Development Goals (SDGs) set by United Nations. Convenient and efficient transit enable inhabitants to reach labor markets, access social support facilities as well as health and education services. This study develops a decision-making support framework for transit agencies to select optimum maintenance, rehabilitation and upgrade alternatives to accomplish good levels of service and improve human development and sustainability indexes. A case study of Costa Rica's great metropolitan area is used to illustrate the study with various budget scenarios. The results show that the proposed system can accomplish significant improvements on both: level of service and human development. It is also confirmed that the explicit consideration of human development and sustainability made a significant difference as compared to the classical approach, which only considers the Level of Service (LOS). The proposed model could be used by other public transit systems.

4.1 INTRODUCTION

Network condition and travelers' satisfaction factors such as travel cost, travel time, comfort, and safety are critical to transit asset management concerns. Traditional decision-making frameworks have been increasingly revised in attempts to reflect some of these issues on budget allocation aimed at improving LOS. This classical approach has been applied and matured cross time since the 1980s. However, such planning neglects sustainable goals, which infrastructure asset managers are expected to encourage in order to boost human development (Wu et al. 2012).

Human development is concerned with nurturing human capabilities of the residents through active participation in processes that improve and shape their lives (UNDP 2016). There is a mutual relation between human development and sustainability and these two concepts share much in common (e.g. poverty, good health, gender equality, and quality education). Human development is in principle what sustainability proponents demand to sustain (Neumayer 2012).

Sustainable transportation plays a critical role in human development and its improvement. Through economic growth; job creation and reduces poverty; providing access to markets and health; empowerment of women and equality in gender, and the well-being of persons with disabilities and other vulnerable groups as per the 17 Sustainable Development Goals (SDGs) (UN 2016a; UN 2016b) (Figure 4-1).

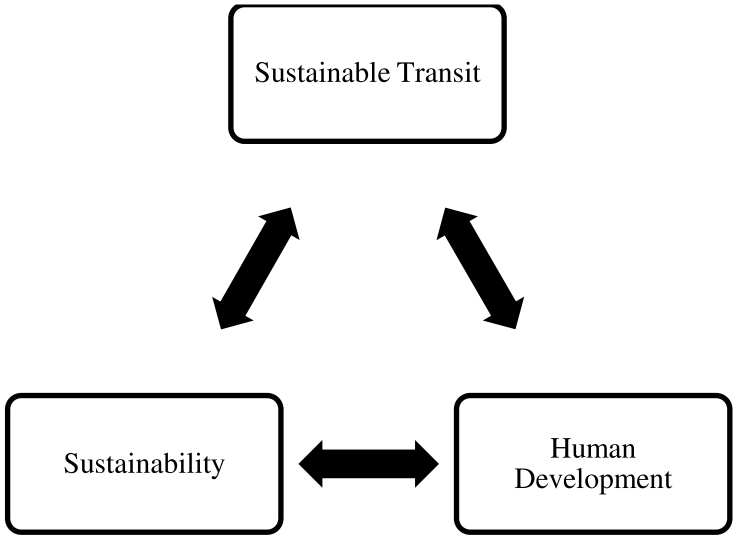

Figure 4-1, Sustainable transit impact on sustainability and human development

A sustainable transport system should be convenient and economically accessible. A safe, secure, resilient, and efficient transportation is vital in middle and low-income nations. Human development issues and sustainability challenges are commonly addressed in transportation projects that seek the expansion of the network while developers try to accomplish SDGs through the modeling of demand and future needs. Although transit-oriented objectives, such as LOS, play a critical role in classical decision-making for existing transportation networks; they could also be managed in order to improve sustainability in the regions served. The most cost-effective alternatives could be selected by transit asset managers in maintenance and rehabilitation plans to improve LOS as well as to advance human development and sustainability.

4.2 LITERATURE REVIEW

Despite this significant potential, sustainable transport has not been given adequate recognition (UN 2016b). Many types of research proved the role of mature transportation in developing sustainable factors such as environment, health, employment, and poverty. For instance, the impacts of expanding public transit on traffic congestion, air, and noise pollution are undeniable in the literature. Syed et al. (2013) conducted a systematic literature review of 61 studies in the U.S. to investigate the association between transportation barriers and health care issues such as rescheduled or missed appointments; delayed care; and missed or delayed medication use. The study concluded that transportation issues are a significant barrier to healthcare access, particularly for low-income groups. Thomas et al. (2018) studied the association between access to transportation and diabetes care visits. A zero-truncated Poisson regression model was applied to assess the independent effect of using reliable transportation on the number of diabetes care visits. The model showed a positive association between the use of transportation and the number of visits. Grant et al. (2016) conducted a study in Tennessee and Mississippi and concluded that each year 4% of children in the U.S. miss an appointment due to a shortage of transportation. In addition to missed appointments, poor management of chronic conditions, problems with the filling of prescriptions and preventable use of emergency room were reported to be associated with transportation efficiency.

Kenyon (2011) highlighted the effect of poor access to transport and low mobility on education exclusion. The results suggested that inadequate access to transport is a substantial barrier to good achievements in higher education. Economic and human development have been proved to be correlated to the extensiveness of civil infrastructure especially roads (Amador-Jimenez and Willis 2012). Taruna Shalini and Boopen (2011) and Ramadan and Feng (2004) concluded that a transit system is a tool for poverty alleviation in urban environments.

In the meantime, several types of research have proved the positive relation between improving the transportation system and employment rates (Sanchez 1999; He et al. 2014). Thakuriah and Metaxatos (2000) conducted a study to assess the role of transportation and residence location of welfare females in their ability to participate steadily in the labor force. The link between residence and employment locations was analyzed by D. B. Hess (2005) and improving public transit in low-wage jobs regions was recommended. Lichtenwalter et al. (2006) and Fletcher et al. (2010) indicate the role of reliable transportation in providing access to employment for low-income families. Finally, Terenteva et al. (2016) proved the contribution of accessibility to transit systems, job creation and attraction of investors.

The Recent framework developed by Mohammadi et al. (2018c) proposed the creation of a decision-making for fighting poverty through a rescue of an abandoned transit system; however, this model addresses only employment factors. LOS as a critical objective, asset deterioration, and population change are ignored in the analysis.

As seen the state of art supports a direct relation between sustainable transit system and human development; however, there is a lack of a decision-making system that supports its implementation as guided by human development factors and that is capable of helping governments and municipalities to allocate their budgets in a cost-effective manner. The main objective of this study is developing such decision-making framework for transit agencies to select optimum alternatives while addressing LOS and improving human development and sustainability across regions.

4.3 METHODOLOGY

Optimum solutions for transit asset management seeks to prioritize among different alternatives on the basis of common indicators for LOS as are described in Figure 4-2. In addition, sustainable development factors such as poverty, health, education, environment, employment, and gender equality could be part of the decision-making to reflect current/future issues and optimize budget distribution in order to improve LOS as well as sustainability.

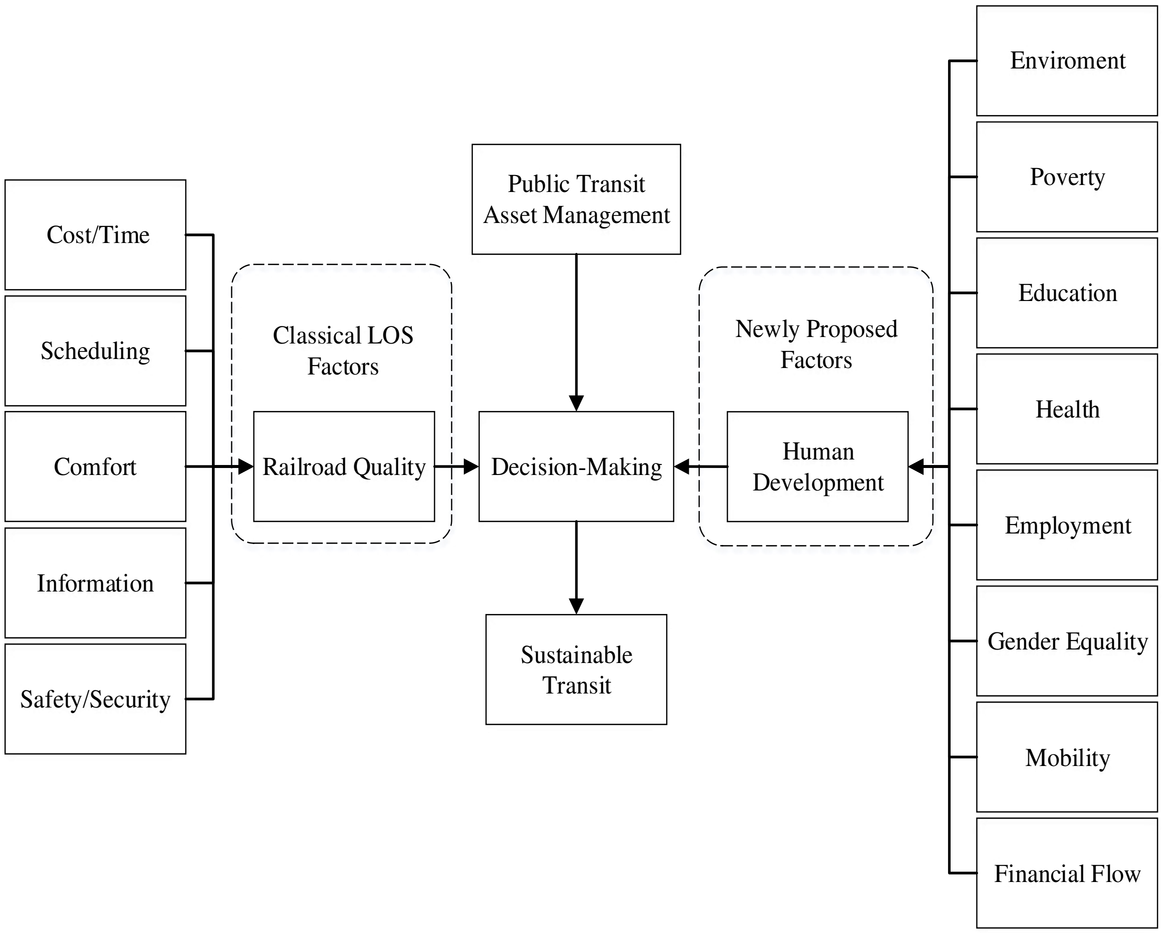

Figure 4-2, Transit asset management decision-making model

Hence, transit planners will assign the budget to improve LOS and public transit could provide cheap, fast, reliable and safe modes for fragile individuals to have better access to the job market, education, and health services while reducing gas emission and air pollution. In this study, human and sustainable development goals are translated into tangible targets that could be optimized through a mathematical framework and give an opportunity to municipalities and governments to objectively distribute available budgets to improve LOS while respecting sustainable development.

4.3.1 Human development assessment

Human development and sustainability in urban and rural communities could be achieved by improving several interdependent indexes, which are defined by UNDP (2016). In terms of transit infrastructure, some goals could be attained by already existing networks through asset management plan that can be proposed by 8 indexes of the environment, poverty, education, health, employment, gender equality, mobility and financial flow in this research. Each region vulnerability respecting these indexes will be assessed and priority in maintenance and rehabilitation tactical/operational planning is given to the most vulnerable districts. Generally, there are complicated relations between socio-economic indicators while improvement or weakness in one indicator could impact on several indexes. For instance, changing in illiteracy rate advances education as well as enhances health knowledge. Therefore, indexes and indicators in this study are defined as global; however, each transit agency could set its own indexes and corresponding indicators considering strategy and policy. Table 4-1 summarizes the main components of human development assessment.

Table 4-1, The main indexes and corresponding indicators for human development assessment

Index	Indicators
Environment	Levels of Air pollution
	Levels of Gas emissions
	Levels of Energy usage
	Percentage of Clean energy usage
Poverty	Poverty gap
	Poverty severity
	Gini index
Education	Rate of public schools per capita
	Average years of schooling
	Illiteracy rate
	Number of students in the upper degree
Health	Rate of public hospitals per capita
	Life expectancy
	Mortality rate for less than 5 years of age
	Percentage of insured people
	Percentage of population with disability
Employment	Unemployment rate
	Job Accessibility
Gender equality	Female/male ratio in illiteracy
	Female/male ratio in high education level
	Female/male ratio in morality
	Female/male ratio in income
	Female/male ratio participating in the labor force
Mobility	Number of international students
	Internet users
	Immigration rate
	Number of Tourists
Financial Flow	Region export/import
	Region investment rate
	Agricultural area

Mathematical approach

This study uses a common and easy to understand mathematical approach to estimate indicators and indexes in a hierarchical method. The defined indicators are observed for each region and results are normalized by feature scaling to bring all values into the range [0,100] in order to be comparable. Zero indicates the lowest level of sustainability and highest priority for improving public transit. For instance, the region with the highest unemployment rate will be scored zero. (Equation 4-1).

$$\tilde{X}_{i,j,r} = 100 \times \frac{(x_{i,j,r} - xmin_{i,j})}{(xmax_{i,j} - xmin_{i,j})} \quad or \quad 100 \times \left(1 - \frac{(x_{i,j,r} - xmin_{i,j})}{(xmax_{i,j} - xmin_{i,j})}\right) \tag{4-1}$$

Where $\tilde{X}_{i,j,r}$ is normalized indicator *j* for index *i* in region *r*, $x_{i,j,r}$ is the measured variable for indicator *j* in region *r*, $xmax_{i,j}$ and $xmin_{i,j}$ are the maximum and minimum observed value for indicator *j* in all regions. According to Table 4-1, for each region (*r*) in this study, 8 indexes and 30 indicators (*j*) could be estimated. To integrate indicators of each index ($I_{i,r}$), a weighted geometric average (Equation 4-2) could be used, which α_j is the corresponding weight to indicator *j* that reflects the importance degree of each indicator. When all weights (α_j) are the same, it can be simplified as (Equation 4-3):

$$Index_{i,r} = I_{i,r} = \left[\prod_{j=1}^{J} \left(\tilde{X}_{i,j,r}\right)^{\alpha_j}\right]^{1/\sum_{j=1}^{J} \alpha_j} \tag{4-2}$$

$$I_{i,r} = \sqrt[J]{\prod_{j=1}^{J} \left(\tilde{X}_{i,j,r}\right)} \tag{4-3}$$

Estimated indexes for each region should be assigned to public transit projects to be analyzed in the decision-making approach (Figure 4-3). Thus, an averaging method is defined to transfer regions indexes to the corresponding railroad segment. For this purpose, the population in each region and its distance to public transit are used to reflect the degree of priority and potential benefit. Based on closest distance, region indexes are assigned to each railroad or bus route alternative (segment) as shown in Equation 4-4. Finally, Equation 4-5 calculates the Human Development Index (HDI) for each segment, which will be then used in the optimization model described later.

$$H_{i,s} = \frac{\sum_{r \in R_s}(I_{i,r} \times \frac{P_r}{\mathrm{D}_r})}{\sum_{r \in R_s}(\frac{P_r}{\mathrm{D}_r})} \tag{4-4}$$

$$HDI_s = H_s = \sum_{i=1}^{I} \beta_i \, H_{i,s} \tag{4-5}$$

Where $H_{i,s}$ is human development index i for segment s, $I_{i,r}$ shows estimated index i in region r, P_r reflects population and D_r presents closest distance of the geographical center to transit segment in the region $r \in R_s$, respectively. Regions are assigned to the closest segment to set affected regions group (R_s) for specific segment s. Finally, HDI for each railroad segment (H_s) is estimated by Equation 4-5 respecting the indexes weight (β_i). Figure 4-3 shows a sample railway segment (s) with 4 assigned regions.

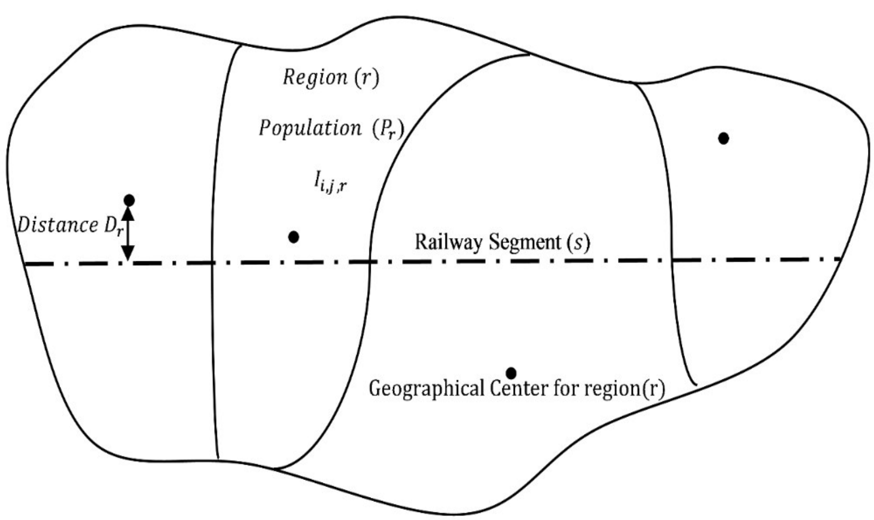

Figure 4-3,Sample railway segment (s) with 4 assigned regions

4.3.2 Serviceability assessment

Each transit alternative (segment) needs to be scored based on classical factors associated to the ability of the railways to provide adequate service, which in turn comes from the overall asset condition, its structural integrity, risk of collapse and perceived ride-smoothness. The literature is rich in serviceability assessment, also refer in some cases beyond the common association to saturation flows, delays and queues at intersections or roadway segments. Level of Service (LOS) assessment (Fraszczyk et al. 2016; Sharma et al. 2016) for one or more factors could be selected to represent transit segment LOS. In this study, one unique index is used. However, it is not the main goal to further characterize or measure the LOS. Hence, $L_{s,t}$ is defined as LOS of segment s in year t.; for which the ranges of 90-100 represent very good, 70-90 Good, 50-70 Fair, 30-50 Poor and 0-30 Very Poor.

4.3.3 Optimization model

A mathematical optimization model is developed to increase LOS while improving human development and sustainability in different regions cross time and achieve optimum benefits in budget distribution and rehabilitation planning. Optimum solutions for each year are chosen by selecting the most cost-effective intervention to public transit segments while respecting the available budget. Dynamic binary linear programming with a decision variable $X_{s,t}$ is used in this study to find the set of best options. The model objective increases both LOS and human development index, which is subjected to the available budget. Each year the decision binary variable ($X_{s,t}$) could be actioned to improve LOS ($Li_{s,t}$) or human development ($Hi_{s,t}$) based on the corresponding applicable treatment, which also considers the decay of LOS ($Ld_{s,t}$) or human development ($Hd_{s,t}$) through time, for each segment. Equations (4-6 to 4-10) present the mathematical approach for optimization model.

$$MAX(\gamma(OHDI_t) + \delta(OLOS_t)) = \gamma \sum_{s=1}^{S}(wl_s \times L_{s,t}) + \delta \sum_{s=1}^{S}(wp_{s,t} \times H_{s,t}) \tag{4-6}$$

With

$$L_{s,t} = X_{s,t}\big(L_{s,t-1} + Li_{s,t}\big) + \big(1 - X_{s,t}\big)\big(L_{s,t-1} - Ld_{s,t}\big) \tag{4-7}$$

$$H_{s,t} = X_{s,t}\big(H_{s,t-1} + Hi_{s,t}\big) + \big(1 - X_{s,t}\big)\big(H_{s,t-1} - Hd_{s,t}\big) \tag{4-8}$$

$$wp_{s,t} = \frac{P_{s,t}}{\sum_{s=1}^{S} P_{s,t}} \quad and \quad wl_s = \frac{l_s}{\sum_{s=1}^{S} l_s} \tag{4-9}$$

Subject to: $0 < \sum_{s=1}^{S} C_{s,t}X_{s,t}l_s \le B_t$ (4-10)

Where:

$$X_{s,t} = \begin{cases} 1 \;\; if\ action\ is\ taken\ on\ segment\ s, in\ \ the\ year\ t \\ 0 \;\; if\ no\ action\ taken\ on\ segment\ s, in\ the\ year\ t \end{cases} \tag{4-11}$$

$OHDI_t$ = Overall HDI in the influenced regions in the year t

$OLOS_t$ = Overall railroad network LOS in the year t

$L_{s,t}$ = LOS of segment s in the year t on a 0 to 100 scale

$H_{s,t}$ = Sustainable development index i of segment s in the year t on a 0 to 100 scale

$C_{s,t}$ = Unitary cost (\$) of rehabilitation action of segment s in the year t

$Li_{s,t}$ & $Hi_{s,t}$= LOS and human development improvement percentage from a year (t-1) to the year t for segment s

$Ld_{s,t}$ & $Hd_{s,t}$ =Dropped portion of LOS and human development percentage from a year (t-1) to the year t for non-selected segment s

wl_s and $wp_{s,t}$ = Show the segment's weight in the network: for LOS based on segment length (l_s) and for human development based on served population ($P_{s,t}$) by segment s in the year t.

γ and δ = Relevant weight for LOS and human development objective, respectively

B_t = Available budget in the year t.

Intervention effectiveness and deterioration for transit infrastructures such as road or railway segment have been commonly studied; however, in this study, it is needed to predict improvement or decay for human development index as a result of railway quality changes. Future research could be done to explore this multi factors relation between transit system and human development in regions.

For the purpose of this study, HDI and railroad quality were collected for more than 120 countries around the world as released by UNDP (2016) and World Bank (2017). Both factors were normalized into a range [0,100] and ranked for the year 2015. Table 4-2 shows the first ten countries in terms of railroad quality, which have higher than 90% HDI. Figure 4-4 shows the direct impacts of transit condition. It compares 126 countries HDI and railroad quality and as it can be seen, the best fitted linear trend could be assigned to these two factors. Therefore, it could be concluded that 10% improvement or decay in LOS could lead to 4.362% impacts on the HDI. This ratio could be customized and precisely defined by transit agencies based on micro-data and local observations.

Table 4-2, The best 10 railroad quality in whole of the world

Railroad Rank	Country	Railroad Quality (%)	HDI (%)
1	Japan	95	90
2	Switzerland	93	94
3	Hong Kong	89	92
4	Spain	82	88
5	Finland	80	89
6	France	80	90
7	Netherlands	78	92
8	Singapore	78	92
9	Germany	76	93
10	South Korea	76	90

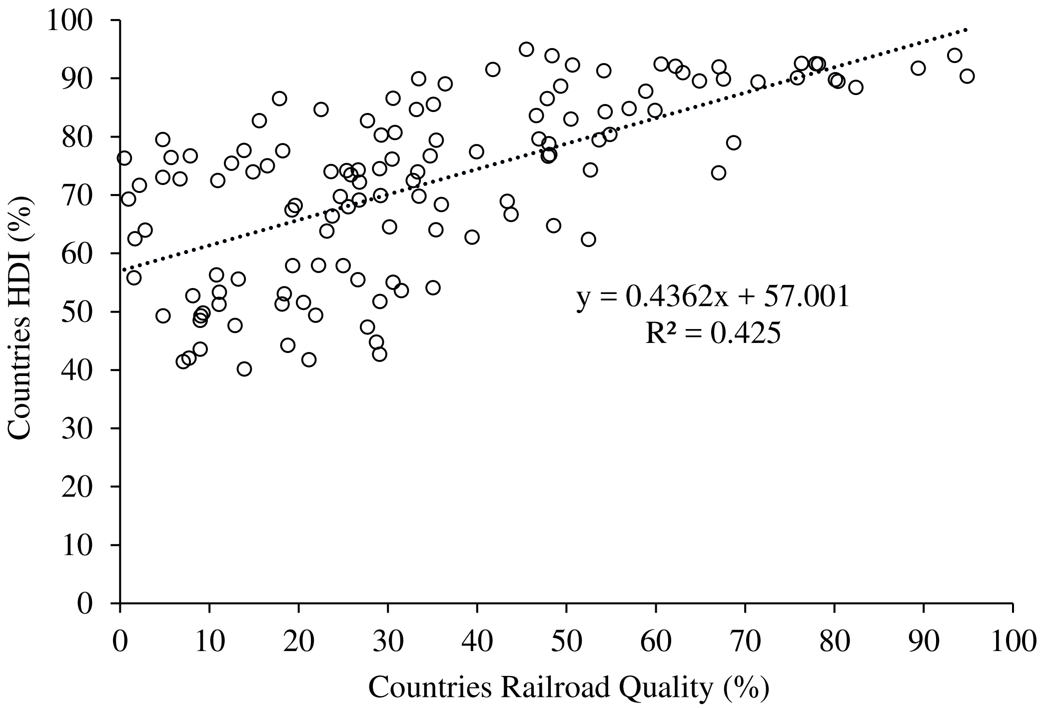

Figure 4-4, Countries railroad quality and HDI comparison

4.4 CASE STUDY AND DATA COLLECTION

This model is applied to Costa Rica railway network (Figure 4-5). This network does not have proper coverage and was closed many years ago. Recently government started the operation and given that the tracks present a high degree of deterioration, reconstruction must be done for each railway segment infrastructure. In a first phase, the tactical question would be which rail segment to be refurbished first in order to improve OLOS as well as regions sustainability. Poorly connected bus routes and road network in this developing country emphasizes the urgent need to boost the old railway network to offer accessibility of cheap, safe, and fast transit mode, particularly for low and middle-income travelers.

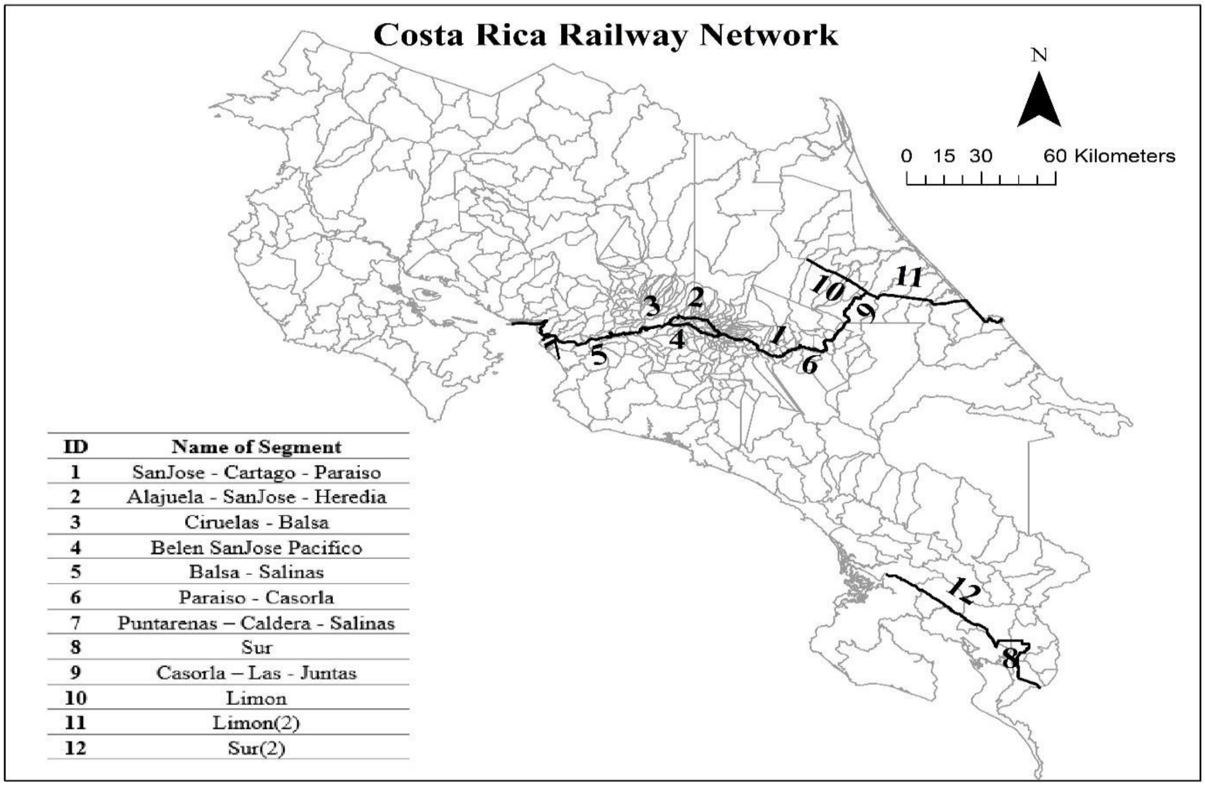

Figure 4-5, Costa Rica railway network

Table 4-3 shows interventions applicability and cost issued as part of the decision-making model based on regional interview and experts' judgment. Minor maintenance includes rail grinding and replacement of damage in rail tracks. Major maintenance concentrates on the horizontal and vertical realignment of a portion of the route, hence involving major changes for the tracks. Reconstruction is required when the need for maintenance has been ignored leading to full sections exhibiting dangerous components fully deteriorated. Table 4-3 presents the impact of each treatment in LOS gain and has been calibrated to reflect effectiveness and cost of preventive actions. Also, the U.S. department of transportation deterioration rate for the railway is used for this analysis (US 2007). Statistical data and observations for social and economic indicators are collected from two main sources of (Knoema 2017) and (INEC 2017) for the year 2011. Also, in this study population rate changes in each zone and inflation rate (3% per year) are considered to make the result more realistic. A five-kilometer buffer is used in the optimization model for the effect of railways on HDI since many regions are far from the railway segments and could not be influenced by improvements or decay on it. Treatments' rules and applicability criteria, buffer zone distance, and population growth rate should be customized for the application in other metropolitan areas. Per instance the availability of first mile/last mile facilities, such as park and ride lots, the degree of multimodality, the weather, and the local idiosyncrasy could change the buffer zone distance.

Table 4-3, Treatment windows for railway segments

LOS (%)		Treatment	LOS Gain (%)	Cost (US$/km)
Lower	Upper			
90.01	100	Do Nothing	0	0
70.01	90	Minor Maintenance	30	100,000
40.01	70	Major Maintenance	60	1,250,000
0	40	Reconstruction	100	5,000,000

4.5 RESULTS AND DISCUSSION

4.5.1 Sustainable development assessment

Five hundred and twelve regions of 89 areas in 7 provinces are assessed in terms of human development indicators and indexes are estimated by Equations (1) to (3) for the whole of the country. Local observations indicate that for the majority of gender equality indicators, women have already reached an equal or better than men level; however, a significant difference is found for the participation of male and female in the labor force that could be explained by women's responsibilities at home for taking care of children. Safe and secure transit system gives chance to more women to use daycares located in other regions and be part of the labor force. Thus, only this indicator is used to reflect gender equality for Costa Rica in this research. In terms of environmental issues, big differences between regions were not observed and this factor is removed from the analysis. Figure 4-6 summarizes indexes and corresponding indicators for Costa Rica regions assessment.

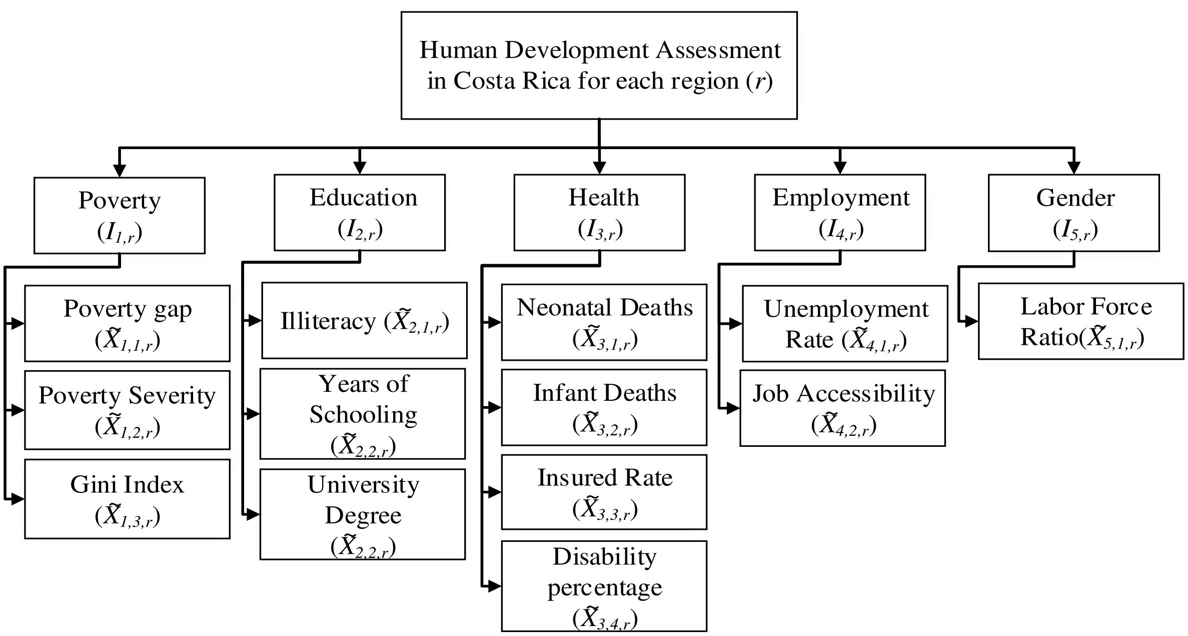

Figure 4-6, Indexes and corresponding indicators for Costa Rica regions

Figures 4-7 to 4-10 present the assessment model results for the four indexes: employment, health, education, and poverty for the whole country through Arc Map platform. The Zoomed frame in these figures for the metropolitan area (San Jose) shows lower (worse) employment index on the central part (capital city) that could be translated by a high density of population in San Jose city, while many far areas have better rates of employment due to less population as well as good job opportunities mainly in agricultural production. As it could be expected, regions surrounding the capital city have better health conditions in comparison to marginal regions, except some small regions with very high rates of infant and neonatal death (Figure 4-8). Education index in the whole of the country emphasizes that improving access to high-quality education for many provinces should be a vital objective (Figure 4-9). Finally, poverty assessment indicates that level of poverty in north and south districts in comparison to middle regions (Figure 4-10).

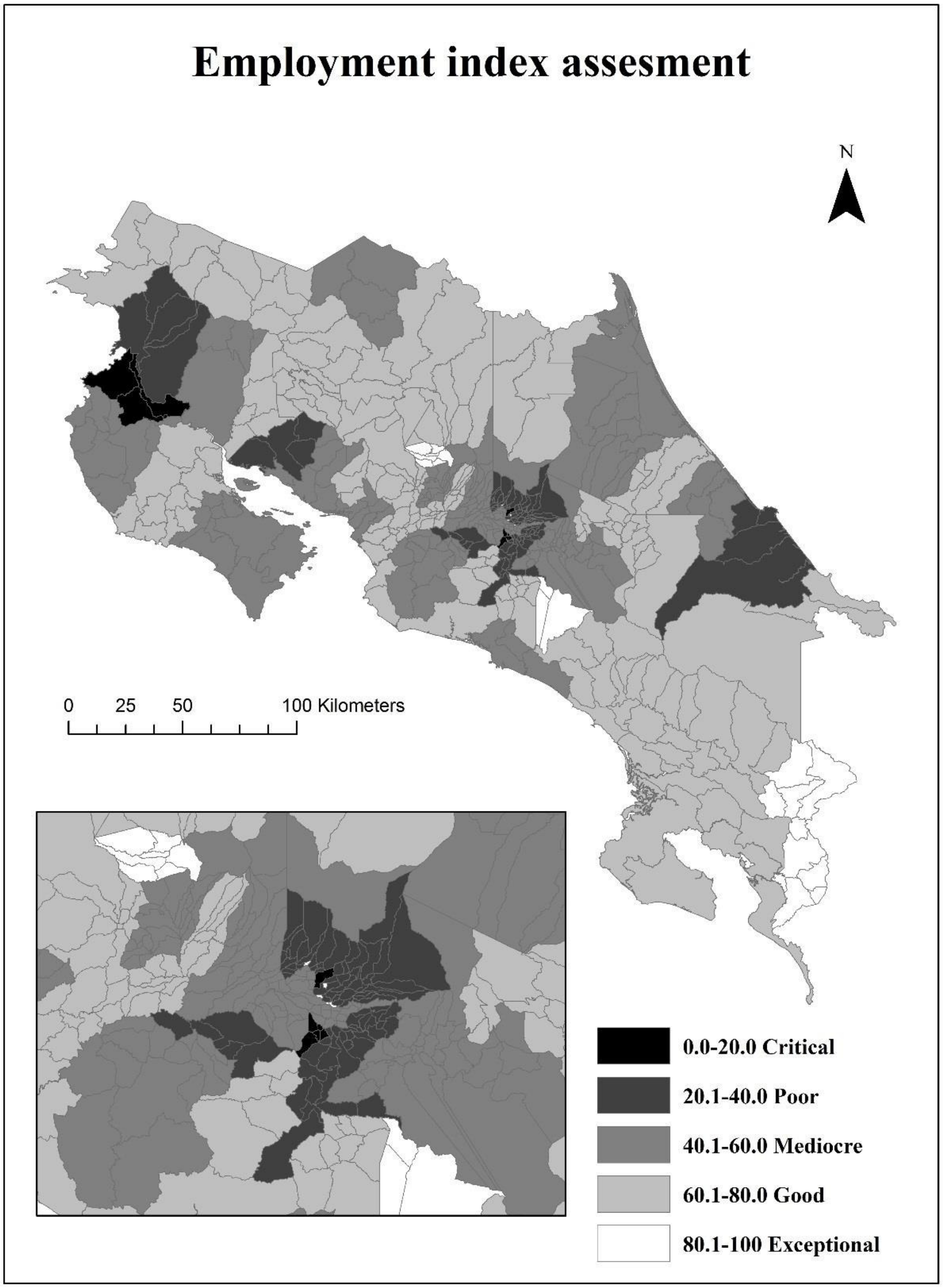

Figure 4-7, Employment index assessment for Costa Rica

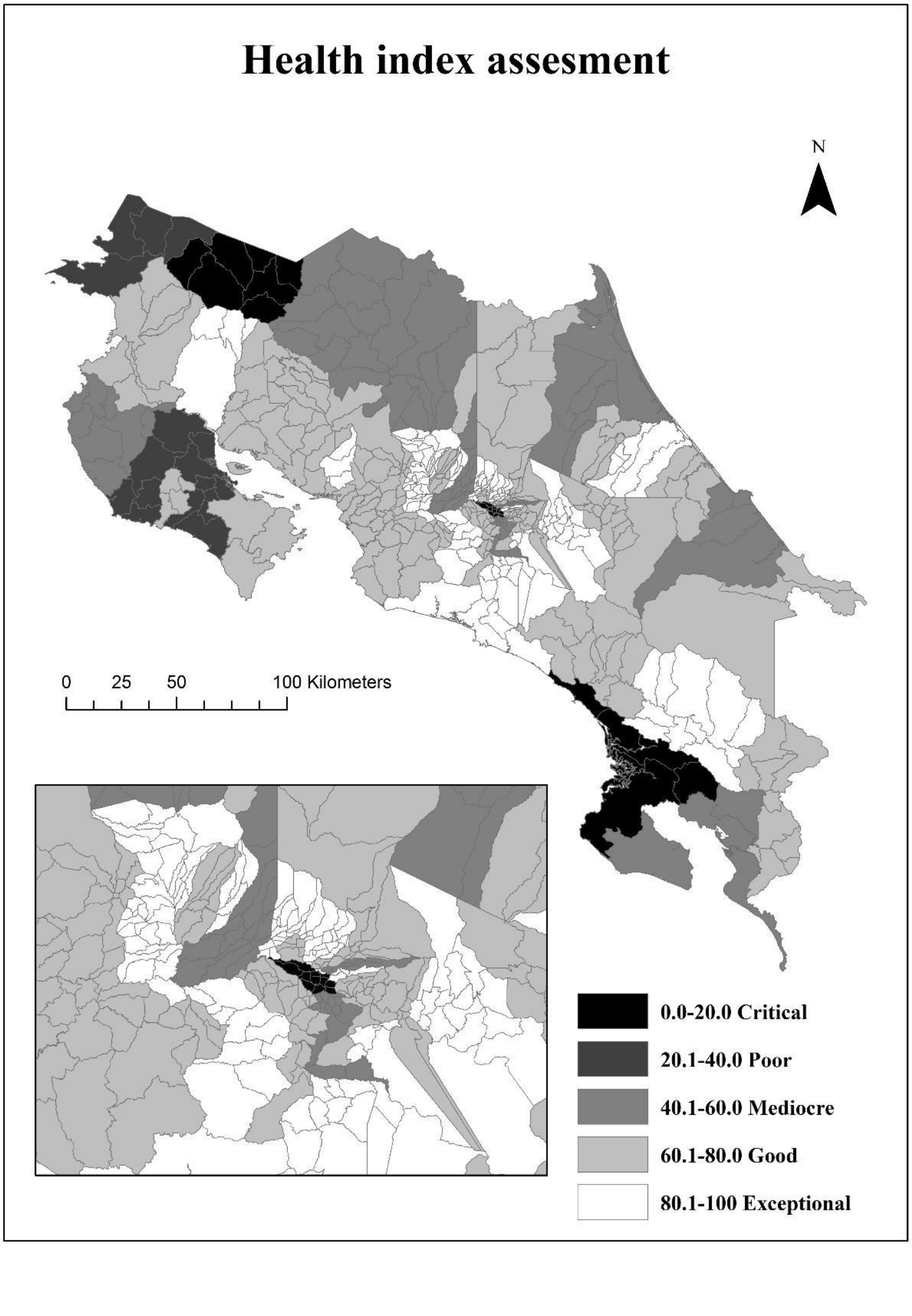

Figure 4-8, Health index assessment for Costa Rica

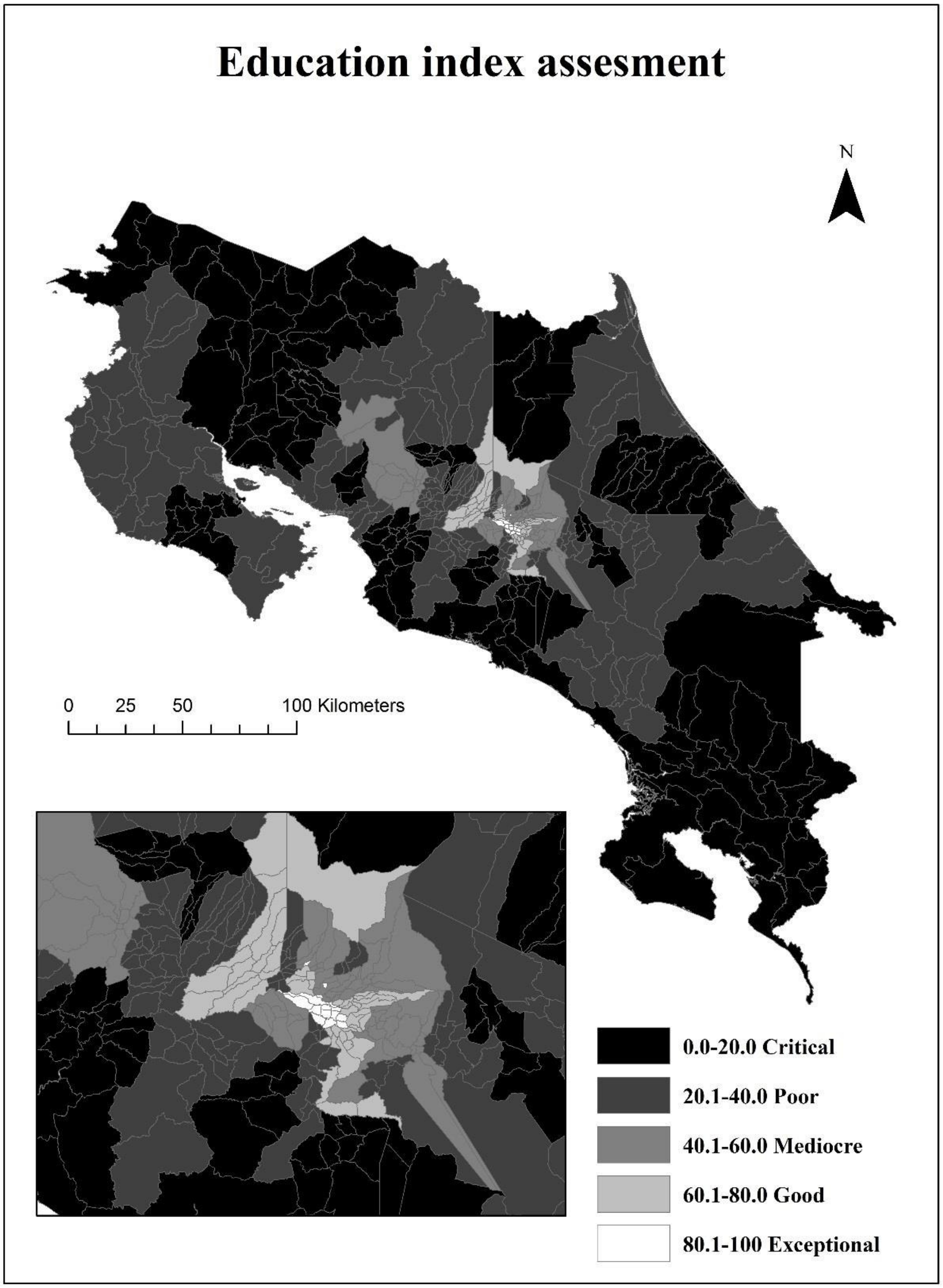

Figure 4-9, Education index assessment for Costa Rica

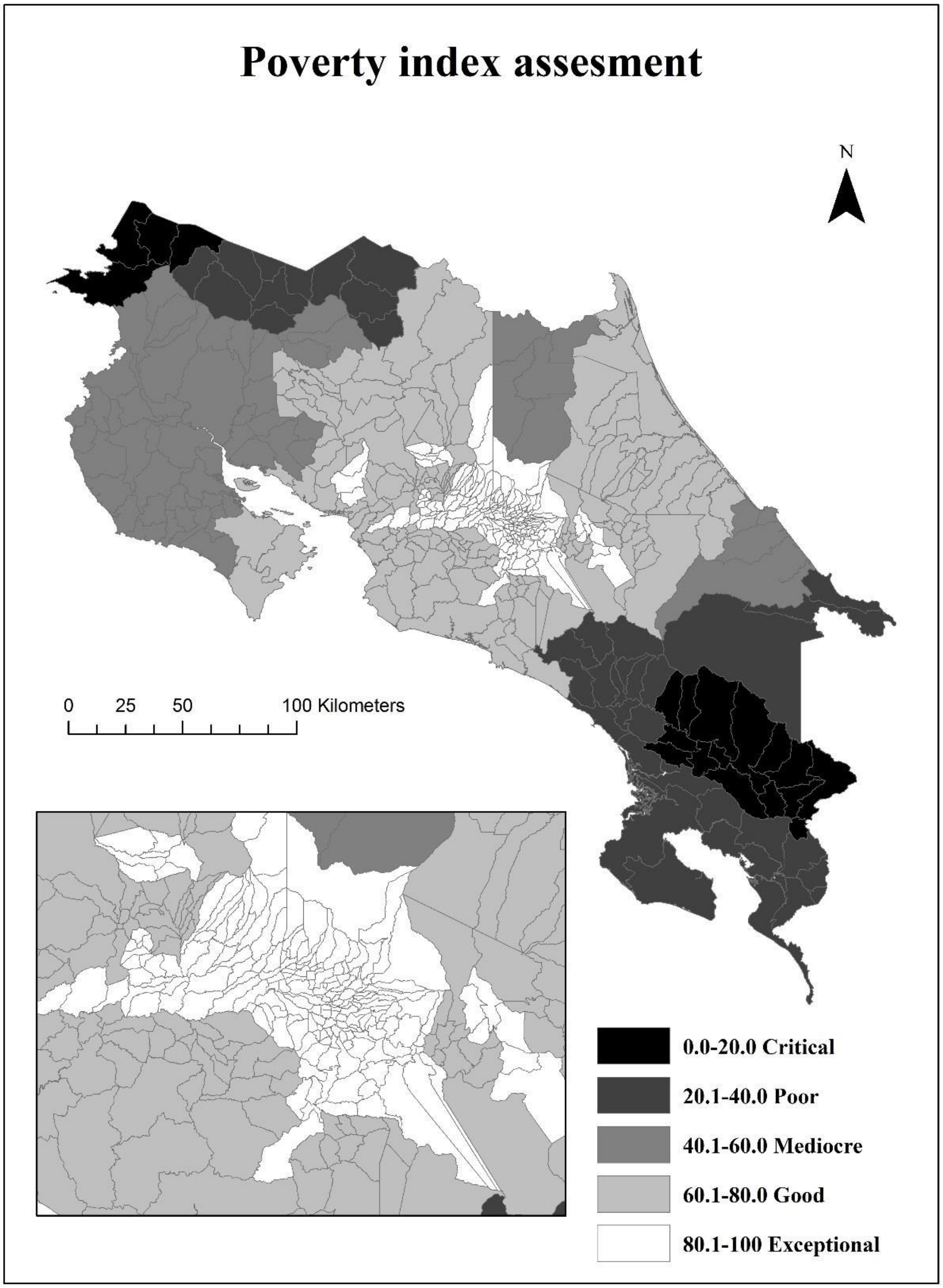

Figure 4-10, Poverty index assessment for Costa Rica

Table 4-4 presents the assessment model results for railway segments (Equation 4-4). As was discussed, central railway segments (San Jose metropolitan area) have low employment index (almost 40%), while people in these crowded areas are benefited from a higher quality of life. “Sur” segments have acceptable employment probably in the agricultural sector; however, are very poor in several factors. Except for a few segments, the overall trend shows that in central regions around the capital city, employment becomes a critical issue, while in marginal districts people are suffering from many human development and sustainability factors such as health, education, and poverty.

Table 4-4, Costa Rica’s railway segments and human development assessment (%)

Railway Segment	l_r (km)	P_r	P_r change rate	Employment (a)	Health (b)	Education (c)	Gender (d)	Poverty (e)
SanJose-Cartago-Paraiso	27	315,403	1.040	39	76	57	75	81
Alajuela-SanJose-Heredia	29	253828	1.047	37	58	57	71	81
Ciruelas-Balsa	15	74,427	1.063	52	54	54	52	71
Belen-SanJose-Pacifico	26	406349	1.044	44	11	74	76	78
Balsa-Salinas	47	41,763	1.066	62	71	19	31	62
Paraiso-Casorla	54	27,850	1.023	48	81	22	25	58
Puntarenas-Caldera-Salinas	27	10,092	1.072	55	63	25	34	60
Sur	47	31,112	1.055	87	64	13	26	19
Casorla-Las-Juntas	20	5,515	1.033	60	82	10	16	41
Limon	30	25,744	1.080	50	76	8	17	36
Limon (2)	60	37,902	1.046	39	73	8	20	25
Sur (2)	60	15,282	1.039	72	0	7	25	0

Different levels of criticality could be assigned to various indexes (Equation 4-5). Sensitivity analysis is done to evaluate how segment human development index (HDI_s) is sensitive to selected weights and results are presented in Figure 4-11. In this case study, there is not a significant difference among weighting alternatives and equal weight represents average expectations.

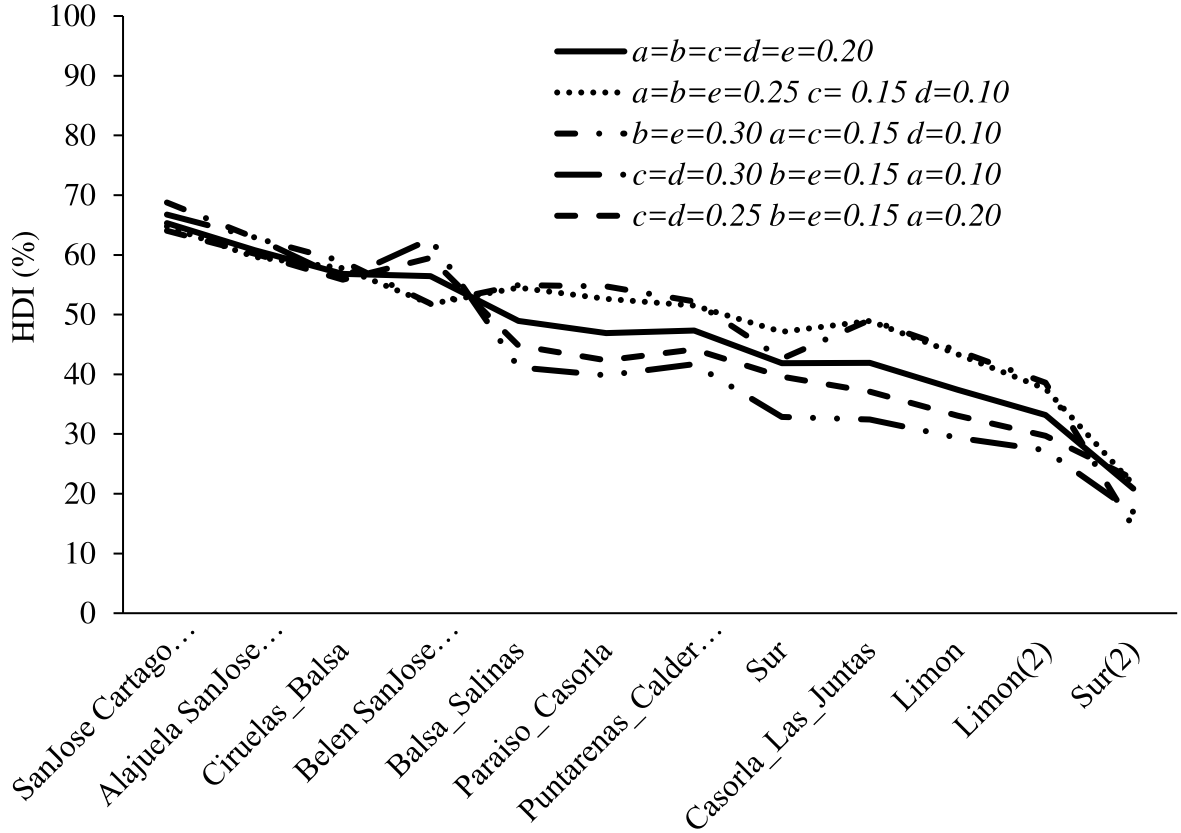

Figure 4-11, Sensitivity analysis of index weights for HDI_s

4.5.2 Optimization model results

The decision-making model finds the most cost-effective solutions based on assessment model outputs and available budget. Analytic solver platform (FrontlineSolvers 2017) software is used for mathematical optimization. Railways are set to 40% LOS as the current value in lack of more accurate assessment.

Optimum budget

The first challenge for the government would be to identify the optimum budget in order to increase OLOS as well as OHDI in the analyzed regions. Additionally, maintenance and reconstruction of railway infrastructure have a nominal cost that is expected to increase following an expected 3% inflation rate. US$60 million per year (50% of the gasoline excise tax) is used as starting budget to be assigned by the government and since all segments are longer than 12 km, the model is run for periods of five years. Four scenarios of budget availability including US$ 60M, 80M, 100M, and 120M per year considering same criticality weights (γ and δ) are analyzed to find the optimum budget (Figure 4-12).

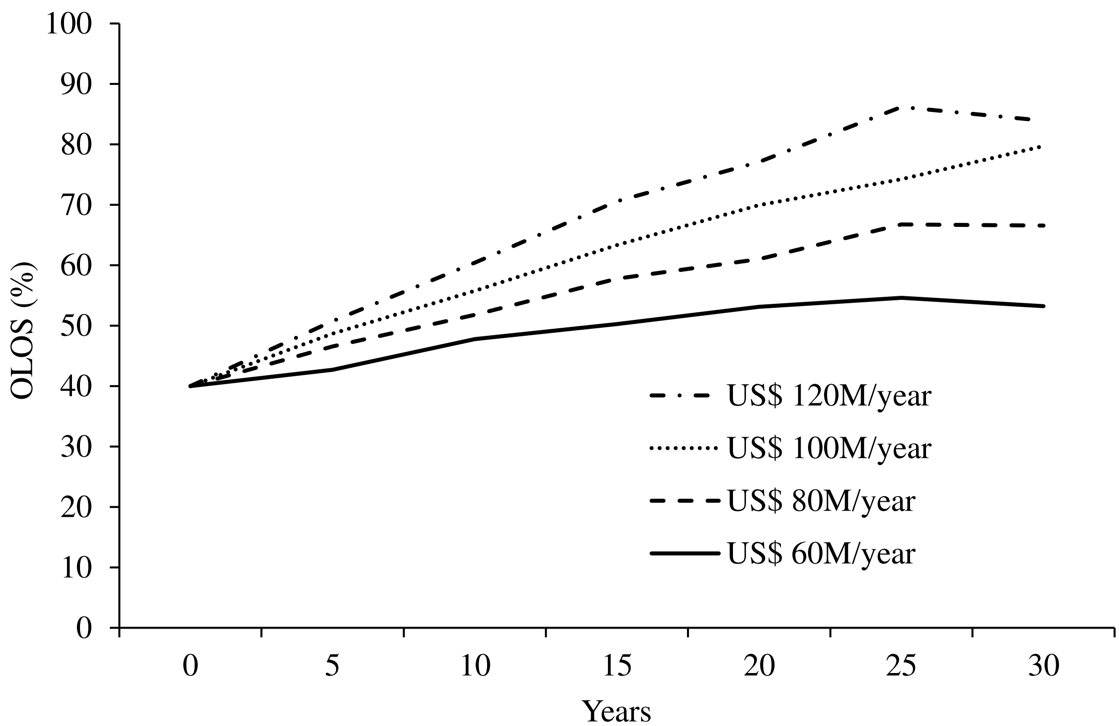

Figure 4-12, OLOS for four scenarios of budget availability

Figure 4-12 indicates that to accomplish an acceptable trend of improvement at least US$ 100,000,000 per year should be invested to experience high OLOS (80%) in the whole network after 30 years of investment. The change in slope towards the end of the analysis period comes from two elements: first, the analysis is done for every 5 years, and secondly, it is attributable to the budget availability and increased cost due to inflation. Until year 25 of the analysis, all budget scenarios picked up at least one reconstruction and some minor maintenance actions in each step of the decision-making. 5, 4, 3 and 1 segments were left and had not been selected for the US$ 60M, US$ 80M, US$ 100M, and US$ 120M scenarios, respectively. In the last time-period (year 30), the US$ 60M and US$ 120M scenarios were unable to use the available budget since the reconstruction cost for the remaining (not selected) segments is more than the available budget. In these scenarios, only minor maintenance could be applied to the other segments based on their conditions, which led to dropping LOS values. However, the US$ 80M and US$ 100M scenarios still could pick one new segment for reconstruction and this resulted in improving level for the US$100M and near constant level for the US$ 80M. In simple terms, it comes from the fact that the network has undergone a stabilization and reached a steady-state-like plateau.

Figure 4-13 shows that even US$60M per year could make a significant impact on human development; increasing the OHID to more than 80%. The model tries to increase objectives by selecting segments in densely populated areas, which result in improved sustainability factors rather than OLOS. Model actions lead to LOS improvement in crowded areas, which goes along with the study objective; however, the overall network' LOS growth needs more investment. Another point could be highlighted: after 15 years, sustainability does not change greatly when shorter and more crowded segments are already in operation, however the model concentrate resources in protecting their condition rather than assigning budget to long segments in low population regions. Therefore, from the sustainability point of view, assigning the available budget to other transit modes such as bus-routes might be a more effective solution; however, such network was unavailable and left outside the modeling scope of this paper.

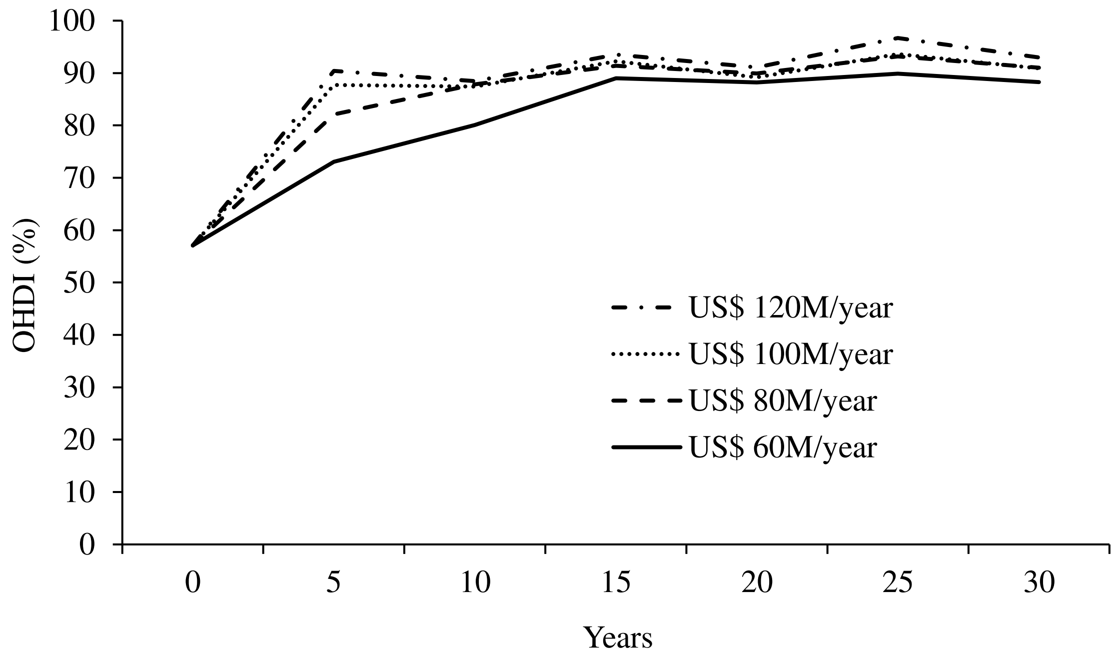

Figure 4-13, OHDI for four scenarios of budget availability

As shown, it is achievable to improve both objectives simultaneously; however, transit agencies are expected to give priority to LOS. Thus, another analysis is done with US$ 100M per year to compare OLOS of the network while model ignores human development objective and measures the explicit impact of its consideration. The results in Figures 4-14 and 4-15 indicate that in these two scenarios, transit agencies reach almost the same LOS regardless of considering human development in planning or not. However, significant improvement in HDI could be achieved by explicitly including it in the planning as proposed by this study.

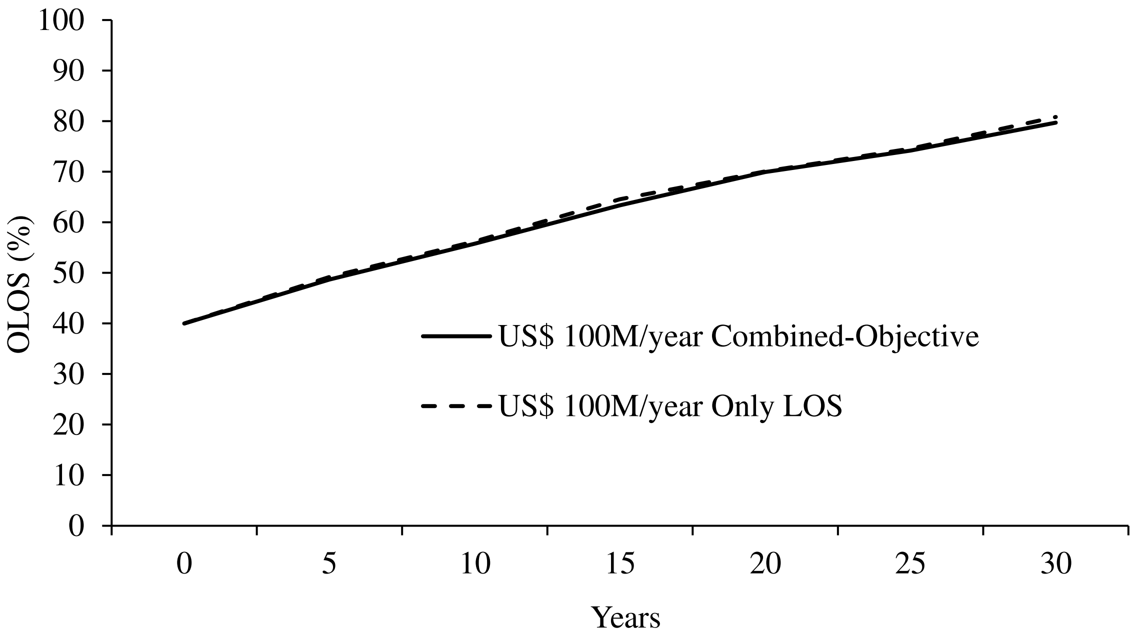

Figure 4-14, Comparison of OLOS in combined-objective and only LOS objective

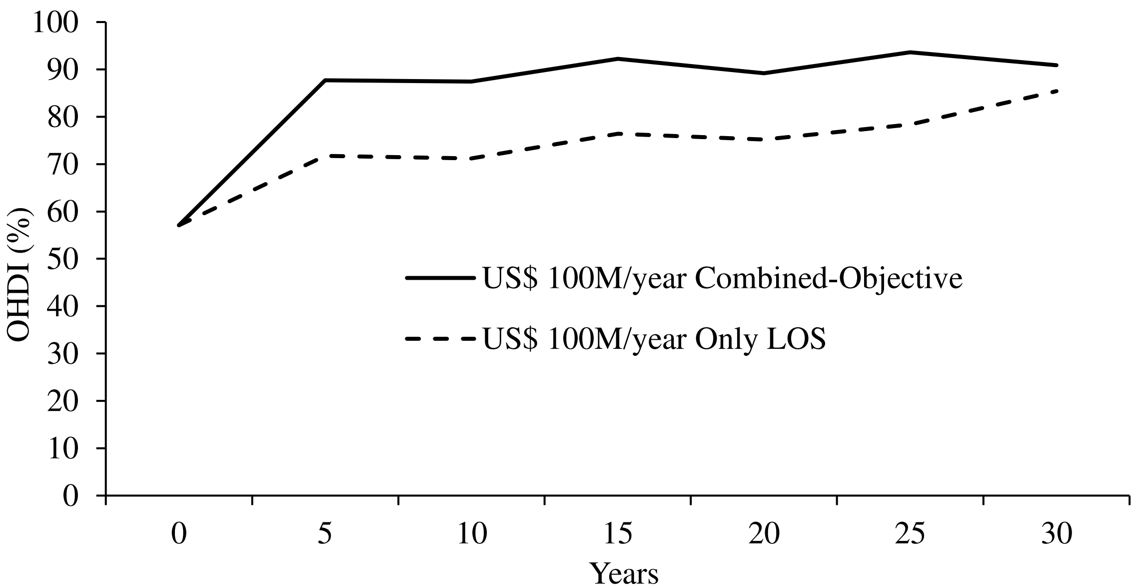

Figure 4-15, Comparison of OHDI in combined-objective and only LOS objective

4.5.3 HDI improvement and railroad maintenance actions in 100MUS/year scenario

Optimization results of the US$100 million per year scenario are discussed in this section in both views of transportation planning and human development. Table 4-5 shows intervention actions for 30 years of planning. As it was mentioned earlier, segments need to be reconstructed in the first action and after 10 years model assigned minor maintenance, which is a common approach in railway maintenance in this period of time. In the first round, the model selects the same three segments that the Costa Rica government has recently chosen to put back in service, and this validates the model. It could be predicted that after two times assigning minor actions, the segment will need major rehabilitation. Selecting sequential segments may result in better mobility and a future study could address coordination in the decision-making process. Table 4-6 compares starting point and 30 years planning for all segments in terms of different indexes. Except for two left segments (Balsa-Salinas and Paraiso-Casorla) in Table 4-5, acceptable improvement could be seen in all segments.

Table 4-5, Planning treatment actions for railroad segments

Railroad segment/Years	5	10	15	20	25	30
SanJose-Cartago-Paraiso	Recon.	-	Minor Main.	-	Minor Main.	-
Alajuela-SanJose-Heredia	Recon.	-	Minor Main.	-	Minor Main.	-
Ciruelas-Balsa	-	Recon.	-	Minor Main.	-	Minor Main.
Belen-SanJose-Pacifico	Recon.	-	Minor Main.	-	Minor Main.	-
Balsa-Salinas	-	-	-	-	-	-
Paraiso-Casorla	-	-	-	-	-	-
Puntarenas-Caldera-Salinas	-	-	Recon.	-	-	Minor Main.
Sur	-	-	-	-	Recon.	-
Casorla-Las-Juntas	-	-	-	-	-	Recon.
Limon	-	-	Recon.	-	-	Minor Main.
Limon (2)	-	Recon.	-	Minor Main.	-	Minor Main.
Sur (2)	-	-	-	Recon.	-	Minor Main.

Table 4-6, Indexes (%) comparison in starting points and after 30 years

Railway Segment	Employment		Health		Education		Gender		Poverty	
	Y0	Y30	Y0	Y30	Y0	Y30	Y0	Y30	Y0	Y30
SanJose Cartago Paraiso	39	68	76	100	57	86	75	100	81	100
Alajuela SanJose Heredia	37	71	58	92	57	91	71	100	81	100
Ciruelas_Balsa	52	95	54	97	54	97	52	95	71	100
Belen SanJose Pacifico	44	82	11	49	74	100	76	100	78	100
Balsa_Salinas	62	56	71	65	19	14	31	26	62	56
Paraiso_Casorla	48	43	81	75	22	17	25	19	58	52
Puntarenas_Caldera_Salinas	55	100	63	100	25	71	34	80	60	100
Sur	87	100	64	99	13	47	26	60	19	54
Casorla_Las_Juntas	60	99	82	100	10	49	16	55	41	80
Limon	50	96	76	100	8	54	17	63	36	82
Limon (2)	39	97	73	100	8	66	20	78	25	83
Sur (2)	72	100	0	48	7	56	25	74	0	48

Note: Y0 denotes current condition and Y30 denotes after 30 years condition

The model impacts for employment and poverty indexes in the central part of the country are compared to 5 and 15 years of network improvement in Figures 4-16 and 4-17. As it can be seen, both indexes have been improved even in the short time in this crowded part of Costa Rica. More sustainable regions with access to job opportunities and quality education for all ages can be expected.

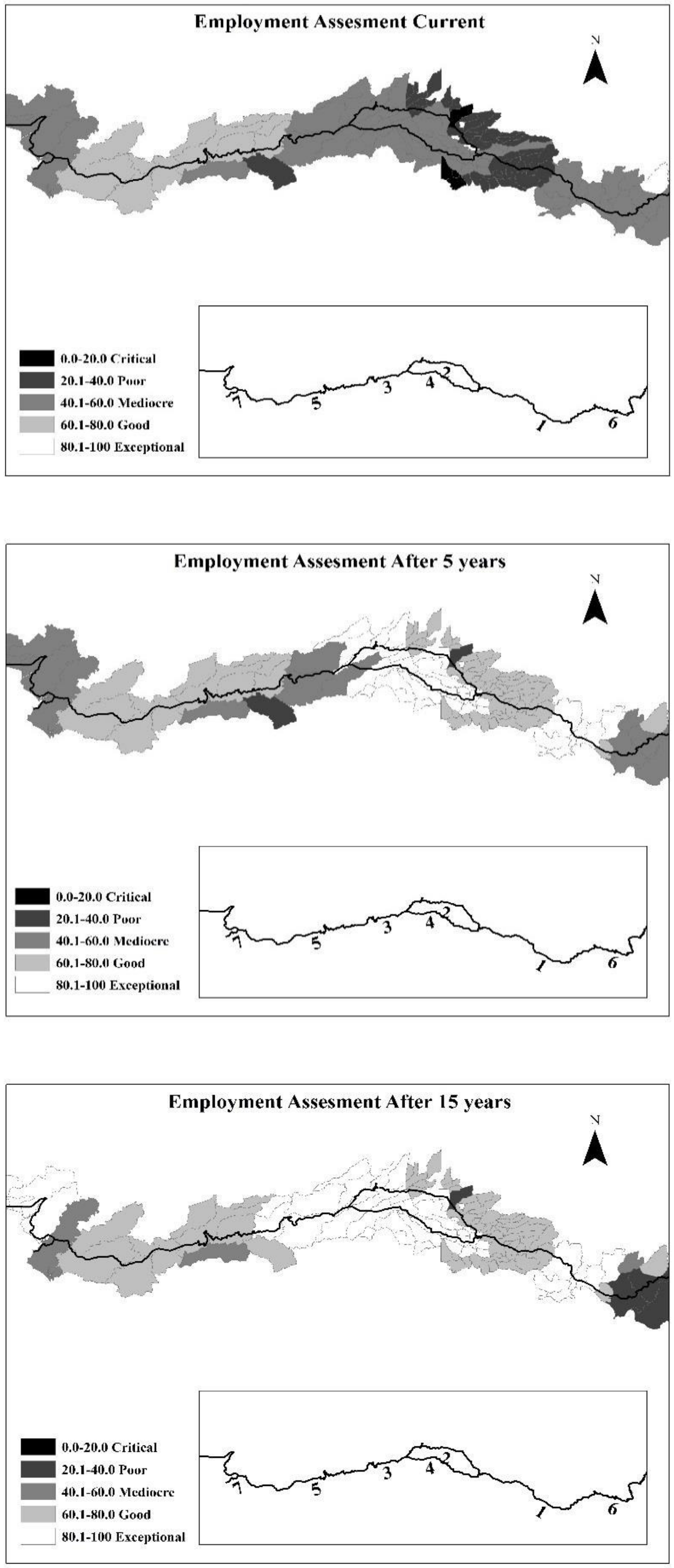

Figure 4-16, Employment assessment, current, after 5 years, and after 15 years

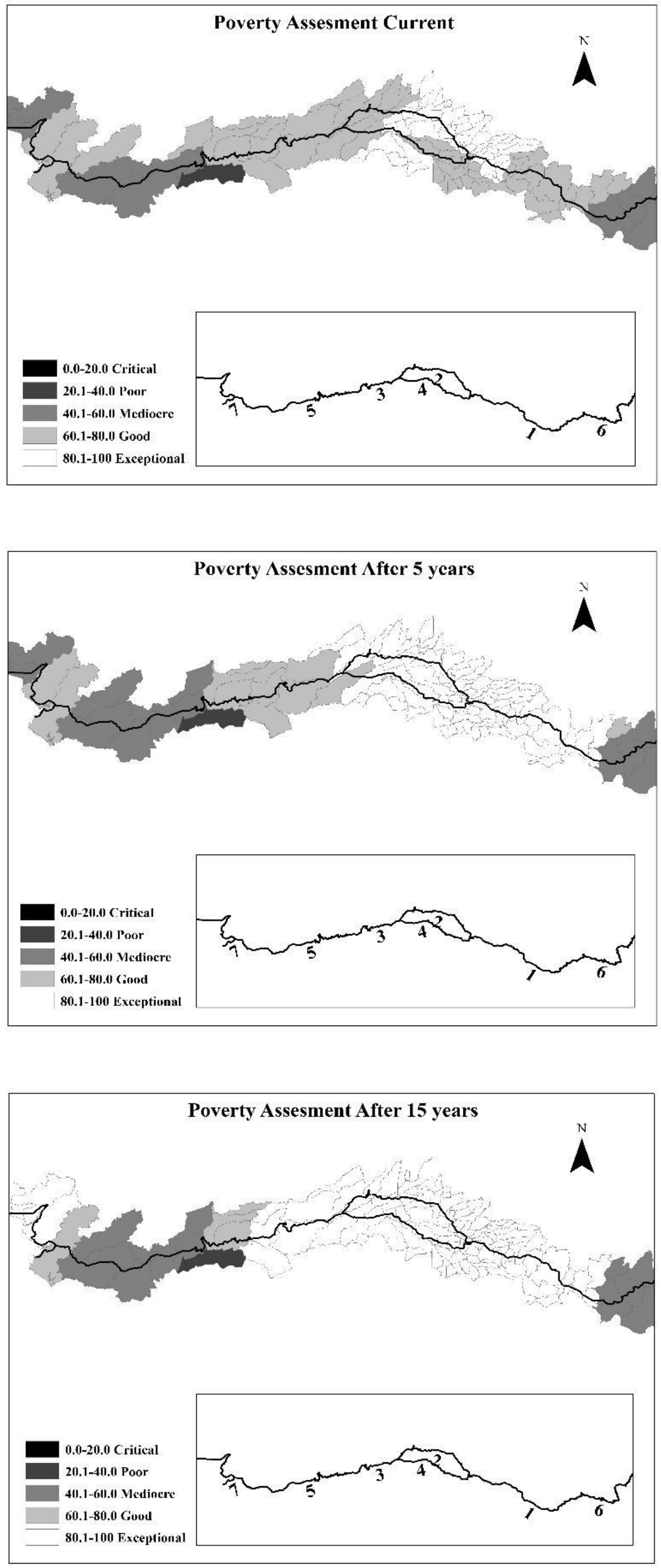

Figure 4-17, Poverty assessment, current, after 5 years, and after 15 years

4.6 CONCLUSION

Sustainable transport plays a critical role to progress the United Nation (UN) 2030 sustainable development goals and it could be achievable through improvements in public transit and human development. A novel framework is proposed to help governments and municipalities select the most cost-effective alternatives in maintenance and rehabilitation of transit networks in order to improve LOS in transportation systems as well as advance human development and sustainability. This framework assesses human development and sustainability through several indexes and uses them on an optimization model, which distributes the available budget to the most vulnerable regions first in terms of both services and human development factors such as health, education, poverty, and employment. A case study of Costa Rica's great metropolitan area is used to illustrate the approach. The results show that the (H_s) is not sensitive to the indexing weights used to combine human development or sustainability indicators. It is also found that the model could improve both objectives: LOS and human development. LOS increased gradually in all scenarios; however, significant changes are achievable with at least US$100 million per year. Meanwhile, sustainability is suddenly improved in the first 5 years in all scenarios because the most impacting transit lines are placed to work attending a good percentage of the urban population. It is also confirmed that with the same budget and explicit formulation containing human development indicators (in addition to LOS) can accomplish same LOS but many superior values of HDI. With US$100 million the model selects first the same three segments that the Costa Rica government has recently chosen to put back in service. The proposed model could be used by all existing public transit networks such as Tramway, Bus Rapid Transit (BRT), Light Rail Transit (LRT), traditional buses and metro to guide planning for their upgrade or expansion.

Chapter 5 : METHODOLOGY (MODEL III)

RELIABLE, EFFECTIVE AND SUSTAINABLE URBAN RAILWAYS, A MODEL FOR OPTIMAL ASSET MANAGEMENT

Chapter 5 fills the main identified gap in the literature regarding, which is lack of a comprehensive and efficient decision-making (optimization) model for maintenance, renovation and upgrading of urban railway systems. Developed models in chapters 3 and 4 can also be used in developing this model in order to address literature gaps, transit agency concerns, and society needs. This chapter is written in a paper format and is under review by the journal of construction engineering and management (ASCE).

Mohammadi, A., Amador, L., and Nasiri, F. (2019). Reliable, effective and sustainable urban railways, a model for optimal asset management, Journal of construction engineering and management (ASCE)(Under submission process).

Abstract: Urban railways play a critical role in the daily life of citizens. However, extensive deterioration of mostly aged systems complicates the management of them in coping with increased demand and the restricted upgrade and renewal budgets. The main objective of this research is to develop a comprehensive decision-making model for managing urban railway systems with the aim of maintaining the highest level of convenience, safety, comfort and reliability in the movement of passengers in a metropolitan area. By considering ridership fluctuations and network expansion scenarios, the proposed model integrates the current and expected future usage rates into the decision-making process. Montreal metro system was considered as the case study area. The results indicate that proactive maintenance scheduling is able to save up to 25% of the cumulative expenditure during a 20-year horizon while improving the overall performance of the system. Comparing the decisions proposed by the model and the government plan for this network serves as a means of presenting the applicability for the model.

The proposed model is applicable to rail rapid transit (underground and surface); Light Rail Transit (LRT); and suburban trains as well as Bus Rapid Transit (BRT) and provides guidance for maintenance, upgrade, and expansion of these systems targeting improvements in their convenience, reliability, and ridership.

5.1 INTRODUCTION

Worldwide millions of passengers expect fast, competitive, and reliable transit systems for their daily transportation. Maintaining urban railway systems as critical and complex transit infrastructure with different types of facilities (rail cars, stations, tunnels, etc.) and many subcomponents geographically dispersed across the network, is a challenge for governments and municipalities. Meanwhile, extensive deterioration of already aged systems complicates the management of the network while coping with increased demand and the corresponding need to plan for capital upgrades with a restricted annual budget. The 2017 American infrastructure report card assigned a level "D-" to the USA's transit sector that means "poor" condition (ASCE 2017). The Canadian report card in 2016 assigned a grade of "Fair" to fixed assets (e.g. stations and tunnels) with 25% of them ranked in poor and very poor condition (CIRC 2016). Effective planning to maintain, rehabilitate, upgrade and expand transit networks is key to the success of transit-oriented strategies. However, without a comprehensive multi-criteria decision-making procedure, it is impossible to achieve optimal actions at the right time within the available budget. The enhanced level of quality of public transportation infrastructure is key to alter users' preferences and encourage ridership. This can be accomplished through reliable and convenient services that support the passenger's mobility needs and provide access to land uses at a reasonable cost and time. There are important interdependencies between the performance of public transit systems, the deterioration of their components and the rate of usage. Improved ride quality delivered by physical assets in better condition (e.g. vehicle comfort) or non-physical features such as train frequency encourages more riders to shift into public transit. Such a change in ridership influences back transit infrastructure's performance increasing the deterioration of many elements of the system. At the meantime, an increase or decrease in future ridership (e.g. due to opening new transit corridors or changes in the social or economic environment) may influence the ridership, which accelerates or decelerates the decay of the infrastructure (Figure 5-1). Therefore, the dynamic fluctuation of ridership (usage rate) and its consequences in deterioration and performance should be captured in transit systems asset management and decision-making.

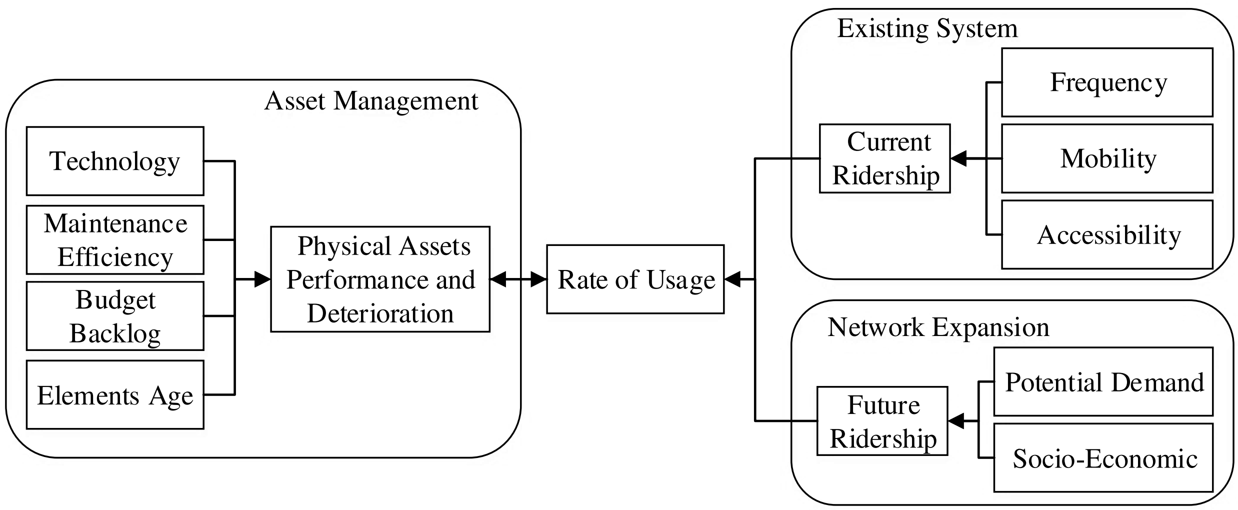

Figure 5-1, Mutual relation between urban railway performance and rate of usage

5.2 LITERATURE REVIEW

Decision-making systems have been advanced gradually in the literature for managing infrastructure such as roads (Faghih-Imani and Amador-Jimenez 2013; and Zhou et al. 2014), bridges (Essahli and Madanat 2012) and water networks (Mohamed and Zayed 2013). However, there is a lack of a decision-making model for maintenance of urban railway systems (e.g. metro and light rail) while implementing other infrastructure models cannot fully fulfill requirements and address natural differences.

The earliest reference found in the literature was done to provide maintenance priority for metro stations (Roy et al.1986) using the ELECTRE III technique (Roy 1978). Paris metro stations were prioritized considering multiple criteria of performance, users' number and income. Later, Hastak and Abu-Mallouh (2001) developed a more advanced model for the same purpose in New York City. The Analytic Hierarchy Process (AHP) (Saaty 1980) was used as a decision-making tool. Similar approaches were used by Semaan and Zayed (2009), Kepaptsoglou et al. (2013), and (Gkountis and Zayed 2015). All these performance assessment models focused on ranking stations for maintenance using a worst-first approach, which does not guarantee to achieve optimum solutions. Some other scholars only concentrated on structural components ignored other critical electrical and mechanical elements (Semaan 2014; Abouhamad 2014; Nishimura et al. 2015; and Taguchi et al. 2016). Gallucci et al. (2012) trusted on assets age as the sole indicator for decision-making and maintenance prioritization, which can fail in addressing most concerns. Ferran and Zayed (2009) implemented a life-cycle cost model to plan for metro rehabilitation. Meanwhile, reviewing applied approaches by transit agencies indicates that there are several main limitations, for instance, the STM uses a worst-first system based on the age of station and expert judgment prioritization (Abouhamed 2014) or the Massachusetts Bay Transportation Authority (MBTA) ranks rehabilitation alternatives considering some criteria such as health, age, and operational impacts respecting budget constraints (Eric 2011).

Current and future ridership play a critical role on the management of existing urban railway systems to maintain adequate operation of the entire system as well as to upgrade services through network expansion and the opening of more corridors. One direct consequence of increased or decreased usage rate lays on the degradation rate of assets, which is a key consideration in long-term planning. For instance, traffic load is one characteristic of track deterioration in railroads (Ferreira and Murray 1997; Sadeghi and Askarinejad 2010; and Elkhoury et al. 2018), which is identified with Equivalent Million Gross Tons (EMGTs) passing the track in a time period at average running speed. In fact, deterioration models should dynamically capture the impact of usage rates for those components in which are more sensitive such as rail track or station stairs. Although the literature is rich in deterioration models; however, in addition to the common limitation of historical data for railway assets, this dynamic feature is often missed in long-term decision-making process.

A recent review study of metro systems conducted by Mohammadi et al. (2018a) concluded that asset management platforms for metro systems are not well-established possibly due to the complexity of their interdependencies and lack of historical data. This study summarized the main observed limitations in developed models in the literature or implemented by transit agencies for maintenance, rehabilitation and replacement plans of urban railway systems (i.e. metro) as: there is lack of a network level model and most proposed models are developed for either stations or tunnels while decision-making should be done in a network level. There are less performance assessment models for transit cars particularly from customer perspective while riders spend more time in vehicles than stations. The impact of network expansion and changing ridership are often ignored, and indicators used to guide decisions are commonly connected to some form of physical deterioration tied back only to the asset's age, missing the overall goal of a transit system to provide reliable, safe, and convenient movements of daily passengers. The budget allocation using mathematical optimization model is widely neglected and worst-first scenarios capable only for single-year planning are commonly used. Asset deterioration prediction is not often investigated, which leads to missing the long-term impacts of decisions and optimal solutions. Finally, use of expert judgments and traditional qualitative approaches are still preferred by transit agencies.

This situation brings to matters the need to rely on a comprehensive decision support model that can simulate and optimize dynamically the operation of the entire urban railway network. The state of art indicates that Maintenance, Rehabilitation, and Replacement (MRR) models for urban railways, which aim for efficient decision-making in a network level has not been studied adequately. Meanwhile, the impact of ridership on current and future rates of usage is also neglected in developed maintenance planning system for this type of critical infrastructure.

Therefore, the main objective of this study is proposing a comprehensive network-level decision-making model for urban railway systems (such as metro) to distribute a restricted budget and achieve optimum solutions with respect a set of performance targets and objectives. Also, the impacts of increasing or decreasing the number of entries to the system either through improving/declining the performance or opening new corridors will be addressed in the planning process for the first time.

5.3 METHODOLOGY

For the purpose of this study, a multi-platfrom decision-making model is proposed in order to identify the optimum MRR scenarios for the existing network as well as the alternatives expansion projects (Figure 5-2).

As can be seen in Figure 5-2, the model includes two parallel platforms of Maintenance Planning (MP) and Expansion Planning (EP). The MP platform is responsible to improve the reliability and performance of existing network from an asset management perspective respecting current and future ridership (rate of usage); available budgets; and performance thresholds. This platform presents a set of MRR actions for the following years. EP platform ranks the alternatives for the network upgrading through line extensions. The output of this platform would be a prioritized list from feasible alternatives for following years; however, at the same time, the impact of this upgrading on network ridership would be reflected in the next platform (MP). Also, newly built segments (e.g. station and tunnel) will be added to the MP platform in the following year. Table 5-1 summarizes key decision-making (optimization and prioritization) elements in both platforms.

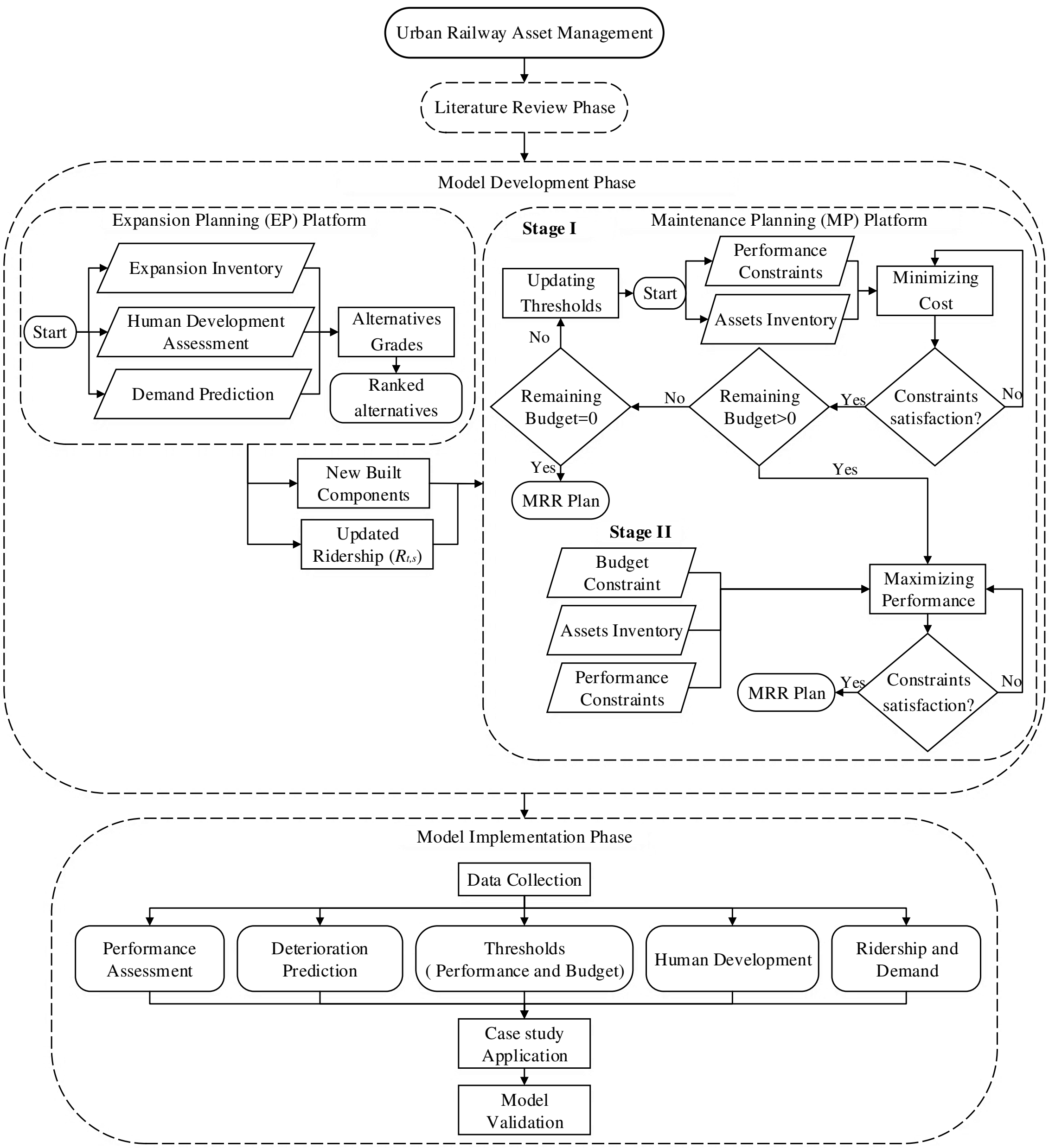

Figure 5-2, Asset management model for urban railway

Table 5-1, Decision-Making elements in both platforms

<table>
<tr><th>Platform</th><th>Objective/s</th><th>Variable/s</th><th>Constraint/s</th></tr>
<tr><td>MP platform (Stage I)</td><td>Minimizing Costs</td><td>Network Elements</td><td>Performance Thresholds</td></tr>
<tr><td rowspan="2">MP platform (Stage II)</td><td rowspan="2">Maximizing Network Performance</td><td rowspan="2">Network Elements</td><td>Performance Thresholds</td></tr>
<tr><td>Available Budget</td></tr>
<tr><td rowspan="2">EP platform</td><td>Maximizing Network Ridership</td><td rowspan="2">Future stops</td><td>Available Budget</td></tr>
<tr><td>Maximizing Human Development Index</td><td>Construction order</td></tr>
</table>

5.3.1 MP platform

MP platform aims to improve the reliability of the network through up-keeping elements condition. The performance of the urban railway network comes from two main parts of fixed assets and rolling stocks in a hierarchical structure (Mohammadi et al. 2018a). Budget distribution and decision-making either could be planned in the network level where all lines and corresponding systems (i.e. fixed assets and rolling stocks) are considered at the same time or specific budget may be assigned to each system and separate decision-making could be arranged (Figure 5-3). Since the same source of budget is used for maintenance of stations, tunnels, and metro cars where enhancing the overall performance of the whole network will be the main goal, in this study, the model is developed making decisions at the highest level to possibly find more optimum solutions; however, transit agencies may implement the same methodology in the lower levels. The hierarchal structure for urban railway (underground) network in the system, subsystem, component, sub-component and element levels can be defined as Figure 5-3.

Performance of the network comes from element condition and reliability. For fixed assets, depends on transit agency approach and policy each element could be assessed by several attributes and criteria as was discussed by Gkountis and Zayed (2015). For rolling stock, a similar approach could be applied; however, assessing comfort level in the rail journey can also be utilized to evaluate elements performance (Mohammadi et al. 2019). As long as performance for elements are determined, scores could be integrated into defined hierarchy relation having sub-components, components and finally segments performance pf_s. Due to data availability or agency policy, upper levels of the hierarchy network (Figure 5-3) may be selected for performance assessment and decision-making; however, this approach gives less flexibility and may not find the optimal solutions.

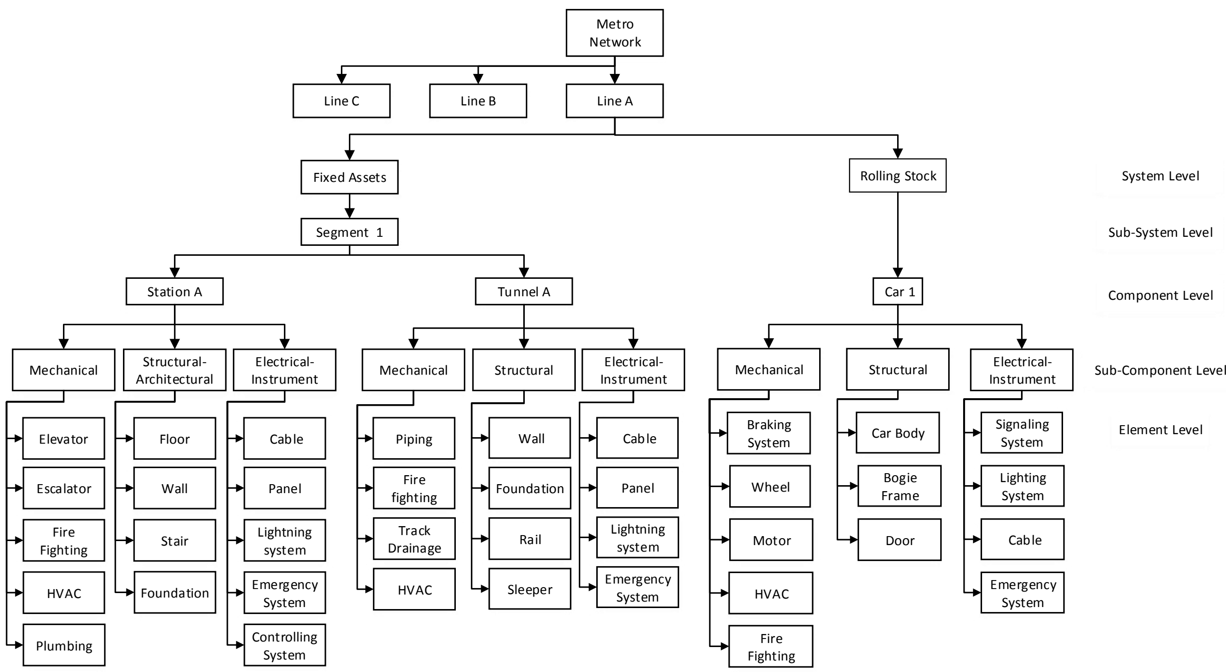

Figure 5-3, Urban railway (underground) hierarchy network

The formulation in this study is defined for the lowest level (element); however, could be easily modified and sub-component level may be chosen. For instance, maintenance interventions could be either planned for each element (e.g. escalator or elevator) or in the upper level for each sub-component (i.e. mechanical or electrical). Using lower levels makes decision-making more complex while gives chance to avoid missing critical elements as well as finding more efficient solutions. For rolling stocks, there is no defined segment and similar hierarchical approach could be used to assess each car (or wagon) and finally, the overall average performance is estimated for the whole fleet in each line. Different formulations could be used to aggregate performance index using Multi-Attribute Utility Theory (MAUT) in various levels of the hierarchy and in this study, a weighted geometric average has been used in the element level to avoid of missing critical assets. Although it helps for controlling assets with very low performance; however, to guarantee safety in the whole of the network, the performance threshold will be defined too.

A two-stage optimization through dynamic binary programming is developed for the purpose of this study. In the first stage, the minimum required budget is estimated for the year (*t*), C_t (Equation 5-1), through binary variables of $Xf_{t,l,s,i,j,k}$ and $Xr_{t,l,n,j,k}$ for fixed assets and rolling stocks, respectively (Equations 5-2 and 5-3). It will be estimated while acceptable performance levels (thresholds) are respected for all elements of segments (*pf*) (Equation 5-4) and vehicles (*pr*) (Equation 5-5). Fixed assets in the planning year (*t*) in each line (*l*) are assessed based on segments (*s*) performance including two components (*i*) of the station and tunnel, which are divided into some sub-components (*j*) of mechanical, electrical and structural while each one has corresponding elements (*k*). A similar approach could be implemented for cars where (*n*) reflects the number of cars in the line.

Stage I:

$$Mininmize C_t = \sum_{l=1}^{L}\sum_{s=1}^{S}\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K} Cf_{t,l,s,i,j,k}Xf_{t,l,s,i,j,k} + \sum_{l=1}^{L}\sum_{n=1}^{N}\sum_{j=1}^{J}\sum_{k=1}^{K} Cr_{t,l,n,j,k}Xr_{t,l,n,j,k} \quad (5\text{-}1)$$

$$Xf_{t,l,s,i,j,k} = \begin{cases} 1 & if\ action\ is\ taken\ on\ element\ k\ in\ sub-component\ j\ in\ compnent\ i\ in\ segment\ s, in\ line\ l, in\ the\ year\ t \\ 0 & if\ no\ action\ taken\ on\ element\ k\ in\ sub-component\ j\ in\ compnent\ i\ in\ segment\ s, in\ line\ l, in\ the\ year\ t \end{cases} \quad (5\text{-}2)$$

$$Xr_{t,l,n,j,k} = \begin{cases} 1 & if\ action\ is\ taken\ on\ element\ k\ in\ sub-component\ j\ in\ car\ n, in\ line\ l, in\ the\ year\ t \\ 0 & if\ no\ action\ taken\ on\ element\ k\ in\ sub-component\ j\ in\ car\ n, in\ line\ l, in\ the\ year\ t \end{cases} \quad (5\text{-}3)$$

Subject to:

$$pf_{t,l,s,i,j,k} \geq PTf_k \ \ for\ k\ (1, 2, ..K), j\ (1,2,..\ J), i\ (1, 2, ..\ I), s\ (1, 2, ..\ S)\ and\ l\ (1, 2, ..\ L) \quad (5\text{-}4)$$

$$pr_{t,l,n,j,k} \geq PTr_k \ \ for\ k\ (1, 2, ..\ K), o\ (1, 2, ..\ J), n\ (1, 2, ..\ N)\ and\ l\ (1, 2, ..\ L) \quad (5\text{-}5)$$

Next, subject to more available funds, the remaining budget will be assigned to other elements (noncritical alternatives in the first stage) to maximize overall performance (Equations 5-6 to 5-13). Overall performance for the whole network, which is aggregated from different lines conditions, is a simple weighted combination of fixed and unfixed assets in each line (Equation 5-6). Relative important weights could be defined by the transit agency for each line, corresponding fixed and unfixed systems including segments, components, sub-components, and finally elements. The performance of each fixed segment or car is estimated based on average weighted (geometric or simple) performance and defined hierarchy structure in Figure 5-3 (Equations 5-7 and 5-8). A time dynamic link is designed to estimate the timely performance of each element respecting assigned binary variables and previous year condition (Equations 5-9 and 5-10). The total cost for all MRR actions must be subjected to available budget BP_t (Equation 5-11).

Stage II:

$$Maximize\ PN_t = \sum_{l=1}^{L} \mu_l \left(\delta_1 \sum_{s=1}^{S} W_s \times pf_{t,l,s} + \frac{\delta_2}{N} \sum_{n=1}^{N} pr_{t,l,n}\right) \tag{5-6}$$

$$pf_{t,l,s} = \sum_{i=1}^{I} \gamma_i \sum_{j=1}^{J} \beta_j \left[\prod_{k=1}^{K} \left(pf_{t,l,s,i,j,k}\right)^{\alpha_k}\right]^{1/\sum_{k=1}^{K} \alpha_k} \tag{5-7}$$

$$pr_{t,l,n} = \sum_{j=1}^{J} \gamma_j \left[\prod_{k=1}^{K} \left(pf_{t,l,n,j,k}\right)^{\alpha_k}\right]^{1/\sum_{k=1}^{K} \alpha_k} \tag{5-8}$$

$$pf_{t,l,s,i,j,k} = X_{t,l,s,i,j,k}\left(pf_{t-1,l,s,i,j,k} + pfi_{t,l,s,i,j,k}\right) + \left(1 - X_{t,l,s,i,j,k}\right)\left(pf_{t-1,l,s,i,j,k} - pfd_{t,l,s,i,j,k}\right) \tag{5-9}$$

$$pr_{t,l,n,j,k} = X_{t,l,n,j,k}\left(pr_{t-1,l,n,j,k} + pfi_{t,l,n,j,k}\right) + \left(1 - X_{t,l,n,j,k}\right)\left(pr_{t-1,l,n,j,k} - pfd_{t,l,n,j,k}\right) \tag{5-10}$$

Subject to:

$$\sum_{l=1}^{L} \sum_{s=1}^{S} \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{k=1}^{K} Cf_{t,l,s,i,j,k} X_{t,l,s,i,j,k} + \sum_{l=1}^{L} \sum_{n=1}^{N} \sum_{j=1}^{J} \sum_{k=1}^{K} Cr_{t,l,n,j,k} X_{t,l,n,j,k} \le BP_t \tag{5-11}$$

$$pf_{t,l,s,i,j,k} \ge PTf_k \quad for\ k\ (1, 2, ..K),\ j\ (1,2,..\ J),\ i\ (1, 2, ..\ I),\ s\ (1, 2, ..\ S)\ and\ l\ (1, 2, ..\ L) \tag{5-12}$$

$$pr_{t,l,n,j,k} \geq PTr_k \text{ for } k\ (1, 2, .. K),\ o\ (1, 2, .. J),\ n\ (1, 2, .. N) \text{ and } l\ (1, 2, .. L) \quad (5\text{-}13)$$

Where:

PN_t= Overall performance (0-100) of the network in the year t.

$pf_{t,l,s}$ = Overall performance (0-100) of the segment s in the line l in the year t for fixed assets.

$pr_{t,l,n}$ = Overall performance (0-100) of the car n the line l in the year t.

W_s and μ_l= Show the segment's and line weights (criticality) in the overall network performance, based on ridership and location.

$pf_{t,l,s,i,j,k}$ = Performance (0-100) of the element k in sub-component j in component i in segment s the line l in the year t for fix assets.

$pr_{t,l,n,j,k}$ = Performance (0-100) of the element k in component j in car n in the line l in the year t.

α_k, β_j, and γ_i = *Relevant weight for elements, sub-components and components, respectively.*

$c_{t,l,s,i,j,k}$ = Cost ($) of rehabilitation action for the element k in sub-component j in component i in segment s in the line l in the year t.

$c_{t,l,n,j,k}$ = Cost ($) of rehabilitation action for the element k in component j in car n in the line l in the year t.

pfi_t, and pri_t, = Performance (0-100) improvement from a year (t-1) to year t for of the selected fixed or non-fixed element.

pfd_t, and prd_t =Dropped portion of performance (0-100) from a year (t-1) to year t for the non-selected fixed or non-fixed element.

PTf_k and PTr_k =Performance threshold (0-100) for of the element k or m, which presents the lowest acceptable performance level.

δ_1, δ_2, and *μ_l = Relevant weight for fixed assets, rolling stocks, and lines, respectively.*

BP_t=Available budget ($) for MRR in the year t.

5.3.1.1 Deterioration model

As one main requirement of long-term decision-making, deterioration must be predicated for each variable to capture the future impacts of current decisions. The model must be able to predict yearly deterioration rates for each element (e.g. elevator or lighting system). Also, in this study, the effects of ridership (usage rate) could be captured in the deterioration trend where increasing or decreasing the number of users may change service life and performance for some assets such as escalator or station stairs. Features related to the rolling stock deterioration, such as the type of train, the speed, the frequency of the service, etcetera, and their consequences, should also be considered in the MP platform.

Existing deterministic or probabilistic methods proposed in the literature could be utilized for developing performance prediction models; however, respecting lack of data as a common obstacle in these types of infrastructure, a customized method is illustrated in this study for the MP platform and later data should be collected by transit agencies to update and calibrate their own model. The Weibull distribution can be implemented as a widely used model in the literature. Semaan (2011) and Gkountis (2014) used this approach for a metro management system with prediction based on assumed service life or current performance respecting apparent age, which is the time passed from the replacement or major rehabilitation. However, this study proposes a customized approach to first, improve prediction model accuracy and second, to develop a dynamic deterioration prediction model considering the effects of usage rates.

Weibull Cumulative Density Function (CDF) is defined as:

$$F(t) = 1 - e^{-(\frac{t-\gamma}{\delta})^{\beta}} \tag{5-14}$$

Where:

β, γ, and δ are shape, location and scale parameters, respectively. Then, reliability (performance) function of time (t) could be presented as:

$$R(t) = 1 - F(t) = e^{-(\frac{t-\gamma}{\delta})^{\beta}} \tag{5-15}$$

The shape parameter (β) equal three represents the most typical trend of asset deterioration (Semaan 2011). Meanwhile, in the time zero it could be assumed that R (0) = 1 as the asset is brand new; therefore, location parameter (γ) would be zero. Now, the equation could be solved to find the scale parameter (δ) for each pair of apparent age and corresponding performance. Recommended service life and corresponding performance (i.e. end of asset life) can be used to find (δ) in case of having no observation; however, at least current observed performance and asset age can give the second scale parameter to capture the specific nature of decay in each case, which comes from several factors such as the environmental (e.g. exposure to harsh weather), the quality and technology (e.g. the manufacture of the escalator), the maintenance approach (e.g. routine maintenance). Customized approach for lack of data would be using current performance or even more observations as well as recommended useful life in the literature for similar asset elements to have more pair points and finally, an average of the scale parameter can be used to develop more realistic and accurate deterioration models. Using average helps to be risk neutral rather than optimistic or pessimistic.

The output would be a customized decay model, which is ready to be implemented in mathematical optimization; however, this study aims to consider the impact of usage rates in asset deterioration while it is commonly neglected in the literature. The rate of usage (e.g. station entry or EMGTs) can impact the degradation of many assets such as the escalator and elevator; stairs, doors and floors; roiling stocks and rail tracks; and gates while some others are only age-based for deterioration such as main structures; cabling and lighting; and piping systems. Thus, a dynamic degradation model is preferable, and Equation 5-15 can be customized to reflect this factor (Equation 5-16).

$$R(t) = e^{-(\frac{t}{\delta})^3} \quad while \quad \delta(t) = f(Usage(t)) \tag{5-16}$$

Where, the scale parameter is a function of usage rates (e.g. station entry), which can dynamically be updated through time. Thus, even for lack of historical data, transit agencies can define specific deterioration model for each element of the single station, which is sensitive to the rate of users. In fact, for sensitive assets to the rate of usage, δ captures the effect of ridership as well as the nature of degradation. In case of lacking data, depending on the sensitivity of degradation to usage rates and taking advantage of this flexible approach, clustering can be implemented classifying segments into usage rate levels (e.g. high, medium, low) to develop deterioration models. Using Weibull distribution as was explained here can be applied by updating scale factor by the rates of usage. This makes model capable to dynamically customizes deterioration model for updated ridership during the decision-making process.

5.3.2 EP platform

In addition to maintenance and renovation, Public Transit (PT) agencies usually plan for upgrading and expanding their networks to catch up with fast urbanization (Seggerman et al. 2007). Decision-making for network extension is often made separately as an independent budget coming from the capital investment program is assigned by government and municipality for opening new corridors. The main common goal in the expansion of the urban railway corridor is increasing overall ridership and encouraging more people to abandon the use of the private car. At the meantime, priority should also be given to PT expansions, which improve human development objectives such as employment rates and education level. For the purpose of this study, a multi-objective decision-making model is proposed to pick the best extension options among available alternatives. The objective of the EP platform is to maximize overall ridership as well as enhancing human development. The EP platform produces two main outputs: the ranked list of future stations and the inputs for ridership analyses to predict the number of entries in existing and future stations, which will be used in the MP platform.

Ridership (usage rate) for each urban railway segment is impacted by several factors of location features (such as population, employment, education level), criticality (such as interconnection of other lines, connection to suburb trains), facilities (such as the elevator), and network level of service. Existing land use and demand forecasting approaches such as activity-based models (ABM) can be used to predict potential ridership for new corridors and prioritize the expansion. The ridership ($R_{t,s}$) for existing segments (s) in the year (t) depends on ridership in the previous year ($R_{t-1,s}$) while for new segments ($Rp_{t,s}$) is forecasted based on demand analyses (e.g ABM). Also, ridership is dynamic and influenced by the trend of modal share change, which is related to the user's perceived convenience and quality of the service while it is also related to the level of quality of the network. For instance, opening more stations may lead to decreasing or increasing ridership in other stations. Thus, $\Delta R_{t,s}$ will be estimated for each segment to capture these impacts (Equation 5-17). Later, $R_{t,s}$ for existing stops will be used in the MP platform (Equation 5-16) to link deterioration model to the rates of usage while ridership for a new station is forecasted in order to prioritize future extension alternatives.

$$R_{t,s} = \begin{cases} R_{t-1,s} \pm \Delta R_{t,s} & 0 < s \leq S \quad (Existing\ segments) \\ Rp_{t,s} \pm \Delta R_{t,s} & S < s \leq S_n \quad (New\ segments) \end{cases} \tag{5-17}$$

Although, the large investments required in expansion projects are often supported by ABM models; however, ABM models are time-consuming and required large data collection campaigns to calibrate and validate (e.g. activity-based 24-hour travel-diaries, traffic counts, hotel interviews, workplace interviews, pedestrian and cyclist interviews, trip generation surveys, parking surveys, border crossing interviews, airport interviews, public transit on board-interviews, revealed and stated preference surveys, etcetera), which makes it difficult for transit agencies to consecutively develop such studies. Thus, in case of no access to such analyses, this research suggests using a customized and simplified approach proposed by Amador and Mohammadi (2019), which is based on accessible and open data (census data), to predict potential ridership and rank expansion alternatives. According to that study, the potential ridership for new stops can be estimated on the population and preference of inhabitants within the catchment zone for each new stop. Also, current entries and the historical trend of change for existing stations and the impact of opening new stops on ridership in previous years can be utilized to forecast the future ridership of existing segments.

The second objective in the EP platform can be improving human development. Therefore, all alternatives (i.e. future railway segments) are assessed respecting human development concerns such as employment rates and education level to estimate overall human development index ($H_{s,t}$) for each new stop as was developed by Mohammadi et al. (2018b). In that study, the level of human development indicators were examined for all inhabitants living in the catchment areas to find $H_{t,s}$ for each railway station. Equations 5-18 and 5-19 show the formulation for evaluating urban railway extension alternatives based on the assessment of surrounded inhabitants.

$$h_{t,s,i} = \frac{\sum_{r \in R}(I_{t,r,i} \times P_r)}{\sum_{r \in R}(P_r)} \tag{5-18}$$

$$H_{t,s} = \sum_{i=1}^{I} \beta_i \, h_{t,s,i} \tag{5-19}$$

Where $h_{t,s,i}$ is human development indicator i for segment (s) in the year (t), $I_{t,r,i}$ shows observed indicator i in block (r) in the year (t), P_r reflects the population in block r where all corresponding blocks are located in the buffer zone R ($r \in R$). Finally, the overall human development index for each segment (station) in the year (t) (H_s) is estimated respecting the indicator weight (β_i) (Equation 5-19).

Then, each station overall grade is estimated based on both objectives (ridership and human development) and their corresponding importance weights. Grades should be normalized (0 to 100) to be comparable. Each year one or more new segments will be selected for expansion respecting available budget. Cost of extension for each segment in year (t) is $CE_{t,s}$ and should cover total extension costs for a new segment including construction of the station and corresponding tunnel. Then, the total used budget in each year should respect the available budget. Whenever one new segment is added to the network, it will be part of the MP platform as a brand-new segment for following year planning. At the same time, the effects of this new stops in the other stations' entry will also be considered.

$$New\ station\ grade = \tau_1 R_{t,s} + \tau_2(100 - H_{t,s}) \quad (5\text{-}20)$$

Subject to:

$$\sum_{s=S}^{S_n} CE_{t,s} \leq BE_t \quad (5\text{-}21)$$

Where:

$R_{t,s}$= Normalized ridership of the segment s in the year t.

$CE_{t,s}$= Cost ($) of building new segment s in the year t.

$\Delta R_{t,i}$ =Dropped or improvement portion of Ridership from a year (t-1) to year t for segment s either from modal share change or action in other segments.

$H_{t,s}$ = Human development index (0-100) of segment i in the year t.

τ_1 and τ_2 = Relevant weight for human development and ridership objectives, respectively.

BE_t=Available budget ($) for extension in the year t.

5.4 CASE STUDY AND DATA COLLECTION

Montreal Metro system is selected as a case study to implement the proposed methodology. This 50-year-old network is expected to face a growth in demand of 27% for the year 2020 in comparison to 2010 (STM 2012). The network started with two lines and 26 stations in 1966-1967 and gradually has been expanded to 4 lines and 68 stations. The system is periodically maintained, and repairs are common to upkeep it in good levels of operational convenience. However, traditional planning approaches such as worst-first and expert judgment have been used for maintenance planning in this network (Abouhamed 2014). Three lines of Blue, Orange, and Yellow are planned to be extended in the future (STM 2012). Thus, the impacts of this extension should be addressed in capital investments and policies for the following years. In a similar manner, the regional trains have been recently expanded and it is possible that another expansion would come with the connection to other neighborhoods (Figure 5-4).

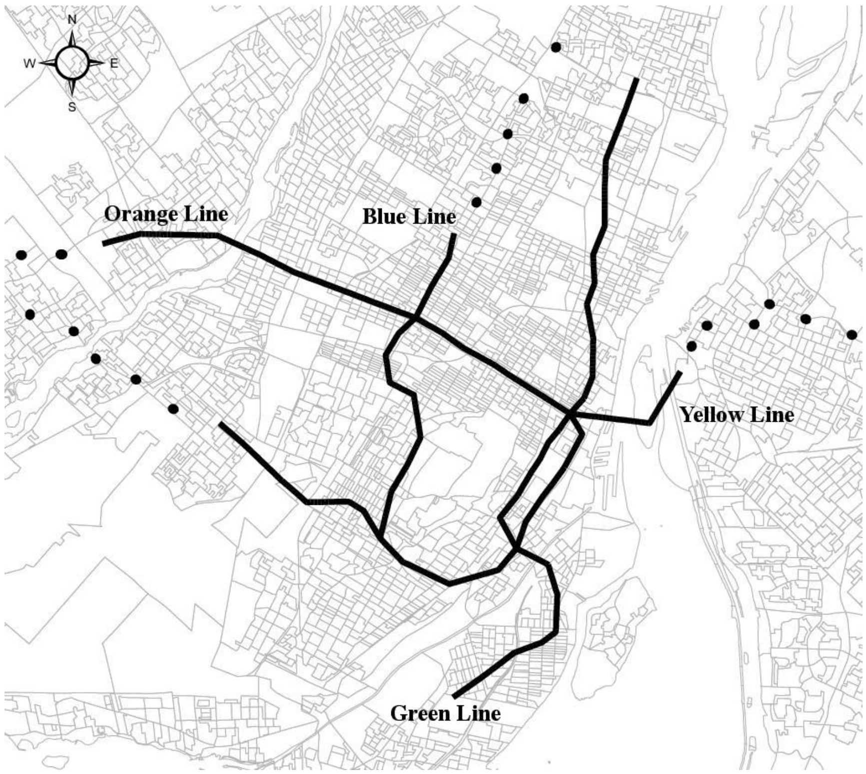

Figure 5-4, Shows the Montreal existing network and future expansion alternatives

The *Gouvernement du Québec* (2016) planned to maintain a high, recurring level of investment to ensure the maintenance and development of public transit infrastructure. In this regard, the 2016-2026 Québec infrastructure plan has set aside almost C$7.1 billion for the bus, commuter train, and metro networks. From 2016 to 2018, the *Société de Transport de Montréal* (STM) is investing C$2.2 billion, or 78% of its total capital expenditure for maintenance and upgrading of the metro system (STM 2015). At the same time, the Quebec infrastructure plan calls for substantial investments in maintaining and rehabilitating the road network and, on the other hand, for its share in major Quebec public transit development projects including the extension of the Montréal metro and more than C$10 billion to be invested in this regard (*Gouvernement du Québec* 2017). Therefore, there are some tactical questions should be answered well by decision makers and transit planners:

- Which assets (station, tunnel or car), when and how to be maintained, renovated or replaced, in order to improve overall levels of service, convenience (safety, and comfort) in the whole network respecting constraints?
- At the same time, how expansion projects could be planned and prioritized to increase network ridership and encourage the modal shift away from the automobiles while supporting the socio-economic development and sustainability through better accessibility to health, education, and job centers (reduced poverty)?
- Meanwhile, how ridership, service upgrades, and network expansion effects could be incorporated in the asset management model of existing systems?

5.4.1 Data collection

MP platform

Maintenance history and current performance of some elements (pertaining to some subcomponent) in stations and tunnels were collected through published reports from 1966 to 2018 (STM 2019). Although requested, the STM did not share more details. Therefore, the decision-making model was developed considering one element in each sub-component for fixed assets. The first renovation program for this metro system called" Reno-Station" started in 1998 and 26 the oldest stations were rehabilitated. It consisted of improving the entrance areas and the accessibility for customers and replacement of architectural, structural, mechanical and electrical elements. This program was followed with "Reno-System", which several new telecommunications systems and operations control processes components were being installed throughout Montreal's underground network. Thus, by reviewing maintenance history (STM 2019; Semaan 2006 and 2011), current age and state of elements were identified.

Since STM has started the next main rehabilitation program after 2010, the model was run from 2010 for 20 years' time horizon to give this chance to compare the outputs with current planning by STM. The EP platform was also run from 2021, which is expected to be the starting time for metro extension in this city. This analysis focuses on fixed assets and 68 segments including stations and corresponding tunnels were identified for the starting point. Each metro segment includes two main parts of the station and tunnel and for each, three components of civil, mechanical, and electrical were defined. In the next lower hierarchy level for each subcomponent, several elements could be identified as was shown in Figure 5-3. Due to lack of data, only one element is selected for each subcomponent (Figure 5-5). Performance condition (0 to 100) was estimated for each element in 2010 based on assets age and collected historical data for implemented maintenance.

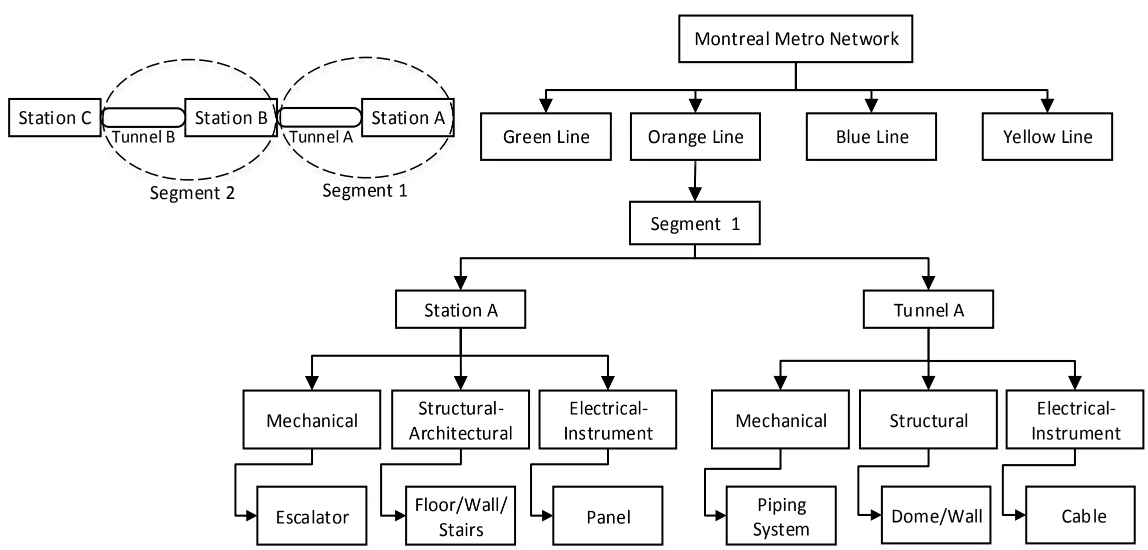

Figure 5-5, Defined hierarchy network for case study

For each selected element in Figure 5-5, the deterioration model should be developed as was explained in the methodology section through a Weibull distribution. Two sources were used in this regard to estimate the scale parameter. The first pair came from recommended useful life (i.e. assuming an asset age in the 40% performance), which was found in the literature (Infrastructure Canada 2016; RTA 2014; Toronto Hydro -Electric System 2009; FTA 2008; Schindler 2019; and Eason 2012). To customize the recommended useful life for the Montreal metro system, previous observations were also used as a reference point, which gives pairs of element performance and age.

As was discussed earlier, the deterioration rate for some elements is a function of usage. Increasing ridership (usage) in this case study can accelerate decay in escalators, stairs, and floors while other elements such as the electrical panel or piping systems are less depended on the number of users. The designed life for the elements comes from a normal loading. For instance, the escalator should be designed for three hours with 100 percent design load, six hours with 50 percent and the rest time with 25 percent (APTA 2015). Thus, increasing or decreasing loading patterns can impact the rate of deterioration. For implementing this model in practical cases, real observations of different stops with various usage rates can be used; however, for the purpose of this study due to data availability, stations were classified in three clusters of high, medium, and low usage rates. By changing the ridership (increase or decrease) for each station in the long-term planning, dynamically the station may be classified in the other clusters and deterioration model will be updated accordingly. For this case study, since there are only two elements subjected to this update and considering the rate of ridership increase the majority of stations will remain in the same cluster, this ridership update is ignored.

Figure 5-6 presents the deterioration models for the escalator. Three deterioration models of high, medium and low usage rate were developed while three scale parameters were estimated based on the recommended useful life in the literature and also the STM inspection, which was made in 2004 for 24 first generation stops. In this study, corresponding useful life for the escalator in 40% performance (reliability) can change from 30 to 20 years for low to a high rate of usage, respectively (Figure 5-6). Figure 5-7 shows six deterioration prediction curves for all elements in this case study. As it was discussed earlier, depending on access to historical observations and inspections, transit agencies can improve the accuracy of the deterioration models using this customized approach or other deterministic or probabilistic models. Whenever the model is implemented to rail tracks or rolling stock, the deterioration model can be updated based on the change in usage rates (e.g. EMGTs) for different lines or across time horizon.

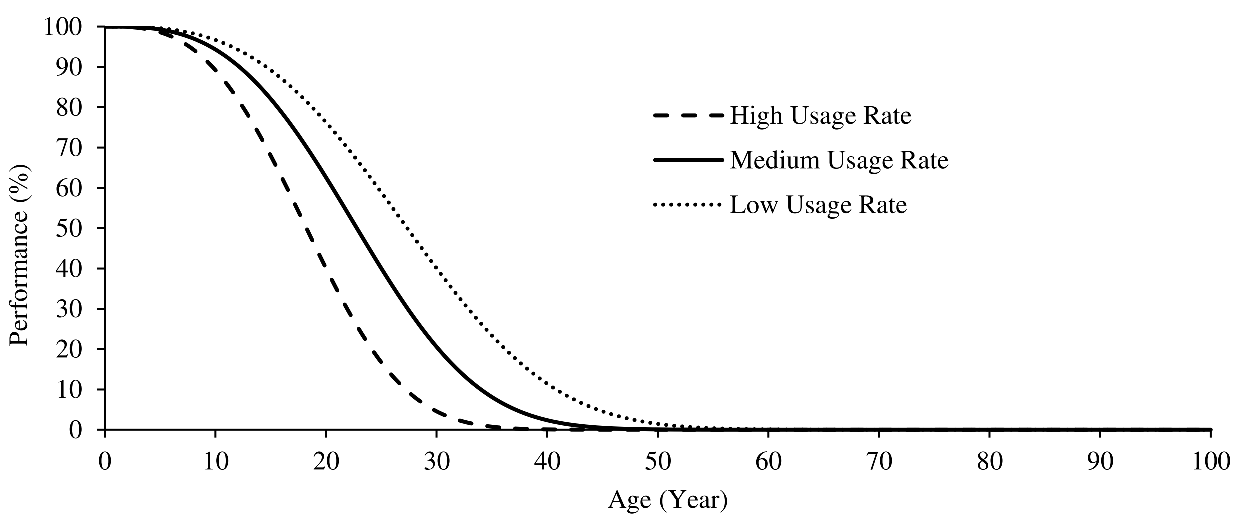

Figure 5-6, Deterioration model for escalator

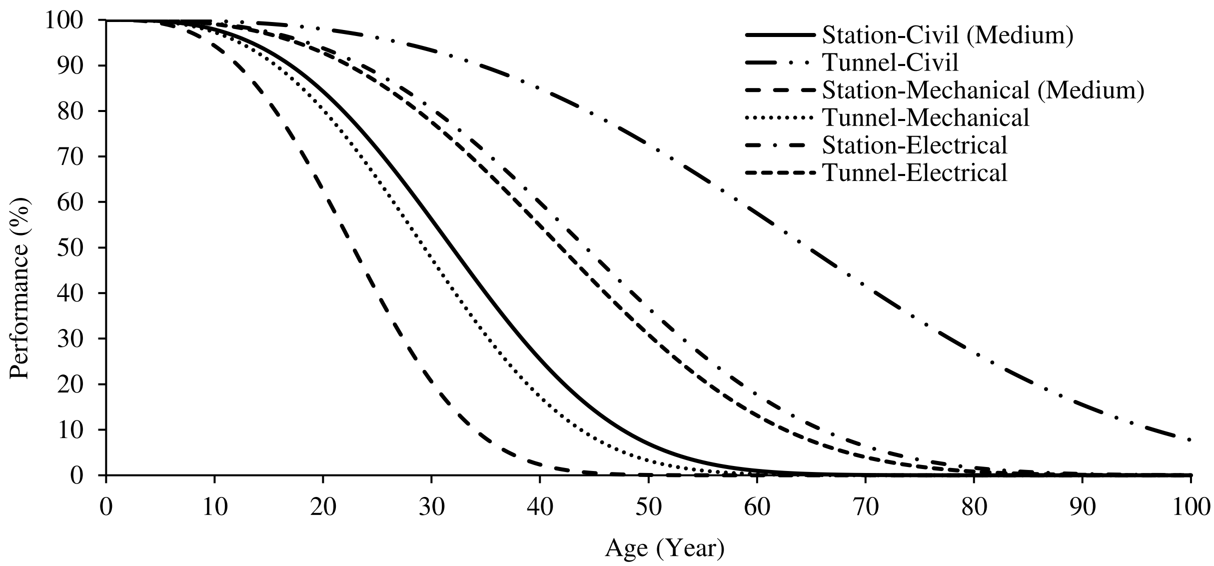

Figure 5-7, Deterioration model for metro elements

Table 5-2 represents the decision rules and treatment alternatives for each element. To develop this table and to estimate the value for each asset, its corresponding maintenance and replacement cost, first, the total construction cost for a brand-new corridor was estimated. The total cost for Orange line extension with building 3 new stations and 5.2 km tunnel in 2007 (i.e. C$ 143,000,000 per kilometer) (TAC 2015) was used as a reference cost for this purpose. This cost is subjected to be increased by an average inflation rate of 1.6 % (Bank of Canada 2019) and the unit rates are updated from 2007 to 2010. The cost breakdown in the station and tunnel was found through literature (Flyvbjerg et al. 2013; Metro 2010; and Hass 2016) to estimate replacement and reconstruction unit costs (Table 5-2). The unit costs for tunnel elements are presented per length of the tunnel to justify the segment length. The suggested costs per station are estimated for an average depth of the station platform (17 meters) and unit rates for civil (floors/stairs/walls) and mechanical (escalator) sub-components are customized by station depth.

Table 5-2, Treatment interventions cost and benefit for all elements

Component	Sub-Component	Element	Treatment	Unit	Cost (C$)	Lower	Upper	Performance Gain (%)
Station	Civil	Floors-stairs	Do-Noting	Station	0	60.01	100	0
			Rehabilitation	Station	6,515,171	40.01	60	50
			Reconstruction	Station	13,030,343	0	40	Brand New
	Mechanical	Escalator	Do-Noting	Station	0	60.01	100	0
			Renovation	Station	1,085,862	40.01	60	50
			Replacement	Station	2,171,724	0	40	Brand New
	Electrical	Panel	Do-Noting	Station	0	40.01	100	0
			Replacement	Station	723,908	0	40	Brand New
Tunnel	Civil	Dome-Wall	Do-Noting	km	0	60.01	100	0
			Rehabilitation	km	11,251,598	40.01	60	50
			Reconstruction	km	22,503,195	0	40	Brand New
	Mechanical	Pump	Do-Noting	km	0	60.01	100	0
			Renovation	km	750,107	40.01	60	50
			Replacement	km	1,500,213	0	40	Brand New
	Electrical	Cable	Do-Noting	km	0	40.01	100	0
			Replacement	km	750,107	0	40	Brand New

EP platform

To develop the EP platform, planned extension by STM was used (STM 2012). The metro expansion plan designed for three lines: Blue to the east, Orange line for both directions (to create a loop), and Yellow line to the south direction into Longueuil City (Figure 5-4). The government gave the priority to the Blue line extension (*Gouvernement du Québec* 2017) starting from 2021 to 2026, which means in average one station per year. Thus, for each year one new segment (station and corresponding tunnel) can be selected in this study from a total of four alternatives, which comes from three lines while there are two options for the Orange line (i.e. one option for each direction). The new segments are evaluated from potential ridership as well as the human development index. The latest (2016) Canadian census data (CHASS 2019) was used to collect statistical data of the population, socio-economic, and socio-demographic characters for municipal blokes within the buffer zone of each station.

To rank future alternatives, 1000 meters buffer zone was considered for the impacted zone by a new metro stop. Amador and Mohammadi (2019) found that opening three new stations in Orange line in 2007 caused a 6.24% net increase in public transit users in 2011 of workers 15 years and older in the 1000 meters buffer zone of new stops while total growth was 7.95%. Using five-year intervals helps to avoid short-term improvement due to expansion as well as fluctuations. Thus, based on the total worker population living in the catchment area by each stop, the potential ridership could be estimated for each new station ($Rp_{t,s}$). In future studies, other types of trip purposes (e.g. education) can also be used for this analysis; however, this study only considered workers given the availability in the census data. Employment rate (%) for population 15 years and over as well as the percentage of postsecondary certificate holders were also used to estimated employment and education indicators in order to find human development index for future stops (Mohammadi et al. 2018b). Meanwhile, several factors should be involved in estimation of $\Delta R_{t,s}$. To estimate current and future ridership for existing segments, the previous observation (e.g. the number of entries in each station) can be used to capture the trend of change. Also, by comparing other stations entry before and after 2007, the impact of opening new station to whole network can be considered. As there was no access to all entry records for the case study, the strategic plan 2020 (STM 2012) was used for this purpose. This plan predicted that by considering only maintenance projects the STM should reach 420 million trips in 2020 in comparison to 363.3 million trips in 2006, which means approximately 15.6% ridership growth in metro users. Thus, 1.04% yearly growth is predicted as an average rate for existing stations. However, the report forecasted for 455 million trips in 2020 with the addition of expansion projects (since 2014), which means 2.4% growth per year on average for any given station from 2014 to 2020. Therefore, these two rates were used in this study to predict future usage rates before and after opening new stations. The 1.04% was adopted as growth for the existing stations in the planning horizon 2010 to 2021 and the 2.4% was the ridership increase on the existing stations after opening new stations (after 2021).

Exploring ridership history as well as the future prediction for segments helps decision makers to apply a smart and more realistic planning by addressing the impact of ridership on asset deterioration as was discussed earlier. Since all stations in this case study are operating in the acceptable levels, minor changes are expected in ridership resulting from station overall performance improvement or decay, thus, could be ignored in this study; however, future researches can address this issue.

5.5 RESULTS AND DISCUSSION

5.5.1 EP platform

Table 5-3 summarizes the EP platform outputs while stations are put in order of construction (i.e. location in the line extension) for each line in the table. For each station potential increase in ridership (entry) is estimated and normalized (0 to 100). The current level of education and employment (normalized) are two indicators represent the human development situation in the corresponding catchment area for each stop. Equal weights are considered to estimate overall human development indexes and grades. As can be seen, the first three Blue line stops have the highest overall grades, which comes from the higher potential ridership due to the compacted buffer zone. Assuming that government financial restrictions impede to invest in the expansion of more than one line at a time and considering the order of stops from a construction perspective, the best approach is giving full priority to the Blue line, which has the highest average (Avg) grade. This approach is fully matched with government decision for the coming expansion. The second priority can be given to the Orange line based on the overall and average grades. Another motivation for pushing this line, which is not captured here, is decreasing the travel time of many commuters by looping the Orange line, which can also encourage more people to use the metro. On the other hand, expanding the Yellow line may also improve mobility in the south; however, more demand predication analyses should be done to capture all these potential benefits.

Table 5-3, Ridership and human development assessment for future stations

Line	Station	Ridership *	Avg	Education *	Employment *	Overall Human Development	Avg	Overall Grade	Avg
Blue	Pie-IX	100.0	58.3	55.4	54.1	54.7	51.2	72.6	53.5
	Viau	83.4		54.0	52.4	53.2		65.1	
	Lacordaire	80.7		51.6	50.3	51.0		64.9	
	Langelier	66.9		51.2	47.4	49.3		58.8	
	Anjou	58.3		54.5	47.8	51.2		53.5	
Yellow	Joliette	28.6	45.0	66.1	51.9	59.0	57.3	34.8	43.8
	Saint-Sylvestre	29.3		68.2	52.8	60.5		34.4	
	De Chambly	60.6		58.2	58.1	58.2		51.2	
	Roland-Therrien	34.9		61.7	57.0	59.4		37.8	
	Cure-Poirier	61.7		52.0	55.9	54.0		53.8	
	Jacques-Cartier	54.6		51.7	54.5	53.1		50.7	
Orange	Poirier	52.1	44.9	53.8	51.6	52.7	54.7	49.7	45.1
	Bois-Franc	74.7		59.2	53.5	56.3		59.2	
	Gouin	27.7		66.4	55.4	60.9		33.4	
	Chomedey	53.7		47.7	48.2	48.0		52.9	
	Notre-Dame	58.3		43.6	49.1	46.4		56.0	
	Saint-Martin	25.7		46.1	47.7	46.9		39.4	
	Souvenir	21.8		50.9	92.4	71.7		25.0	

Note: * normalized

5.5.2 EM platform

Stage I was run for 20-year time horizon started from 2010 to elaborate the minimum required budget to satisfy the performance threshold of 40% for all selected elements across the network. In this approach, the model only concentrates on critical elements to satisfy constraints (Equation 5-4). Figure 5-8 presents both yearly and total required budget (C$). For the first year, C$45 million is required to take care of critical assets called backlog, which is a common obstacle in managing public infrastructure. As can be seen, the average required budget has been increased through this time horizon while several huge jumps were observed after year 8 (2018) and it is not usually easy for governments to handle these increased costs.

Figure 5-9 shows the corresponding performance resulted from this budget allocation scenario. Although opening new stations from the eleventh year (2021) helped raise in overall performance in the Blue, and later Orange line, the trend is declining where the overall performance dropped to less than 80% by 20 years (Figure 5-9).

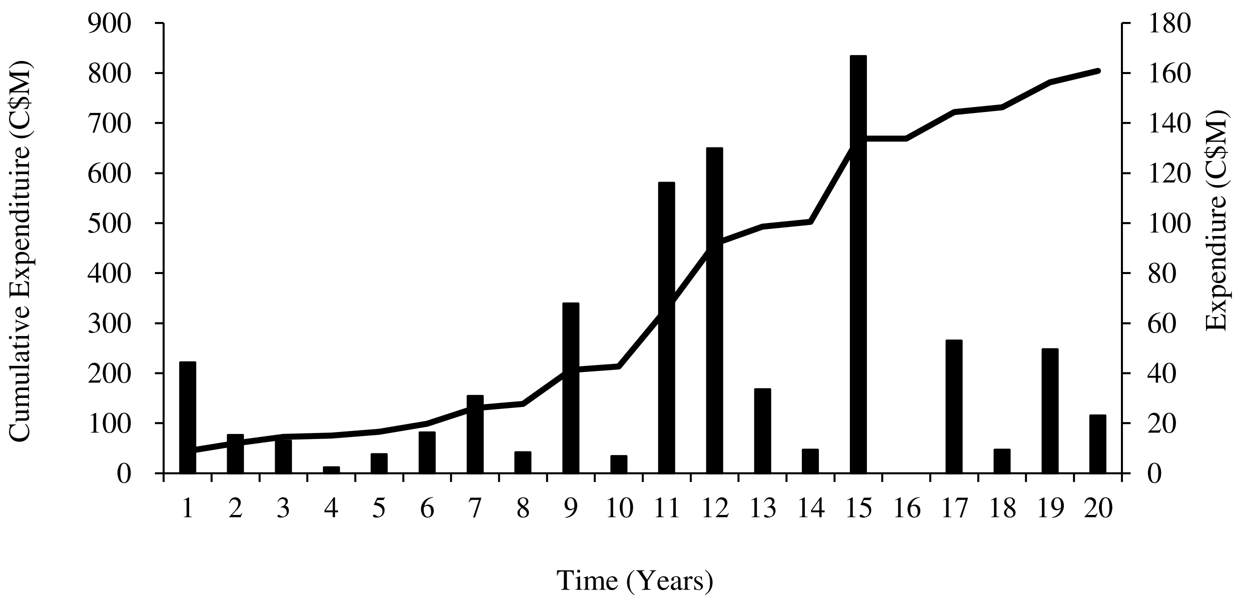

Figure 5-8, Required budget in stage I

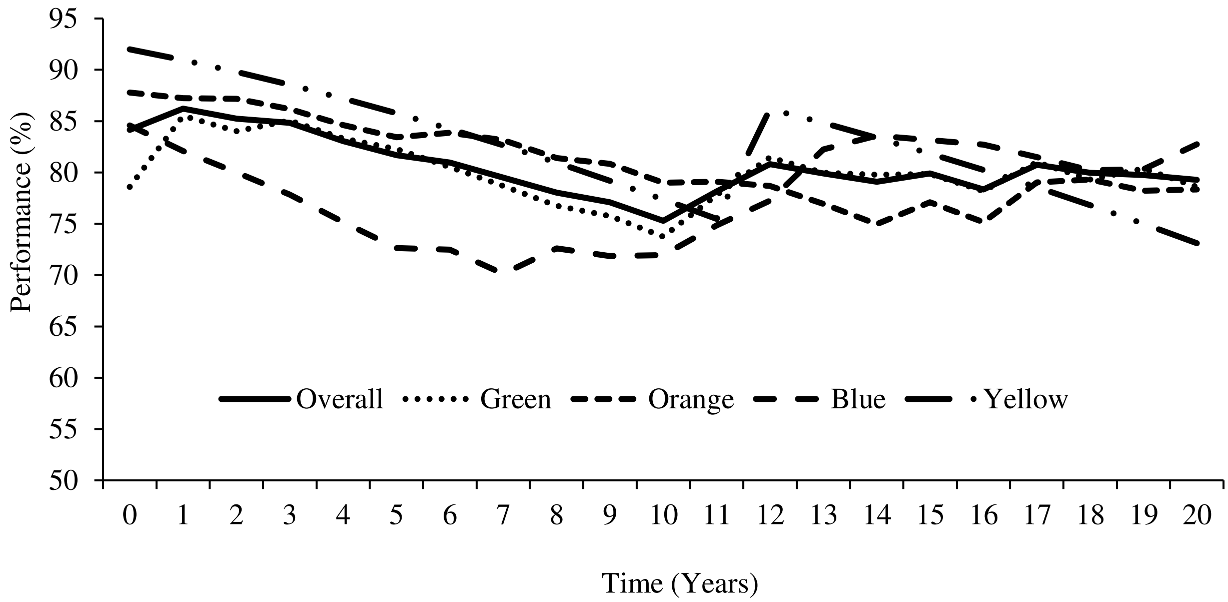

Figure 5-9, Corresponding performance in the stage I

In stage II, the maximum available budget for each year should be defined. The average spent money in the first stage for 20 years' time horizon was C$40 million. Excepting the first year, at the beginning less budget was spent by the model replacing critical elements. Thus, three scenarios were designed based on maximum budget availability of C$25, 30, and 35 million while the assigned budget for the first year would be the same as the stage I. These budget caps similar to unit costs for interventions were subjected to the inflation rate for the following years. A same performance threshold of 40% was implemented as a constraint. The model was run three times and Figure 5-10 compares the cumulative expenditure (C$) for all scenarios. As the figure shows if government assigns maximum C$25 million per year, a couple of times, more than defined cap should be spent to satisfy performance threshold; however, C$30 million starting point would be enough for this purpose while C$35 million was sometimes more than enough.

Figure 5-11 shows the impact of each scenario on the overall network performance across the time horizon. Except for stage I, which gradually overall performance was dropping and only opening new stations in year 11 (i.e. 2021) made it up, the rest always kept up (more than 80% performance) the overall performance while the much less total budget was spent. This efficiency in stage II comes from doing major maintenance to avoid later replacement, which proves the beauty of using proactive maintenance. Stage I only satisfies performance thresholds and could lead to faster-declining performance while by spending more money on maintenance, renovation, and rehabilitation, stage II could save asset owners from more expensive future replacement.

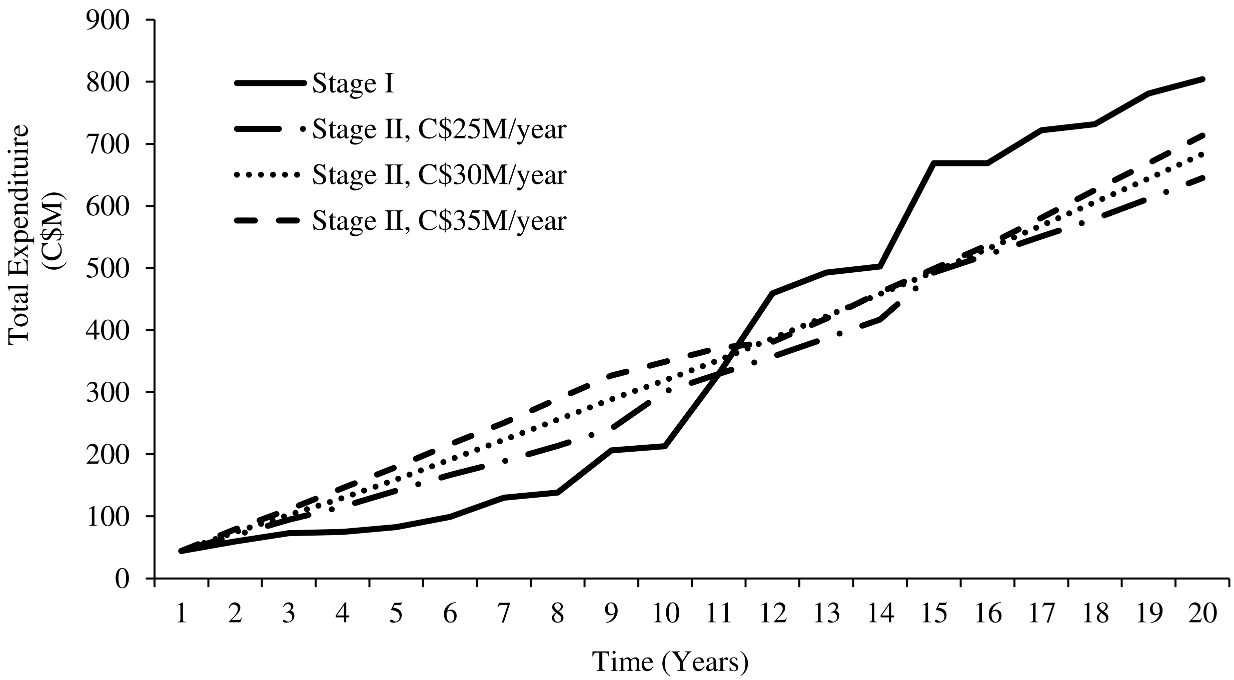

Figure 5-10, Comparing cumulative expenditure in stage I and stage II

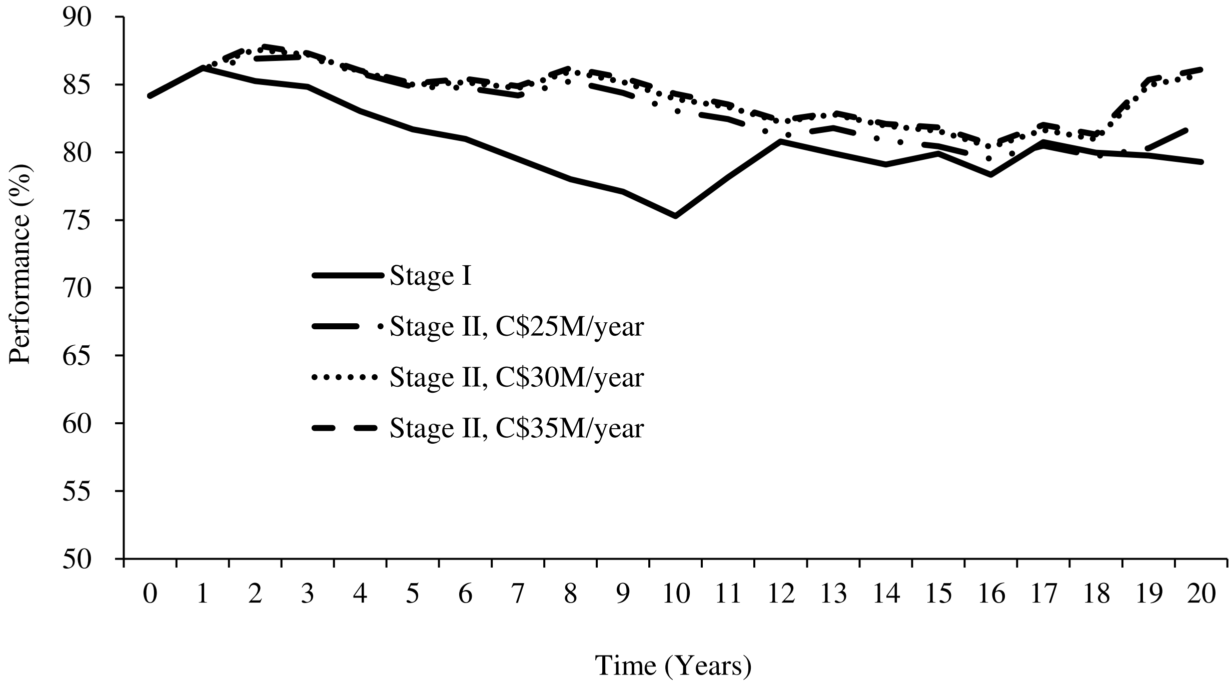

Figure 5-11, Comparing overall network performance in stage I and stage II

From a life cycle cost perspective, the stage II scenarios might be criticized as more budget should be spent in advance. Therefore, the present value method (Equation 5-22) was used to compare more precisely the four scenarios based on the average interest rate of 1.15% (Bank of Canada 2019). Table 5-4 compares all scenarios from cumulative expenditure, present value and average performance in this study.

$$Present\ Value = \sum_{t=1}^{20} \frac{C_t}{(1+i)^t} \tag{5-22}$$

Table 5-4, Comparing stage I and II from life cycle cost and achieved performance

Items	Stage I	Stage II		
		C$25M/year	C$30M/year	C$35M/year
Cumulative Expenditure (C$)	804,217,822	644,979,370	683,536,744	713,405,389
Present Value (C$)	710,668,027	576,721,100	612,076,263	639,033,269
Average Performance (%)	81	83	84	84

The long-term plan indicates that C$25 million could be the most efficient approach in case the government will be able to raise budgets for a couple of specific years; otherwise, C$30 million gives a smooth budget allocation. However, the combination of these scenarios could also be tested where the maximum available budget at the beginning might be more or less and vice versa.

5.5.3 Maintenance and Expansion practices in Montreal

Generally, it is not easy to validate decision-making models particularly the one presented in this case study given that not all assets where studied (i.e. whole elements, sub-components, and components). For the purpose of this study, the suggested maintenance and expansion plan by the models were compared with the transit agency (STM) approach. Coincidentally, for EP platform, giving priority to Blue line is the same decision as the government has made for expansion of the network indicating model works well. For maintenance and renovation plan for existing assets (MP platform), it seems STM often relies on age-based approach, which prioritizes intervention according to asset age, and has its own limitations in capturing reality and finding the optimal solutions. In this time horizon (2010-2030), STM is running Reno Metro, which is included two maintenance and replacement programs of Reno-System (Phase II to IV) and Reno-Infrastructure (Phase I and II) to modernize and renovate metro system (STM 2019).

Escalators as one critical element in the level of service of the stations are also part of this program. Previously in 1997-2000, STM replaced 79 old escalators from the first opened stations. In the second round starting from 2016, 24 escalators will be replaced, and 39 escalators will undergo a major refurbish. These escalators are selected due to the average age of 30 years (STM 2019); however, it seems the STM in the second round also planned for proactive maintenance instead of only reactive ones. The decisions made by models for escalators were compared with the published plan by STM for replacement and renovation. The stage II and I planned years for interventions are compared for chosen stations by STM for replacement in this program (Table 5-5). Considering 2016 (the seventh year of planning) as the start time of replacement by STM, similar decisions were made by the model in stage I, which only replaces elements at the end of service life. It could be concluded that these escalators have not been fully renovated before and STM possibly used a similar approach as the stage I. Analyzing decisions for the same stations in the second stage (C$30/year million) indicates that model gave priority to these elements to accelerate major renovation and avoid replacement to increase the life span as well as optimize spending budgets in long-term planning. Except for the first year, which model only removed the backlog, escalators in these stations are ranked in the top priority for action.

Table 5-5, Planned year of renovation and replacement in stage I and II

Station Name	*Saint-Michel*	*Édouard-Montpetit*	*Jean-Talon*	*Namur*	*Côte-des-Neiges*	*de la Savane*	*Fabre*
STM	After 2016 (i.e. year 7)						
MP platform, Stage I	6	10	17	6	8	6	8
MP platform, Stage II (C$30 M)	2	4	13	3	4	3	3

Some other similarities have been observed for structural elements of the stations. STM also did some renovations in stations and *Berri-UQAM* as the most important station was renovated from 2010 to 2018 and some other stations such as *Snowdon*, *Guy-Concordia*, *Villa-Maria*, *place-d'Armes*, and *McGill* were also chosen for renovation. The model in stage II (C$30 million) also picked these stations during a similar time period (2010 to 2018), which shows that it could be trusted.

5.7 CONCLUSIONS

A comprehensive network-level decision-making model is proposed to handle maintenance and renovation plans for urban railway systems. The model including two platforms of maintenance and expansion planning is able to capture the impact of ridership fluctuations and network expansions through into the decision-making process. The model was implemented in the Montreal metro system; however, due to data limitations, six elements in all 68 fixed segments (i.e. station and corresponding tunnel) were selected. MP platform was run in two stages and through four budgeting scenarios while the impact of usage rate was considered and comparing results indicated that proactive maintenance (C$25/year) million was able to save C$150 million (25%) cumulative expenditure after 20 years while the overall performance was also slightly (2%) improved. There is a good matching between the EP platform and government plan for the extension. Similar replacement decisions were made for the escalator by STM and the proposed model in stage I, which confirms applying the reactive maintenance approach for those elements. By having access to more complete performance assessment and historical data, future studies can apply a full model.

The proposed system can be applied on rail rapid transit (underground and surface); Light Rail Transit (LRT); and suburban trains as well as Bus Rapid Transit (BRT) to guide planning for their maintenance, upgrade, and expansion to achieve higher levels of convenience and reliability, which then encourage higher transit ridership.

Chapter 6 : SUMMURY, RESEARCH CONTRIBUTIONS, LIMITATIONS AND FUTURE WORKS

6.1 SUMMURY

The main objective of this research was to develop a comprehensive model for managing urban railway systems, such as the metro, that supports strategic decisions to maintain the highest level of convenience, safety, comfort and reliability in the metropolitan area. To overcome the gaps found in the literature, these proposed steps was taken:

Step I: Developing an understanding of convenience with special concentration on the level of service from the passenger's perspective. The idea was to model, quantitatively and practically, aspects relevant to the user convenience for transit vehicle's comfort. **Step II**: Development of a decision-making model to mimic the operation of the transit systems capturing indirect impacts such as human development and sustainability. **Step III**: Development of an optimization model to analyze investment scenarios for the upgrade and expansion of the railway network, while up-keeping the existing operation at acceptable levels of service, guiding policies, and respecting budget limitation. This was included the relationships between the transit system and human development issues, addressing fighting poverty; supporting accessibility to health, education and job centers; and encouraging the modal shift away from the automobiles.

6.2 RESEARCH CONTRIBUTIONS

This research could be used by several public transit systems. The platforms and models can handle urban railway systems such as Light Rail Transit (LRT), metro, and suburban trains as well as Bus-Rapid-Transit (BRT) and tramway to guide planning for their maintenance, renovation, upgrading and expansion to achieve higher levels of convenience and reliability, which then encourage higher transit ridership. The main contributions of this study could be summarized as below:

- Comprehensive literature review in the second chapter prepared a good foundation for future studies in urban railway asset management platforms and solutions. The framework developed in the second chapter is suitable for further research of underground as well as LRT, BRT, tramways, and suburban trains while addressing both customers' and agencies' concerns and expectations.
- The third chapter filled literature gaps including lack of a quantitative performance assessment platform for rail cars while the customer's perspective and concerns are also addressed. The proposed model in this chapter is applicable to railway systems (underground and surface) and other rail transit systems such as Tramways and suburban train to evaluate the level of comfort in the rolling stocks. The assessment results further could be used for decision-making and optimum budget distribution in the maintenance and rehabilitation of both cars and track assets. Also, comfort measurements could be applied to the transit modal choice analysis and land-use planning.
- The proposed model in the fourth chapter could be used by all existing urban railway systems as well as other public transit networks such as BRT, and traditional buses to guide planning for their maintenance, upgrade, and expansion. This platform linked the human development and sustainability issues to asset management of transit infrastructure for the first time to address novel raised concerns and expectations. The proposed decision-making model enhanced classical approaches to optimally distribute the available budget to the

most vulnerable regions in terms of both the level of service and human development factors such as health, education, poverty, and employment.

- Finally, the fifth chapter covered the main gap in the literature, which is the lack of a network-level decision-making (optimization) model for urban railway systems. Taking advantage of the previously developed models, a comprehensive optimized decision-making model was proposed to find the optimum long and medium-term scenarios in maintenance, rehabilitation, upgrading and extension planning for urban railway assets while addressed for the first time the role of ridership (usage rate) trends in the planning process.

6.3 LIMITATIONS AND FUTURE WORK

As it was summarized in the second chapter, there are several open research windows of asset management for urban railway systems, which are not addressed in this study. In addition, further studies can be conducted in expanding (or adapting) proposed models in this research. Other potential future works are categorized respecting proposed models one to three:

Model I:

- Future studies can consider more functional factors for car assessment related to mechanical or electrical aspects.
- Addressing user comfort in demand predication as was explained is a potential future research to improve transit planning.
- Using an expanded survey with more details to improve model accuracy and prioritize factors.
- Testing model through a newly built system to update the model.

Model II:

- Comparing before and after (opening or advancing rail systems) human development assessment and calibrating model in a more accurate way.
- Testing model for other case studies capturing more indicators.
- The combined objective approach was used to solve the multi-objective optimization model to take advantage of flexibility and sensitivity analysis for weights and also to avoid complexity for practitioners. However, other approaches also can be tested in future studies.

Model III:

- Collecting more historical data to improve deterioration models for different asset types.
- Testing a case study with more elements by collecting enough data.
- Addressing uncertainty in both deterioration and effectiveness in decision-making model.

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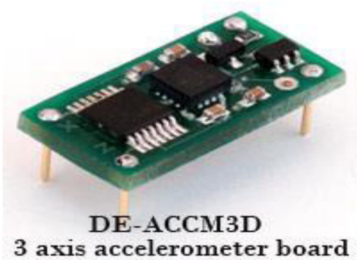
APPENDICES

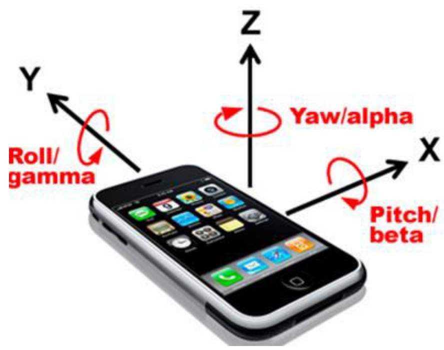
APPENDIX A: Sample devices used in Model I

Vanier Graphical Analysis app

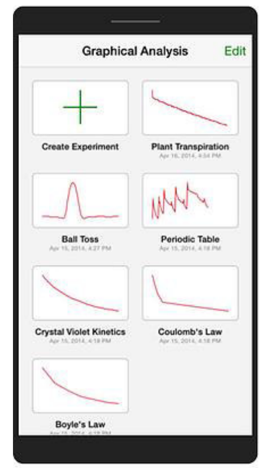
http://www.variableinc.com

Acceleration:





iPhone 6



Relative Humidity and Temperature:

Node+ sensor

www.variableinc.com

Vaisala RH and Temperature Meter

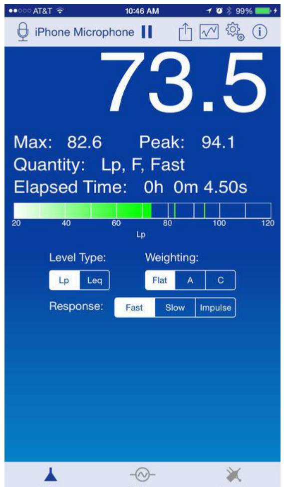
https://www.vaisala.com

Noise:

SoundMeter app

https://itunes.apple.com

iPhone 6



Casella Sound Level Meter

http://www.casellasolutions.com

Lighting and CO2:

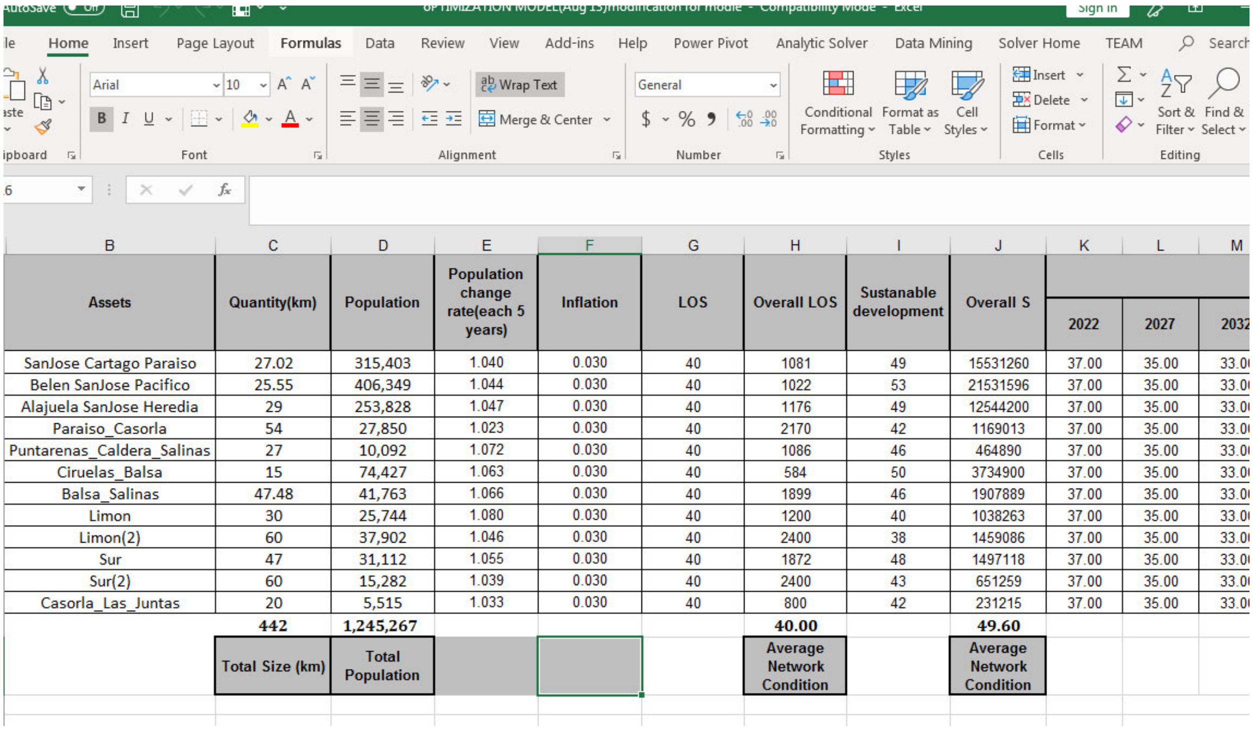
Node+ sensor

www.variableinc.com

Cooke Light Meter

https://www.calright.com

APPENDIX B: Sample screenshots for Model II

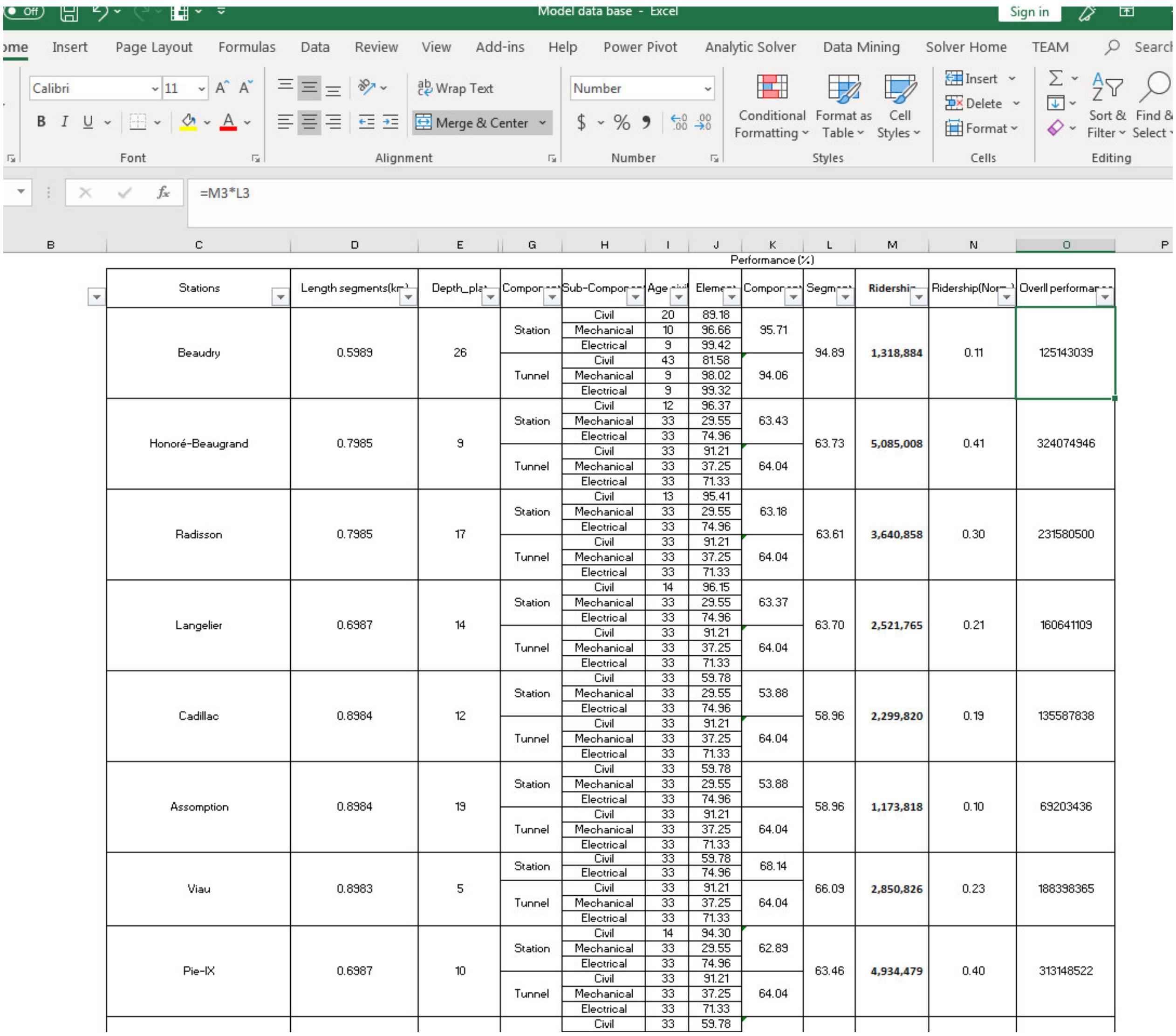


Assets	Quantity(km)	Population	Population change rate(each 5 years)	Inflation	LOS	Overall LOS	Sustanable development	Overall S	2022	2027	2032
SanJose Cartago Paraiso	27.02	315,403	1.040	0.030	40	1081	49	15531260	37.00	35.00	33.0
Belen SanJose Pacifico	25.55	406,349	1.044	0.030	40	1022	53	21531596	37.00	35.00	33.0
Alajuela SanJose Heredia	29	253,828	1.047	0.030	40	1176	49	12544200	37.00	35.00	33.0
Paraiso_Casorla	54	27,850	1.023	0.030	40	2170	42	1169013	37.00	35.00	33.0
Puntarenas_Caldera_Salinas	27	10,092	1.072	0.030	40	1086	46	464890	37.00	35.00	33.0
Ciruelas_Balsa	15	74,427	1.063	0.030	40	584	50	3734900	37.00	35.00	33.0
Balsa_Salinas	47.48	41,763	1.066	0.030	40	1899	46	1907889	37.00	35.00	33.0
Limon	30	25,744	1.080	0.030	40	1200	40	1038263	37.00	35.00	33.0
Limon(2)	60	37,902	1.046	0.030	40	2400	38	1459086	37.00	35.00	33.0
Sur	47	31,112	1.055	0.030	40	1872	48	1497118	37.00	35.00	33.0
Sur(2)	60	15,282	1.039	0.030	40	2400	43	651259	37.00	35.00	33.0
Casorla_Las_Juntas	20	5,515	1.033	0.030	40	800	42	231215	37.00	35.00	33.0
	442	1,245,267				40.00		49.60			
	Total Size (km)	Total Population				Average Network Condition		Average Network Condition			

2022							
New population	Action	Treatment	New Condn "LOS"	Overall "LOS"	New Condn "S"	Overall "S"	Cost
327993	1	Replace	100.00	2702	92.86	30458306	156,617,927
424060	1	Replace	100.00	2555	96.61	40967559	148,097,263
265731	1	Replace	100.00	2940	93.04	24723606	170,413,289
28491	0	Do nothing	37.00	2007	40.67	1158618	0
10818	0	Do nothing	37.00	1004	44.76	484205	0
79115	0	Do nothing	37.00	540	48.87	3866669	0
44511	0	Do nothing	37.00	1757	44.37	1975181	0
27803	0	Do nothing	37.00	1110	39.02	1084940	0
39646	0	Do nothing	37.00	2220	37.19	1474324	0
32824	0	Do nothing	37.00	1732	46.81	1536507	0
15878	0	Do nothing	37.00	2220	41.31	655881	0
5697	0	Do nothing	37.00	740	40.62	231390	0
1,302,567							
				49	66.0	83.39	475,128,479
				CONDITION	Overall	CONDITION	COST
					500,000,000		

2027							
New population	Action	Treatment	New Condn "LOS"	Overall "LOS"	New Condn "S"	Overall "S"	Cost
341,086	0	Do nothing	88.00	2378	87.63	29888747	0
442,543	0	Do nothing	88.00	2248	91.37	40436715	0
278,192	0	Do nothing	88.00	2587	87.81	24426780	0
29,146	0	Do nothing	35.00	1899	39.79	1159839	0
11,597	0	Do nothing	35.00	950	43.89	508950	0
84,100	1	Replace	100.00	1460	92.49	7778696	98,105,896
47,440	0	Do nothing	35.00	1662	43.50	2063761	0
30,028	0	Do nothing	35.00	1050	38.15	1145539	0
41,470	1	Replace	100.00	6000	80.81	3351047	403,174,914
34,629	0	Do nothing	35.00	1638	45.94	1590805	0
16,497	0	Do nothing	35.00	2100	40.44	667068	0
5,885	0	Do nothing	35.00	700	39.75	233892	0
1,362,612							
				56	69	83	501,280,809
				CONDITION	Overall	CONDITION	COST
						524,871,521	

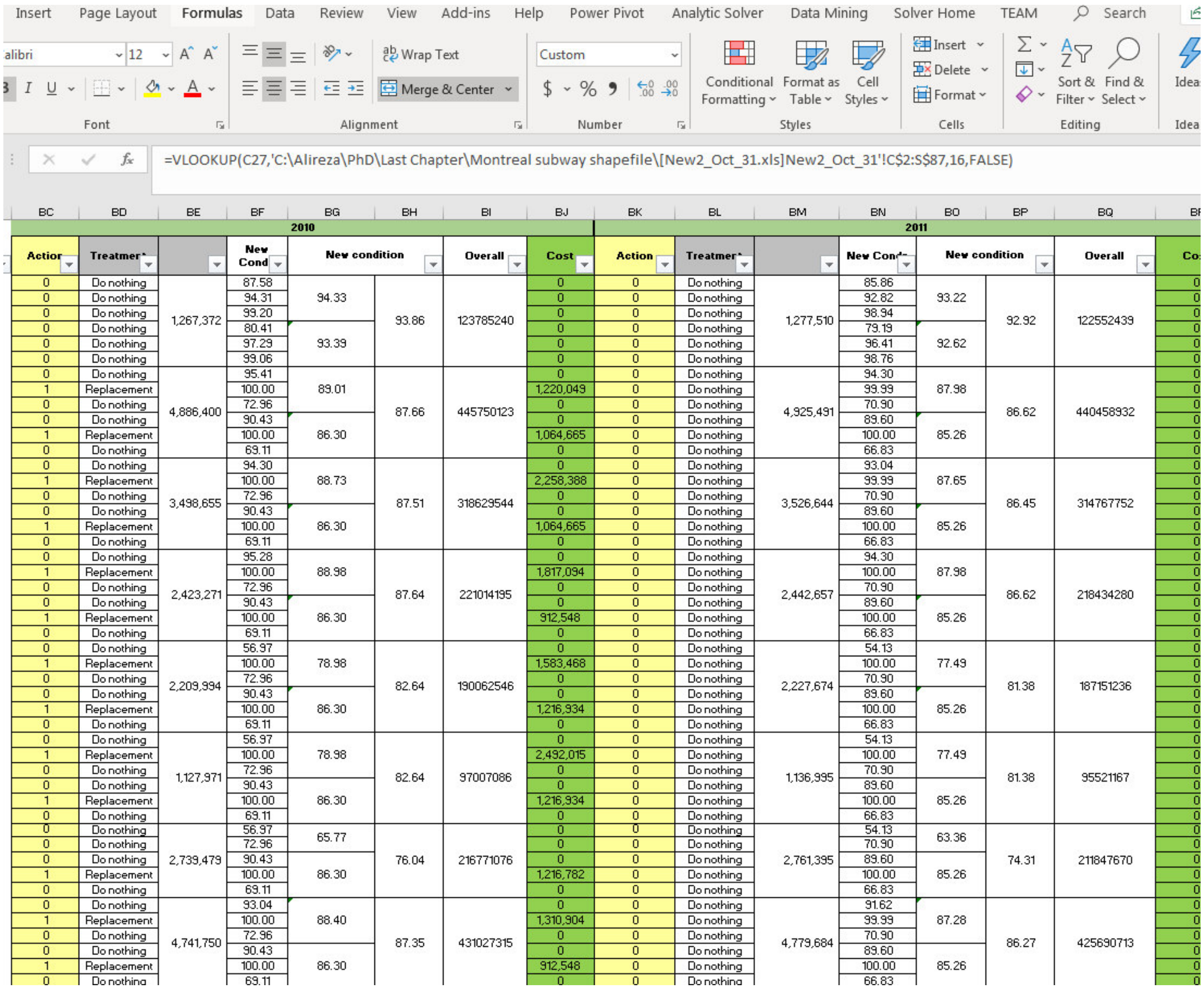
APPENDIX C: Sample screenshots for Model III



Model data base - Excel

=M3*L3

Stations	Length segments(km)	Depth_pl...	Compon...	Sub-Compon...	Age	Eleme...	Compon...	Segm...	Ridershi...	Ridership(Nor...	Overll performan...
Beaudry	0.5989	26	Station	Civil	20	89.18	95.71	94.89	1,318,884	0.11	125143039
				Mechanical	10	96.66					
				Electrical	9	99.42					
			Tunnel	Civil	43	81.58	94.06				
				Mechanical	9	98.02					
				Electrical	9	99.32					
Honoré-Beaugrand	0.7985	9	Station	Civil	12	96.37	63.43	63.73	5,085,008	0.41	324074946
				Mechanical	33	29.55					
				Electrical	33	74.96					
			Tunnel	Civil	33	91.21	64.04				
				Mechanical	33	37.25					
				Electrical	33	71.33					
Radisson	0.7985	17	Station	Civil	13	95.41	63.18	63.61	3,640,858	0.30	231580500
				Mechanical	33	29.55					
				Electrical	33	74.96					
			Tunnel	Civil	33	91.21	64.04				
				Mechanical	33	37.25					
				Electrical	33	71.33					
Langelier	0.6987	14	Station	Civil	14	96.15	63.37	63.70	2,521,765	0.21	160641109
				Mechanical	33	29.55					
				Electrical	33	74.96					
			Tunnel	Civil	33	91.21	64.04				
				Mechanical	33	37.25					
				Electrical	33	71.33					
Cadillac	0.8984	12	Station	Civil	33	59.78	53.88	58.96	2,299,820	0.19	135587838
				Mechanical	33	29.55					
				Electrical	33	74.96					
			Tunnel	Civil	33	91.21	64.04				
				Mechanical	33	37.25					
				Electrical	33	71.33					
Assomption	0.8984	19	Station	Civil	33	59.78	53.88	58.96	1,173,818	0.10	69203436
				Mechanical	33	29.55					
				Electrical	33	74.96					
			Tunnel	Civil	33	91.21	64.04				
				Mechanical	33	37.25					
				Electrical	33	71.33					
Viau	0.8983	5	Station	Civil	33	59.78	68.14	66.09	2,850,826	0.23	188398365
				Electrical	33	74.96					
			Tunnel	Civil	33	91.21	64.04				
				Mechanical	33	37.25					
				Electrical	33	71.33					
Pie-IX	0.6987	10	Station	Civil	14	94.30	62.89	63.46	4,934,479	0.40	313148522
				Mechanical	33	29.55					
				Electrical	33	74.96					
			Tunnel	Civil	33	91.21	64.04				
				Mechanical	33	37.25					
				Electrical	33	71.33					
				Civil	33	59.78					



BC	BD	BE	BF	BG	BH	BI	BJ	BK	BL	BM	BN	BO	BP	BQ	BR
2010								2011							
Actior	Treatmer		New Cond	New condition		Overall	Cost	Action	Treatmer		New Con	New condition		Overall	Co
0	Do nothing	1,267,372	87.58	94.33	93.86	123785240	0	0	Do nothing	1,277,510	85.86	93.22	92.92	122552439	0
0	Do nothing		94.31				0	0	Do nothing		92.82				0
0	Do nothing		99.20				0	0	Do nothing		98.94				0
0	Do nothing		80.41	93.39			0	0	Do nothing		79.19	92.62			0
0	Do nothing		97.29				0	0	Do nothing		96.41				0
0	Do nothing		99.06				0	0	Do nothing		98.76				0
0	Do nothing	4,886,400	95.41	89.01	87.66	445750123	0	0	Do nothing	4,925,491	94.30	87.98	86.62	440458932	0
1	Replacement		100.00				1,220,049	0	Do nothing		99.99				0
0	Do nothing		72.96				0	0	Do nothing		70.90				0
0	Do nothing		90.43	86.30			0	0	Do nothing		89.60	85.26			0
1	Replacement		100.00				1,064,665	0	Do nothing		100.00				0
0	Do nothing		69.11				0	0	Do nothing		66.83				0
0	Do nothing	3,498,655	94.30	88.73	87.51	318629544	0	0	Do nothing	3,526,644	93.04	87.65	86.45	314767752	0
1	Replacement		100.00				2,258,388	0	Do nothing		99.99				0
0	Do nothing		72.96				0	0	Do nothing		70.90				0
0	Do nothing		90.43	86.30			0	0	Do nothing		89.60	85.26			0
1	Replacement		100.00				1,064,665	0	Do nothing		100.00				0
0	Do nothing		69.11				0	0	Do nothing		66.83				0
0	Do nothing	2,423,271	95.28	88.98	87.64	221014195	0	0	Do nothing	2,442,657	94.30	87.98	86.62	218434280	0
1	Replacement		100.00				1,817,094	0	Do nothing		100.00				0
0	Do nothing		72.96				0	0	Do nothing		70.90				0
0	Do nothing		90.43	86.30			0	0	Do nothing		89.60	85.26			0
1	Replacement		100.00				912,548	0	Do nothing		100.00				0
0	Do nothing		69.11				0	0	Do nothing		66.83				0
0	Do nothing	2,209,994	56.97	78.98	82.64	190062546	0	0	Do nothing	2,227,674	54.13	77.49	81.38	187151236	0
1	Replacement		100.00				1,583,468	0	Do nothing		100.00				0
0	Do nothing		72.96				0	0	Do nothing		70.90				0
0	Do nothing		90.43	86.30			0	0	Do nothing		89.60	85.26			0
1	Replacement		100.00				1,216,934	0	Do nothing		100.00				0
0	Do nothing		69.11				0	0	Do nothing		66.83				0
0	Do nothing	1,127,971	56.97	78.98	82.64	97007086	0	0	Do nothing	1,136,995	54.13	77.49	81.38	95521167	0
1	Replacement		100.00				2,492,015	0	Do nothing		100.00				0
0	Do nothing		72.96				0	0	Do nothing		70.90				0
0	Do nothing		90.43	86.30			0	0	Do nothing		89.60	85.26			0
1	Replacement		100.00				1,216,934	0	Do nothing		100.00				0
0	Do nothing		69.11				0	0	Do nothing		66.83				0
0	Do nothing	2,739,479	56.97	65.77	76.04	216771076	0	0	Do nothing	2,761,395	54.13	63.36	74.31	211847670	0
0	Do nothing		72.96				0	0	Do nothing		70.90				0
0	Do nothing		90.43	86.30			0	0	Do nothing		89.60	85.26			0
1	Replacement		100.00				1,216,782	0	Do nothing		100.00				0
0	Do nothing		69.11				0	0	Do nothing		66.83				0
0	Do nothing	4,741,750	93.04	88.40	87.35	431027315	0	0	Do nothing	4,779,684	91.62	87.28	86.27	425690713	0
1	Replacement		100.00				1,310,904	0	Do nothing		99.99				0
0	Do nothing		72.96				0	0	Do nothing		70.90				0
0	Do nothing		90.43	86.30			0	0	Do nothing		89.60	85.26			0
1	Replacement		100.00				912,548	0	Do nothing		100.00				0
0	Do nothing		69.11				0	0	Do nothing		66.83				0

APPENDIX D: List of Publications

Journal Papers

1) **Mohammadi, A.**, Amador-Jimenez, L., and Nasiri, F. (2018). Review of asset management for metro systems: challenges and opportunities. Transport Reviews, 1-18.

2) **Mohammadi, A.**, Elsaid, F., Amador-Jimenez, L., and Nasiri, F. (2018). Optimising public transport for reducing employment barriers and fighting poverty. International Journal of Sustainable Development and Planning, 13(6), 860-871

3) **Mohammadi, A.**, Elsaid, F., and Amador-Jiminez, L. (2018). Optimizing transit maintenance and rehabilitation to support human development and sustainability: A case study of Costa Rica's railroad network. International Journal of Sustainable Transportation, 1-14.

4) **Mohammadi, A.**, and Amador, L. (2019), Simplified pavement performance modelling with only two-time (one-year interval) observations: case study of Montreal Island. Journal of Transportation Engineering: Part B: Pavement (ASCE) ***(Accepted).***

5) **Mohammadi, A.**, Amador, L., and Nasiri, F. (2019). A Multi-Criteria Assessment of the Passengers' Level of Comfort in Urban Railway Rolling Stocks. Journal of sustainable cities and society ***(Under Review).***

6) **Mohammadi, A.**, Amador, L., and Nasiri, F. (2019). Reliable, effective and sustainable urban railways, a model for optimal asset management, Journal of construction engineering and management (ASCE) (***Commented***).

7) **Mohammadi, A.,** Igwe, C., Amador, L., and Nasiri, F., (2019), Applying lean construction paradigm in pavement asset management systems, Journal of Engineering, Construction and Architectural Management ***(Under Review).***

8) Amador, L., **Mohammadi, A.**, Abu-Samra, S., and Maghsoudi, R. (2019). Resilient Storm Pipes: A Multi-stage Decision Support System. Journal of Structure and Infrastructure Engineering ***(Accepted).***

9) Hwangbo, W., Amador, L., Kachua, S., and **Mohammadi, A.** (2019). A Value-based Optimization Approach on Optimal Resource Allocations for Municipal Infrastructure Assets. Inter. journal of Infrastructure Asset Management ***(Accepted/minor comments).***

10) Igwe, C., **Mohammadi, A.,** Hammad, A., and Nasiri, F., (2019) Multi-criteria decision-making approach for selecting reduction technique for lean construction waste, Journal of Construction Management and Economics ***(Under Review).***

11) Amador, L., and **Mohammadi, A.** (2019). Does transit supply impact on public transit share and facilitate access to education and employment? Journal of Case Studies on Transport Policy. ***(Under Review).***

Conference Papers

12) **Mohammadi, A.**, Zakikhani, k., Zayed, T., and Amador, L. (2019). Rubble-mound breakwater construction simulation, International Journal of Construction Management, ICC7th, Greater Montreal, June 12-15.

13) **Mohammadi, A.,** Igwe, C., Amador, L., and Nasiri, F., (2018), Novel asset management framework for road maintenance. CSCE 2018 Annual Conference in Fredericton, NB June 13-16, 2018.

14) **Mohammadi, A.** (2018) Critical Infrastructure Management : Ports. CTRF 53th Annual Conference, Crowne Plaza Gatineau-Ottawa, June 3-6, 2018.

15) Igwe, C., **Mohammadi, A.,** Nasiri, F., and Hammad, A. (2018) House of waste: What is it and its implication for project symposium. Project Management Symposium. 10-11 May 2018. University of Marlyland, U.S.

16) **Mohammadi, A.**, Amador, L., and Nasiri, F. (2017) Underground Transit System Management; New Issues. CTRF 52th Annual Conference, May 28-31, Winnipeg, Manitoba.

17) Amador, L., **Mohammadi, A.**, and Nasiri, F. (2017) A cooperative environment to incorporate comfort on modal choices and trip assignment. ITS world congress, Oct 29-Nov 2, Montreal, Quebec.

18) Amador, L., **Mohammadi, A.**, and Nasiri, F. (2017) Level of comfort, and safety in urban subway. 4th International Conference on Transportation Information and Safety, ICTIS - 2017 Aug 8-10, Banff, Alberta ***(Presenting paper and winner of the best presentation award).***

19) **Mohammadi, A.**, Nasiri, F., and Amador, L. (2016) Asset evaluation and optimization framework for urban subway system by MCDM. 23th GESCC Conference, McGill University, June 10.