Modeling Socio-economic Impacts of Infrastructure Works

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ABSTRACT

Modeling socio-economic impacts of infrastructure works

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One-third of Canadian municipal infrastructure is in fair, poor or very poor condition, thus increasing the risk of service disruption (FCM, 2016). This represents a call for major construction works, which cause considerable business closures and increased travel delays. Therefore, the quantification of socio-economic impacts on businesses, residents, and road users due to construction works, has become important for municipalities. However, there is a lack of research on the quantification of socio-economic impacts at macro-level. In previous research efforts, developed quantification models were mostly site-specific, at micro-level, with no clear distinction between proposed categories of impacts. The main objective of this research is to model social costs of municipal infrastructure interventions at macro-level. First, the indicators that constitute tangible and intangible social costs of infrastructure works were identified and studied. Second, models were developed for each indicator to predict social cost variables. Third, non-linear regression models were built on the relationship between social cost variables and predictor variables, using the method of least squares. The following infrastructure assets are included in this research: potable water, wastewater and storm water pipes and roads. This research demonstrates that social cost indicators related to infrastructure works can be modeled by non-linear regression functions, thus enabling to assess social costs at a large scale. Then the social costs were incorporated in

a Decision support system to compare three scenarios of renewal policies. The first scenario that is avoiding open-cut road reconstruction until the buried pipe replacement, results in the highest total costs and the best levels of service (LOS). The second scenario that is avoiding pipe replacement until the road reconstruction, results in the lowest total costs and the lowest LOS. This is because of the increase of pipe failures. Finally, the third scenario that is mixing both of the aforementioned strategies, results in the in-between solution with lower total costs and acceptable LOS.

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I would like to express my deepest gratitude to the One True, Living GOD creator of the heavens and the earth, to the Lord JESUS and to the HOLY SPIRIT. I am nothing without GOD and every breath I take testifies His goodness over my life. The journey of the PhD studies is at end, I praise the Holy and Mighty Name of the MESSIAH JESUS who is coming very soon.

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NOMENCLATURE

TCM: Traffic control measures
VAD: Vehicle accident damage
VED: Vehicle delays
PED: Pedestrian delays
VMO: Vehicle maintenance and operations
OEV: Obstruction for emergency vehicles
PRL: Parking revenue loss
TRL: Tax revenue loss
NBIL: Net business income loss
PSRL: Property sale-and-rent loss
PR: Productivity reduction
HLL: Human life loss
AI: Accidental injuries
SI: Service interruption
LQR: Life quality reduction
PSD: Property structural damage
DDC: Dirt and dust cleaning
BUD: Buried utility damage
AAD: Asset accelerated deterioration
AP: Air pollution
SGP: Soil and groundwater pollution
GAS: Green amenity damage
ER: Ecosystem restoration
AB: Administration burden
CC: Citizens' complaints
UWA: Unforeseen work activities
ULR: Urban landscape damage

CHAPTER 1: INTRODUCTION

1.1. OVERVIEW

Potable water, wastewater, storm water and road systems are core infrastructure assets that are critical to the quality of life of Canadians, and almost 60 % of them is owned and maintained by municipalities (FCM, 2016). They should be managed in a sustainable way through renewal decisions integrating both financial and non-financial outcomes. For example, equipment and labor costs as well as traffic and noise disturbance should be considered in buried pipe renewal decisions. Four types of decision outcomes are identified: economic, social, cultural and environmental so that the analysis and the integration of those in renewal policies result in a sustainable infrastructure asset management (NAMS, 2004).

Adverse impacts related to public infrastructure works such as business losses, air pollution, traffic disruptions and accidents, are often referred as "social costs" (Gilchrist and Allouche, 2005). These costs should be mitigated to achieve an efficient renewal program (Rahman, *et al*., 2005). For example, coordinating works among adjacent infrastructure such as water, sewer and road assets, will reduce social costs as opposed to performing works separately over a short period. Municipal infrastructure management with little or no consideration to coordination of works can cause significant public complaints due to high social costs; thus, giving an impression that resources are not managed properly (Halfawy, 2008; CNRC, 2003). In addition, this creates a negative image of municipal officers, knowing that nearly 60 % of Canada's core public infrastructure is managed by municipalities.

During the period running from 2007 through 2014, business owners and the City of Montreal bore high social costs related to buried pipe and road reconstruction on major commercial arteries, to name a few: Saint-Laurent Blvd., Du Parc Avenue, Bernard Avenue, Saint-Catherine St., etc. Business owners were highly frustrated with accessibility and parking issues, dust and dirt pollution, reduced sale's income and water interruptions. The City of Montreal in turn invested hundreds of thousands of dollars to support businesses and bring customers back to the place through marketing campaign. Therefore, in 2015, the City moved forward with a new integrated roadwork planning to mitigate work impacts. It offers palliatives such as speaking to stakeholders to gauge their needs, coordinating works among all players (e.g., Hydro-Quebec, Gaz-Metro, Bell, and contractors), giving bonuses to contractors to finish work early, and keeping businesses running during long-lasting construction work. In addition, a Coordinating Bureau was created to achieve better coordination of infrastructure works. However, there was no standardized protocol to categorize and anticipate work-related social costs.

Programs of works on buried pipe and road lines from the Water Department and Transportation Department of the City of Montreal should be synchronized as much as possible to reduce adverse impacts on society. 75 % of key factors to achieve coordination of works among various infrastructure assets are at the organizational level and 25 % at the technical level (Hafskjold, 2010). At the organizational level, the complexity of coordination is explained by the fact that assets are managed by different departments with different mandates and funding; whereas at the technical level, the complexity stems from the fact that assets are treated at different timings and subject to different degrees of maintenance (CNRC, 2003). Therefore, effective coordination at the organizational level can be achieved by the creation of a Coordinating Bureau to ensure communication between various infrastructure providers. However, at the technical level, a quantification protocol for work-related social costs needs development to justify integrated renewal projects among various assets.

1.2. PROBLEM STATEMENT

This research identifies three problems, which are discussed in the next sections. The first is the need to categorize social costs to civil engineers (Ormsby, 2009). The second is the limitations in data collection to assess social costs (Najafi, 2004). The third is the limitations in available assessment models to predict them.

1.2.1. Need to establish a generic protocol to categorize social costs

Discrepancies in social cost categorization and nomenclature were observed in literature. In general, social costs were categorized per: a) impacts such as traffic disruption, business loss, health and ecological degradation (Gilchrist and Allouche, 2005), b) costs whether direct, indirect or intangible (Rahman, et al., 2005), and c) bearers of costs whether municipality, road user or society at large (Manuilova, *et al.*, 2009). Discrepancies in nomenclature were depicted in Tableau 2.2. In addition, there was no clear distinction between tangible and intangible costs. Therefore, a standardized way to categorize work-related impacts has yet to be reached in civil engineering.

1.2.2. Limitations in data collection to assess social costs

The accuracy of social costs is subject to limitations in available and manageable information on both data and quantification methods. Typically, social cost assessment is data-intensive. This research identifies three types of data:

- *Data extracted from the Data Repository or the Geographical Information Systems*. These data are often subject to prior treatment before they can be used as input variables into the assessment models. Data treatments can involve spatial analyses or queries with a certain number of assumptions, especially when there is no unique identifier between databases. For example, if we have two databases, one for buildings and another for road segments, a spatial query should be performed to link each building to a specific road.
- *Data obtained through interviews with relevant parties or experts*. This includes also data from literature or field survey. For example, the Value of time lost in traffic can be obtained through a survey or from literature commonly as the hourly wage rate even though it fails to represent the true value that people place on their time. Another example is the Number of vehicles circulating in a road, which should be recorded in-situ per the kind of vehicle (automobile, bus, heavy and light truck), the period of the day (morning, afternoon and evening) and the day of the week (Monday to Friday, Saturday and Sunday). This is practically time-consuming. Cost data of various items can be difficult to obtain if access to information is jeopardized by: confidential accounts, calls not returned, intangible losses, etc.
- *Data assessed from innovative ideas*. These data required a set of assumptions and creative techniques to arrive at an estimated value. They are mostly related to intangible impacts such as human life loss or productivity reduction at work place due to machinery

noise. Data such as the Number of decibels produced by an infrastructure project or the Value of the risk that people are willing to accept in losing their life in traveling on a road under works, are complex to estimate.

1.2.3. Limitations in available assessment models to predict social costs

The assessment of social costs demands careful and innovative considerations (TBCS, 1998). Most of available assessment techniques were site-specific, at project level, and could not be applied easily at macro-level (for an entire road network) given time-consuming data collection. In addition, the following limitations can be outlined:

- Uncertainty and variability of input variables were not comprehensively considered in available techniques. Uncertainty deals with variables whose possible values are associated to a random phenomenon, such as occupancy rates of parking spaces, road accidents and vehicle maintenance costs. Variability deals with variables that vary over time, such as vehicle density traffic which fluctuates per the time of the day and the day of the week.
- Road status during works whether partially or completely closed is not clearly defined in available techniques. Most of the techniques proposed the same equation in both cases. However, detouring vehicle traffic can impact a greater number of vehicles than allowing vehicles to go through the work zone.
- Most of available techniques were proposed for single projects (often on one type of assets) of open-cut reconstruction or trenchless rehabilitation. There was a lack in considering bundled projects resulting from coordination of works among various assets, such as combination of open-cut and trenchless techniques in the same renewal project.
- Impacts on Public Transportation Agency and Police, such as increased service costs due

to additional bus lines and drivers and costs of police presence, are not found in literature.

- Side-effects of work impacts are not captured, such as unplanned water interruptions (which increase risks of fire in restaurants and losses of frozen products in groceries, both equipped with cooling water systems) and prejudices to other projects.
- Possible compensations given by the municipality to businesses are not studied. They allow mitigating impacts on losing businesses or parties, even though they are transfer costs in a society point of view by increasing internal costs for the municipality and decreasing external costs for business owners.
- Quantification of intangible impacts is often controversial. For example, the value of human life loss (HLL) is based on forgone earnings or insurance payouts for death. Likewise, the value of time (VOT) lost in traffic is based on average hourly wage. However, these methods fail to reflect effects on victim's surroundings for HLL and the real cost that people are willing to pay to save their time for VOT.
- No regression models had been proposed to assess social costs at large scale to overcome the fastidious data collection required to assess them. Social cost regression models can be very useful for two main reasons: they ease the social cost assessment for an entire road network and they can easily be incorporated in decision support systems for the consideration of external costs related to infrastructure projects.

1.3. RESEARCH OBJECTIVES

The observations in previous section lead to the objective of this research that is to model social costs related to municipal infrastructure interventions in all conditions. This will be achieved through specific objectives outlined in the following section.

1.3.1. Specific Objectives

The research objective is divided into the following specific areas:

(1) Identify and study the indicators that constitute tangible and intangible social costs of infrastructure works;

(2) Assess and predict social costs;

(3) Develop non-linear regression models on the relationship between social cost variables and predictor variables.

(4) Optimize the coordination among municipal infrastructures.

First, the best indicators to categorize social costs related to infrastructure works are identified and studied. Second, models are developed for each indicator by taking into consideration multiple deterministic and probabilistic variables, as well as social parameters, to obtain social cost variables that constitute response variables for regression models. Then the non-linear regression models were built on the relationship between social cost variables and predictor variables, using the method of least squares. Finally, the developed regression models were incorporated in a decision support system to optimize coordination scenarios of works among three municipal systems: water, sewer and road.

1.3.2. Expected contributions

This research provides civil engineers the best social cost indicators to categorize adverse impacts resulting from infrastructure works. It proposes non-linear regression functions to model social cost indicators with a set of key predictor variables. Compared to previous research, the prediction of social costs integrates important parameters such as time of the day, day of the week, land use and road function. The proposed approach is not project-specific, but rather can be applied at large to an entire road network to simulate work-related impacts. Social costs can be used by managers to set hierarchy levels or weighting factors of work impacts for a road network. Social costs can also be integrated in decision support tools to run scenarios of different renewal policies and compare their results. Social cost mapping can be reported to officials, residents and stakeholders. This can raise people's awareness of adverse impacts resulting from public works, build third parties' support by anticipating mitigation measures, and promote restrictive practices such as pavement degradation fee, contractor penalty fee for delays and permit fee for excavation with tariffs based on social cost values.

1.3.3. Scope and limitations

The scope of this research is limited to social costs resulting from interventions among the following infrastructure assets: potable water, wastewater and storm water pipes and roads. Works on other buried infrastructure assets such as gas and electrical lines are excluded. Interventions could refer to a single project on one type of assets or a bundled project on more than one type of assets. The latter case portrays a "multidisciplinary" coordination of municipal infrastructure projects, which is achieved when uncoordinated (or departmental) projects are put together to propose one integrated/bundled project. The coordinating process is limited in this research to infrastructure assets located within the same road corridor, which is a street block from one intersection to another. The choice to stick to a street block is motivated by the fact that public works are usually performed within this boundary. Eventually, planned interventions on municipal assets can lead to unplanned asset failures such as pipe breaks during works. Even though these unplanned failures can increase social costs, for example to such an extent as to evacuate residents and businesses, the associated adverse impacts are not considered in this study.

1.4. TASKS

The methodology of the current research consists of four specific objectives. The first three sub-objectives are illustrated in Figure 1.1 and can be broken into many tasks as explained in this section. The last sub-objective consists in one task of using social costs to optimize coordination of works. Review of literature was necessary through all these steps.

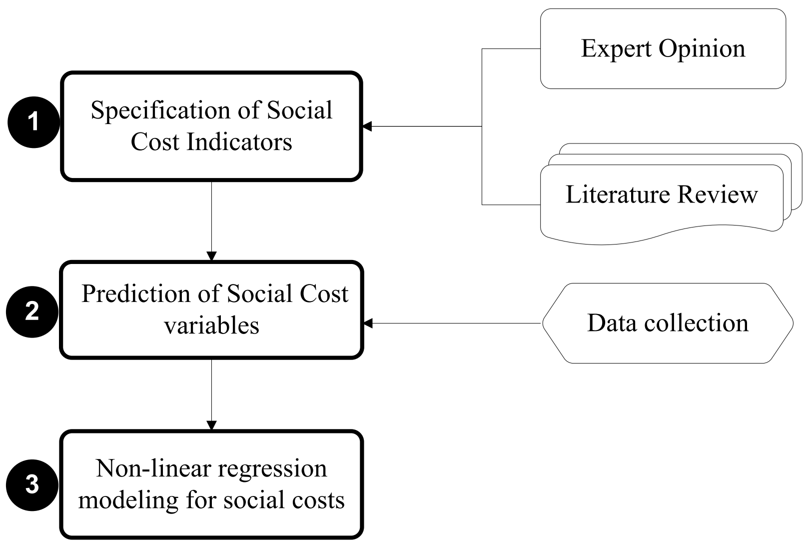

Figure 1.1: Research methodology

The first specific objective could be broken in two tasks:

- TASK 1: To identify indicators of social costs
- TASK 2: To select best indicators to specify social costs for municipal infrastructure works

Step 1 would be supported by comprehensive literature reviews as well as interviews with experts and municipal planners. Interviews will help to capture hidden social costs not found in literature. Social costs are categorized under domains, this resulting in a list of key social cost indicators.

The second specific objective could be broken into three tasks:

- TASK 3: To identify key parameters
- TASK 4: To develop models
- TASK 5: To predict social cost variables

Key parameters are known parameters related to project specifications such as the type of works (open-cut, trenchless) and related to the site vulnerability such as the land use (residential, commercial, and institutional). They are used to develop models, which are new or upgraded from literature. The models were implemented to compute social cost variables in numerous cases of different infrastructure projects on more than a thousand roads in the City of Montreal. Their implementation required a large amount of data that were extracted from the different databases or collected from different parties by phone calls, emails and one-on-one interviews. The resulting social cost variables were validated through expert opinions, real cost collection or comparison of results with two different methods. This step results in vectors of social cost variables used as response variables for regression analyses.

The third specific objective could be broken into two tasks:

- TASK 6: To design regression models
- TASK 7: To calibrate and validate regression models

In Step 3, regression models are developed for each indicator based on the project type or duration, and the road status during works whether partially or completely closed. The parameters of regression functions were estimated through least squares method. This step results in social cost regression functions.

1.5. THESIS ORGANIZATION

Chapter 2 presents the literature upon which the research was carried out. The specification of existing social cost indicators and previous techniques to assess them are presented. Chapter 3 presents the whole methodology research. First, a standardized categorization of social costs is proposed, where social cost indicators are classified under eight domains. A chart has been designed to determine whether an indicator is tangible or not. Second, models to predict social cost variables are explained, with associated variables and parameters. Third, the non-linear least squares regression model is described. Chapter 4 deals with the data collection and challenges. Chapter 5 discusses the implementation of non-linear regression functions and the results of the integration of social costs in InfraModex decision support system to compare three typical renewal scenarios. Finally, Chapter 6 presents the thesis conclusions and recommendations.

CHAPTER 2: LITERATURE REVIEW

2.1. OVERVIEW

This research found various literatures in social cost specifications and assessment techniques. The structure and content of the literature is outlined in Figure 2.1. Section 2.2 covers the definition of social costs to civil engineers. Analyses of existing social cost categorizations depict current discrepancies in the nomenclature of social cost indicators. Section 2.3 presents current approaches to predict social costs and limitations in available assessment techniques. A review of previous parametric models used and a brief description of regression models to be used for social cost assessment are presented. Sections 2.4 and 2.5, deal with limitations in existing models and the decision support system InfraModex to be used in this study for optimisation.

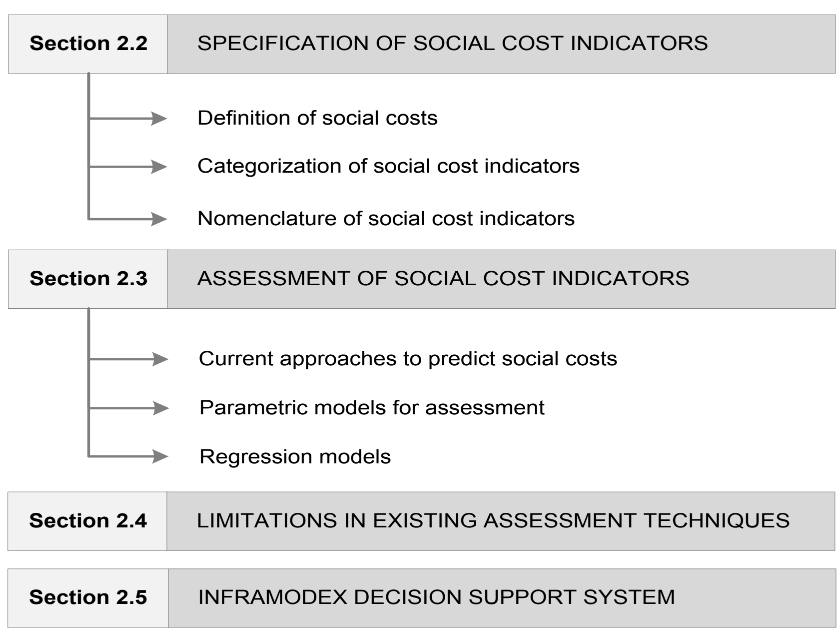

Figure 2.1: Chapter 2 Content Diagram

2.2. SPECIFICATION OF SOCIAL COST INDICATORS

Since the 2000s, researchers have investigated adverse impacts related to municipal infrastructure works (Matthews, *et al*., 2015; De Marcellis-Warin, *et al*., 2013; CERIU, 2010; Ormsby, 2009; Manuilova, *et al*., 2009; Werey, *et al*., 2005; Gilchrist, *et al*., 2005; Rahman, *et al*., 2004; Najafi, 2004). They attempted to assess these impacts in dollar value and referred to them as social costs which were broken down into several social cost indicators. Gilchrist and Allouche (2005) define a social cost indicator as a measurable cost item, quantifiable in monetary terms and resulting from one or more construction-related adverse impacts near the construction work area. The following sections present an overview of social cost definition, categorization and nomenclature.

2.2.1. Definition of social costs

Even though the concept of social costs is relatively new to civil engineering (i.e. in the beginning of 2000s), social costs are well-studied topics in Economics, with research dating back to 1850s (Ormsby, 2009). Social costs were introduced in Economics to consider positive or negative externalities resulting from undertaking an activity; thus, represent the overall impact of an activity on the welfare of the society. In a project cost analysis, decision-makers initiating a project will typically assume internal or private costs while third parties not involved in the decision will bear external costs. Therefore, social costs in Economics encompass internal and external costs.

On the contrary, social costs in civil engineering are exclusively external costs resulting from infrastructure works; thus, do not include private costs normally specified in the contract bid. Therefore, social costs have been defined as the monetary equivalent of resources consumed by parties and typically not directly accounted for in construction projects (Allouche, 2005; Rahman, *et al*., 2005). They are not part of the contract bid, with utilities having no direct responsibility apart from possible compensations (Manuilova, et al., 2009; Werey, et al., 2005).

However, the exclusion of contractual costs from social costs can be challenged because some cost items are engaged in the bid solely to mitigate adverse impacts and thus should be considered as social costs, to name a few: by-pass installation, urban landscape reinstatement and traffic control measures. In addition, works can generate implicit effects resulting in internal costs borne by municipalities such as losses in parking meter and ticket revenues. Therefore, social costs to municipal engineers encompass internal costs borne by the municipality and external costs borne by other parties.

In a nutshell, the current definition of social costs should be revised to the monetary equivalent of resources consumed by all parties in terms of both internal costs included in and excluded from the contract bid that are borne by decision-makers, and of external costs borne by all remaining parties. Note that both internal costs included in and excluded from the bid are often referred as direct and indirect costs to the municipality. This fact has led to an exchangeable use of the terms social cost, indirect cost and external cost in the literature.

2.2.2. Categorization of social costs

Table 2.1 illustrates different dimensions of social cost categorizations upon which indicators are built.

Table 2.1 : Social cost categorizations

Dimensions	Categories	Authors
Construction phase	• Design and planning • Construction • Post-construction	Najafi, 2004
Impacted area	• Traffic • Economic activities • Environment degradation, health and safety • Adjacent utilities	Gilchrist, *et al*., 2004 CERIU, 2010
Bearer of cost	• Municipality • User [(1)] • Society	Ormsby, 2009 Manuilova, *et al*., 2009
Type of cost	• Direct • Indirect • Intangible	Rahman, *et al*., 2005 Manuilova, *et al*., 2009
Accuracy of cost	• Accurate • Estimate • Guestimate	Manuilova, *et al*., 2009
Time frame [(2)]	• Immediate • Short term • Long term	Rahman, *et al*., 2005 Manuilova, *et al*., 2009

(1) User costs affects solely users and are separated from all other costs to society
(2) In which the cost occurs

A two-dimensional categorization was proposed with the *bearer of cost*-axis and the *type of cost*-axis, in such a way that costs borne by the *municipality* are either *direct* or *indirect* and costs borne by the *society* either *indirect* or *intangible* (Manuilova, et al., 2009). Figure 2.2 illustrates a four-dimensional categorization with *bearer of cost*-axis, *type of cost*-axis, *accuracy of cost*-axis and *time frame*-axis, in such a way that *direct* costs are *accurate* and borne by *municipality immediately*, *indirect* costs are *estimated* and borne by the *society* at a *short run* and *intangible* costs are *guestimated* and borne by the *society* at a *long run* (Rahman, et al., 2005).

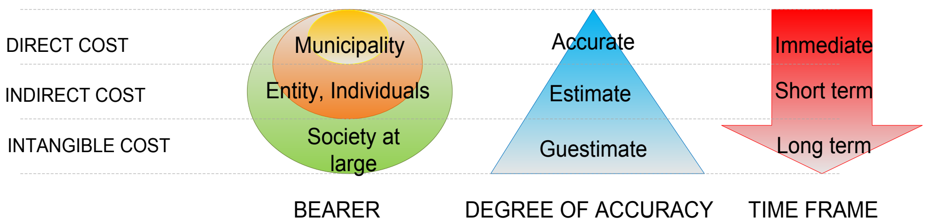

Figure 2.2: Four-dimensional social cost assessment

Furthermore, local regulations and policies play a role in social cost assessment. Figure 2.3 shows that external impacts could be supported by the municipality in the form of possible compensations, thus increasing internal costs and reducing external costs (Werey et al., 2005). Note that in the society point of view, compensations are merely transfer costs as opposed to the municipal point of view.

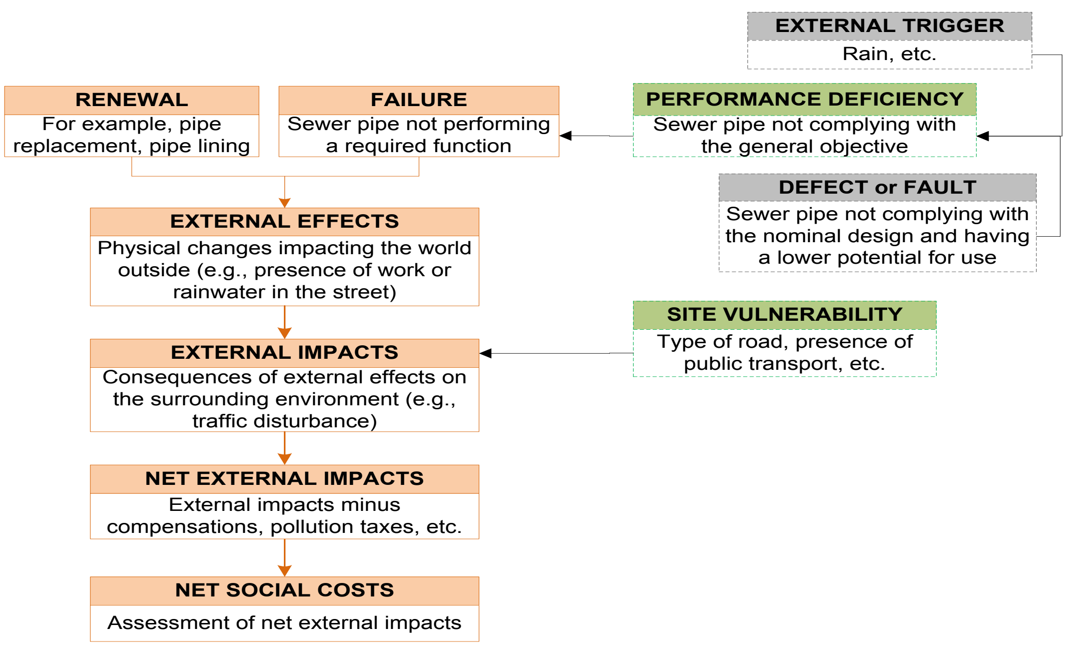

Figure 2.3: Net social cost valuation

2.2.3. Nomenclature of social cost indicators

Table 2.2 summarizes the nomenclature of social cost indicators originally formulated by different authors for eight types of impacts: road safety and traffic issue, local economy disruption, life quality loss, add-on construction work, urban landscape damage, adjacent utility damage, ecological environment damage and litigation and legal fees. Discrepancies in the nomenclature are explained by the following observations:

a) Use of different names to designate one single indicator: e.g., *Loss of income*, *Business loss*, *Lost business income*, *Loss of trade*, *Lost business revenue*

b) Lack of adequate names for some indicators: e.g., *Noise and vibrations* standing for the loss of property value due to noise and vibrations

c) Mixture of non-descriptive versus self-explanatory names: e.g., *Health and safety* versus *Accidental injury and death*

d) Micro-segmentation of some indicators: e.g., a single indicator for one author, *Municipal revenue loss*, is divided into two by another, *Lost parking meter revenue* and *Lost parking ticket revenue*

In addition, interviews with experts point out new specific indicators, adapted to the socio-economic context of Montreal City and not discussed in literature, such as *Costs of police presence* on worksites, *Increased costs of bus service* borne by the STM (Montreal Public Transport) and *Increased administration costs* borne by the municipality to support businesses and provide road accessibility at any time.

Table 2.2 : Summary of existing social cost indicators

○ = quoted and qualitatively assessed ● = quoted and quantitatively assessed √ = quoted only	a) Najafi, 2004	b) Rahman, et al., 2004	c) Gilchrist, et al., 2005	d) Werey, et al., 2005	e) Manuilova, et al., 2009	f) Ormsby, 2009	g) CERIU, 2010	h) De Marcellis, et al., 2013	i) Matthews, et al, 2015
ROAD SAFETY AND TRAFFIC ISSUE									
Traffic control measures			√						
Traffic accidents			√		√				
Repair costs		√							
Increased collision rate						●	●	√	
Damage of goods							●		
Traffic disruptions		●		○					
Travel delay					●		●	●	●
Vehicular traffic disruption	●								
Fuel consumption			√						
Obstruction to emergency vehicles						●	●	√	
Increased pedestrian travel time						●			
Increased vehicle operating cost					●	●	●	●	
Vehicle operating cost									●
Increased vehicular travel time			●			●			
LOCAL ECONOMY DISRUPTION									
Municipal revenue loss		●			●				
Loss of parking spaces			√				●		
Loss of parking revenue									●
Lost parking meter revenue						●		●	
Lost parking ticket revenue						●		●	
Compensations and tax rebates						●			
Reduction in tax revenue			√					√	
Business and trade loss	●								
Loss of income			√				●	√	
Business loss		√			√				
Lost business income						●			
Lost business revenue									●
Loss of trade				○					
Lost property value due to noise						●			
Noise and vibrations					●			●	
Productivity reduction			●						
Psychological and physical ailments						●			
Noise and vibration							●	●	
LIFE QUALITY LOSS									
Service interruption				○				√	
Water and wastewater service interruption						●			
Temporary service provision							●		
Reduced quality of life			√					√	
Dust				○			√		
Noise	●	●		○					
Noise pollution costs									●

○ = quoted and qualitatively assessed
● = quoted and quantitatively assessed
√ = quoted only

	a) Najafi, 2004	b) Rahman, et al., 2004	c) Gilchrist, et al., 2005	d) Werey, et al., 2005	e) Manuilova, et al., 2009	f) Ormsby, 2009	g) CERIU, 2010	h) De Marcellis, et al., 2013	i) Matthews, et al, 2015
Health and safety		√			√				
Health and disability insurance			√						
Accidental injury and death						●	●		
Road rage			√						
Safety									●
Pedestrian safety	√								
Site and public safety	√								
ADD-ON CONSTRUCTION WORK									
Unforeseen overhead costs		√			√				
Unforeseen construction costs		√			√				
Reinstatement costs		√			√				
Emergency services		√			√				
Redundant systems and temporary services		√			√				
URBAN LANDSCAPE DAMAGE									
Property damage						●			
Repair costs		√							
Damage to adjacent structures	√								
Damage and lost amenity of recreational facilities						●			
Dirt and dust		●				●	●	√	
Cost of dust control									●
Heavy construction and air pollution	√								
ADJACENT UTILITY DAMAGE									
Accelerated road degradation			√						
Service life reduction		●			●		●	√	
Pavement service life reduction due to excavation						●			
Pavement service life reduction on alternate routes due to increased traffic						●			
Decreased road surface									●
Damage to detour road	√								
Road and pavement damage	●								
Damage to adjacent utilities	√								
Adjacent buried utility damage						●			
ECOLOGICAL ENVIRONMENT DAMAGE									
Restoration cost			√						
Air pollution					√				
Environmental degradation		√							
Air pollutant and GHG emissions						●	●	●	
Environmental damage and contamination						√		√	
Groundwater pollution				○					
Environmental impacts	●						√		
LITIGATION AND LEGAL FEES									
Property claims		√							
Citizens' complaints	●						●		

Note: Non-monetary quantitative assessment is considered as qualitative assessment

2.3. ASSESSMENT OF SOCIAL COST INDICATORS

Given that adverse impacts resulting from public works can range from tangible effects such as parking revenue losses to intangible as air pollution, approaches for predicting social costs should integrate methods to value damage of goods without market prices. The current approaches used in Economics are presented in the next section, followed by limitations with respect to their application in the assessment of social costs related to infrastructure works. The last section deals with parametric models developed for social cost valuation.

2.3.1. Current approaches for predicting social costs

Approaches for predicting social costs are divided into two methods: stated preference and revealed preference (see Figure 2.4). They were originally applied in Economics to estimate customer's preference/behaviour given a set of alternatives (Varian, 2005; Kroes and Sheldon, 1988). In civil engineering, stated preference methods refer to techniques that use survey-based data to state individuals' losses, and revealed preference to those that exploit market data to reveal individuals' losses.

2.3.1.1. Stated preference methods

Stated preference methods require purposed-design surveys which provide respondents with a set of alternatives to sort in decreasing order or to select one of them (Kroes and Sheldon, 1988). The best-known methods are: contingent valuation and choice experiment. Contingent valuation is obtained by directly questioning individuals on their Willingness-to-pay (WTP) to have more of a good or service, or their Willingness-to-accept compensation (WTAC) to have less of it. For example, respondents could be asked questions such as "how much would you be willing to pay to avoid traffic accidents in the work zone?" or "how much would you be willing to accept to be delayed for an hour in road traffic?" This method is conducted preferably through face-to-face interviews and telephone or mail surveys as well. The choice experiment valuation is achieved by asking individuals to choose one among many alternatives. For example, if trees along the roadside can hinder works, residents could be asked to choose between "preserve trees and install new pipes at higher costs" and "remove trees and renew old pipes at lower costs".

In general, stated preference methods are easy to control because researchers define conditions which are being evaluated by respondents. They offer flexibility in being capable to deal with many explanatory variables and get variations in these variables from multiple respondents' observations (Kroes and Sheldon, 1988). By nature, they are susceptible to bias problems both in the sample and in the responses (Gilchrist and Allouche, 2005). The first is due to people' background and misperceptions combined with their age, gender and level of income. The second is because people tend to over or under state their responses under hypothetical situations and may not necessarily do what they say.

2.3.1.2. Revealed preference methods

Revealed preference methods assume that the preference of individuals can be revealed in their purchasing behaviours, thus require "revealed preference" data to examine all explanatory variables expressed in engineering units. Different revealed preference methods are available (see Figure 2.4) and presents limitations on collected data such as the lack of variability and the strong correlation between explanatory variables.

Figure 2.4 illustrates examples of commonly used stated and revealed preference methods. They are complementary and can be used in conjunction to avoid the problems of stated intention versus revealed behaviour (Kroes and Sheldon, 1988). The Value of Statistical Life (VSL) is separated from the rest of revealed preference methods because of the dilemma associated to the fact that some people consider human life priceless. However, techniques of VSL value human life based on revealed preference data.

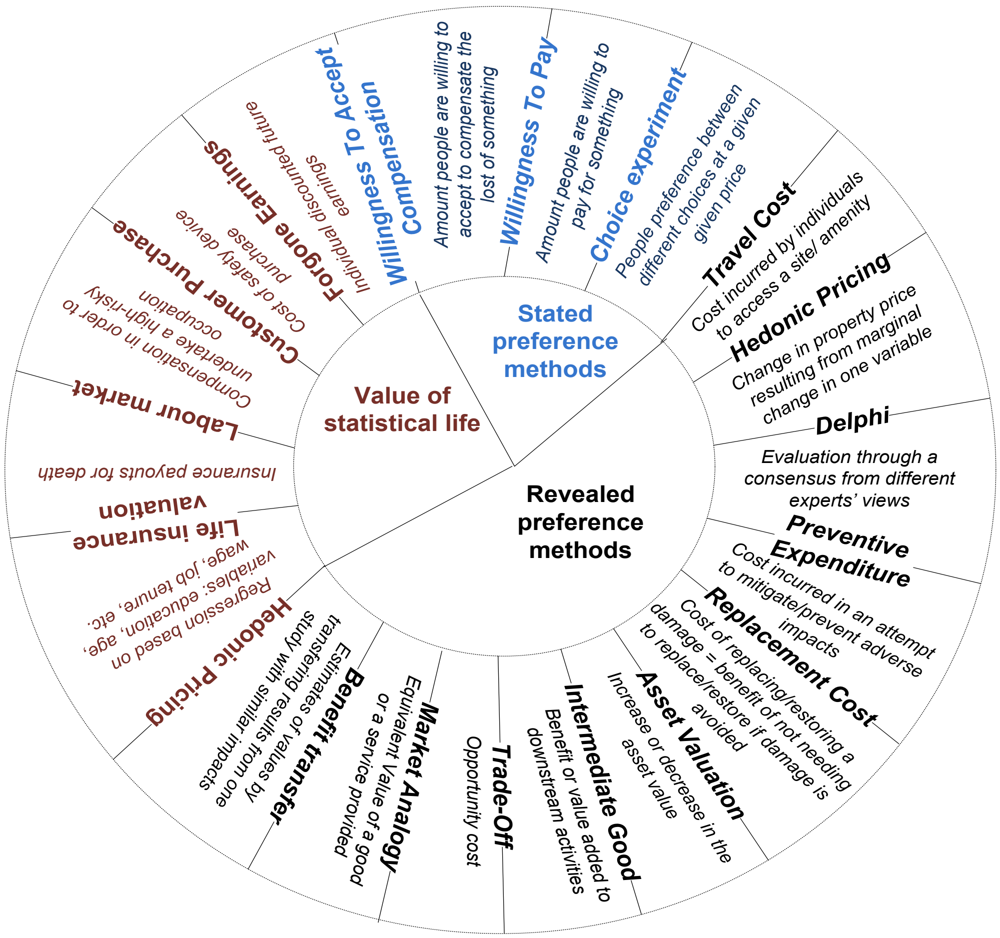

Figure 2.4: Examples of common assessment methods

Stated and revealed preference methods are often referred as shadow pricing methods. The latter are applied to monetize non-marketed goods such as air and nature, or to convert monopolistic market prices into competitive ones (FLOODsite, 2006). In the first case, financial effects of transfer payments such as taxes and subsidies should be removed. These methods require a lot of assumptions, thus often leading to a fairly guestimated value. Table 2.3 illustrates that stated preference methods are rarely used to assess adverse impacts related to infrastructure works compared to revealed ones.

Table 2.3: Use of stated versus revealed preference methods (SPM vs. RPM)

	SPM	RPM								
Authors	WTP	Market analogy	Asset valuation	Trade-off	Benefit transfer	Salary conversion	Preventive expenditure	Hedonic pricing	Life insurance	Replacement cost
a) Najafi, 2004		√								
b) Rahman, et al., 2004			√	√	√					
c) Gilchrist, et al., 2005		√				√	√			
d) Werey, et al., 2005		√								
e) Manuilova, et al., 2009	√	√		√	√			√	√	
f) Ormsby, 2009		√	√	√	√	√	√	√		
g) CERIU, 2010		√	√	√	√	√	√			√
h) De Marcellis-Warin, et al., 2013		√		√	√	√			√	
i) Matthews, et al., 2015		√		√						

The following section is an overview of previous parametric models used to assess social cost indicators. Readers can skip this section and go straight to Chapter 3 of Research methodology which presents selected indicators and upgraded versions of parametric models.

2.3.2. Parametric models for assessment

The following subsections present previous parametric models which are grouped under eight categories of impacts: 1) road safety and traffic issue, 2) local economy disruption, 3) life quality loss, 4) add-on construction work, 5) urban landscape damage, 6) adjacent utility damage, 7) ecological environment damage and 8) litigation and legal fees. All these models use revealed preference data.

2.3.2.1. Road safety and traffic issue

Impacts on road safety and traffic were divided into three: traffic measures, traffic accidents and traffic disruptions as illustrated Table 2.4.

Table 2.4: Assessment methods for road safety and traffic issue

Indicators	Revealed preference methods
Traffic measures	
Traffic accidents	Market analogy
Traffic disruptions	Trade-off, travel cost
Vehicle operating costs	Trade-off
Vehicle delay costs	Trade-off
Pedestrian delay costs	Trade-off
Obstruction to emergency vehicle	Travel cost

- *Traffic measures*

Costs of traffic measures in terms of control, inspection and administration are often engaged in the contract bid (Gilchrist and Allouche, 2005). No assessment methods were found in literature. In the context of the City of Montreal, costs of police presence on major work sites, which can amount up to $60,000 a week and are paid by the police budget, are traffic measure costs that are missed in literature.

- *Traffic accidents*

Even though there is little evidence to support correlation between works and accidents, works can potentially increase traffic collisions with the presence of traffic control devices, safety features and construction equipment and machineries (Manuilova, et al., 2009). In addition, external factors such as weather conditions and drivers' behaviors can trigger traffic accidents. Traffic accidents were assessed in two forms as illustrated in Table 2.5. The first is by using fixed costs of collision per vehicle-distance traveled (Ormsby, 2009). The second is by multiplying the likelihood of the accident by its expected impacts in money terms (CERIU, 2010).

Table 2.5: Parametric models for traffic accidents

Author	Social cost indicator	Abbr.	Detailed calculations
	Traffic accidents		
(f)	Increased collision rate	ICR	ACC × L × DTD × PD
(g)	Damage of goods	DG	P × N × C

ACC = average cost of collision [$/veh-km]
L = length of the work zone route [km]
DTD = daily traffic density [veh/day]
PD = Project Duration [days]
P = probability of accident [%]
N = number of occurrences
C = average Costs of impacts per accident [$]

Table 2.6 shows a Canadian average cost of collision per vehicle distance traveled (Manuilova, *et al*., 2009). They were factored twice by 0.6 and 0.63 to reflect the decrease of collision rate in urban areas and higher percent of collision rate in construction zone respectively (Ormsby, 2009). Table 2.7 shows average costs of impacts per accident used by Saskatchewan Government Insurance for cost benefit analysis (Manuilova, *et al*., 2009; De Marcellis, *et al*., 2013). Cost elements considered in collision rates are not clearly specified but include all kinds of elements such as material damage, productivity loss and health degradation. More research is needed in this area and we strongly recommend separating tangible from intangible costs for the sake of clarification.

Table 2.6: Average costs of collision

Types of vehicles	Manuilova et al. (2009)	Ormsby (2009)
	For entire traffic fleet including highways	*For construction zone in urban areas*
Urban/interurban vehicle	CA (2006) $154.38/1000veh-km	CA (2009) $60.86/1000veh-km
Urban/interurban bus	CA (2006) $482.32/1000veh-km	CA (2009) $190.16/1000veh-km
Freight vehicle/truck	CA (2006) $164.99/1000veh-km	CA (2009) $65.05/1000veh-km

Table 2.7: Costs of impacts per accident in Saskatchewan

Types of impacts *	Valuation (2006)
Crash	\$3,500
Injury	\$16,000
Death	\$96,000

* Material resource mobilization (hospital, emergency services, etc.)

- *Traffic disruptions*

Traffic disruptions were divided into four: vehicle operating costs (VOC), vehicle delay costs (VDC), pedestrian delay costs (PDC) and obstruction to emergency vehicles (OEV). Traffic disruptions are reflected in increments in travel time and route, leading to traffic delays which can be measured through field studies, empirical formulae or traffic modelling tools (Ormsby, 2009). They were commonly estimated as opportunity costs of forgone work activities by setting the value of time lost in traffic at the hourly wage rate. Existing assessment models for traffic disruptions are illustrated in Table 2.8.

o *Vehicle operating costs*

Vehicle operating costs (VOC) were separated into two: costs for additional fuel consumption (VOC_f) and costs for increased maintenance (VOC_m) which include other non-fuel operating costs. Increased maintenance refers to vehicle depreciation resulting from longer travel route or time and increased stop-and-go cycles that damage shocks, mufflers, tires, axles and chasses. VOC were assessed by using an average operating cost (AOC) in dollar per vehicle-kilometer driven that considers both fuel and maintenance (CAA, 2013). In case of a partial road closure allowing traffic through the work zone, VOC were divided into two: VOC_{fq} for queuing vehicles and VOC_{fd} for vehicles taking detours (De Marcellis, *et al*., 2013; Najafi, 2004). Specifically, VOC_f were assessed for each type of vehicles (automobile, bus, light and heavy truck) to reflect their differences in fuel consumption (De Marcellis, *et al*., 2013).

- *Vehicle and pedestrian delay costs*

Vehicle delay costs (VDC) were assessed as opportunity costs of forgone work activities by setting the value of time (VOT) lost in traffic at the hourly wage rate. The latter is borne by each passenger in circulation. In case of a partial road closure allowing traffic through the work zone, VDC were divided into two: VDC_q for queuing vehicles and VDC_d for vehicles taking detours (De Marcellis, *et al*., 2013). Specifically, VDC were assessed for each type of vehicles to give higher VOT to light and heavy trucks. In literature, case studies were presented with a knowledge of detour patterns; thus, removing the need of traffic simulation tools to forecast behaviors of drivers' choice between taking detours and waiting in queues. Likewise, pedestrian delay costs (PDC) were assessed as opportunity costs of forgone activities borne by pedestrians and people in bikes, strollers and wheelchairs. PDC is significant when the number of pedestrians is important; thus, were often neglected for off-peak hours in business areas. In case of a partial sidewalk closure, remaining adjacent walkways could potentially be used as alternate routes per people safety/comfort desire to get to their destination. Note that accessibilities to buildings are always provided.

- *Obstruction to emergency services*

Costs for obstruction to emergency vehicles were assessed in the same manner as delay costs, except for the value of time set at the emergency response time such as response fees associated to a call or penalty charges for exceeding predetermined response times. Emergency vehicles are limited to ambulance, police and fire, even though regular vehicles can also provide emergency services in rushing to hospital or airport (Ormsby, 2009). Given that these vehicles are supplied with communication devices ensuring up-to-date traffic conditions plus location of road works, potential accessibility issues are mitigated; thus, leaving only additional travel time concern.

Table 2.8: Parametric models for traffic disruptions

Authors	Social cost indicators	Abbr.	Detailed calculations
(b)	Traffic disruptions		VOC + VDC + PDC
(b)		VOC	$\Delta L \times AOC \times DTD \times PD$
(e), (h), (i)	Travel delay		VDC + PDC
(g)			VDC + PDC + VOC
(g), (e)		VDC	$\Delta T \times VOT \times ANPV \times DTD \times PD$
(h)			$VDC_q + VDC_d$
(i)			$\Delta T \times VOT \times DTD \times PD$
(h)		VDC_q	$\Delta T_q \times \sum_i^n ANPV_i \times VOT_i \times \sum_j^m NV_{ij}$
(h)		VDC_d	$\Delta T_d \times \sum_i^n ANPV_i \times VOT_i \times \sum_j^m NV_{ij}$
(e), (g), (h), (i)		PDC	$\Delta T \times NPD \times VOT \times PD$
(a)	Vehicular traffic disruption		$VOC_f + VDC$
(a)		VOC_{fq}	$FP \times \Delta AFCV \times DTD_q \times PD$
(a)		VOC_{fd}	$\Delta L \times FP \times AFCVK \times DTD_d \times PD$
		VDC	$VDC_q + DVC_d$
(a)		$\Delta AFCV$	$LR \times \Delta AFCVK$
(f), (g)	Obstruction to emergency vehicles	OEV	$\Delta T \times VERT \times NTD \times PD$
(f)	Increased pedestrian travel time	PDC	$\Delta T \times NPD \times VOT \times PD$
(f)		ΔT	$LR_{wc} / WS_{wc} - LR_{nc} / WS_{nc}$
(f)		ΔT_c	$RW / WS + T_L$
(f)		T_L	10-30 sec
(f)	Increased vehicle operating cost	VOC	$\Delta L \times AOC \times DTD \times PD$
(g)			$VOC_f + VOC_m$
(g)		VOC_f	$\Delta AFCV \times FP \times DTD \times PD$
(h)			$VOC_{fq} + VOC_{fd}$
(h)		VOC_{fq}	$FP \times \sum_i^n \Delta AFCV_i \times \sum_j^m NV_{q_{ij}}$
(h)		VOC_{fd}	$\Delta L \times FP \times \sum_i^n AFCVK_i \times \sum_j^m NV_{d_{ij}}$
(h)		$\Delta AFCV$	$AFCVH \times \Delta T$
(g)		VOC_m	$\Delta L \times AOC_m \times DTD \times PD$
(h)			$\Delta L \times \sum_i^n AOC_{m_i} \times \sum_j^m NV_{ij}$

(i)	Vehicle operating cost	VOC	$\Delta L \times OCA \times DTD \times PD$
(f), (c)	Increased vehicular travel time	VDC	$\Delta T \times VOT \times ANPV \times DTD \times PD$
(f)		ΔT	$TT_{wc} - TT_{nc}$
(f)		ΔL	LR_{wc} - LR_{nc}
(f)		ΔL_{eq}	$\Delta T \times AVS$

DTD = daily traffic density [veh/day]
ΔL = increment in travel length [km]
AOC = average operating costs [$/veh-km] solely for maintenance and non-fuel operating costs
PD = project duration [days]
ΔAFCV = increment in average fuel consumption per vehicle [liter/veh]
FP = fuel price [$/liter]
ΔL = additional travel length [km]
AFCVK = average fuel consumption per vehicle-kilometer driven [liter/veh-km]
LR = length of the travel Route [km]
AFCVH = average fuel consumption per vehicle-hour driven [liter/veh-hour]
ANPV = average number of passenger per vehicle [per/veh]
OCA = operating cost allowance [$/veh-km]
ΔT = increment in travel time [hr]
TT_{wc} = travel time in work conditions [hr]
TT_{nc} = travel time in normal conditions [hr]
LR = length of travel route
LR_{wc} = length of travel route under work conditions
LR_{nc} = length of travel route under normal conditions
AVS = average vehicle speed [meter/sec]
VOT = value of Time [$/hr-per]
NPD = number of pedestrians per day [per/day]
WS = walking speed [m/s]
RW = road width [m]
ΔT_C = crossing delay [s] if crossing is required
T_L = traffic light waiting time [s]
VERT = emergency response time [$/min]
NTD = number of trips per day [trips/day]

Where i = 1 to n (total number of vehicle types) and j = 1 to m (PD)

Two problems are identified from previous studies on the assessment of traffic delay costs. The first is the use of the hourly wage rate as the value of time (VOT) lost in traffic. The second is the use of a constant value of the daily traffic density (DTD) for the duration of works. The use of a VOT based in personal income fails to represent the true value that people place on their time. By nature, the VOT will depend on the time of the day which is often related to the types of trips. For instance, morning rush hours are most likely commuting trips (home-work or school-work). More research should be done for establishing a VOT that reflects opportunity costs of deprivation from productive, leisure or educational time. For the time being, the use of the local average wage rate is commonly accepted and specifically weighted per trip purposes (business or non-business) or vehicle types (buses, automobiles or trucks).

Traffic investigations reveal that the DTD varies per the day of the week and the time of day (Manuilova, *et al*., 2009). Indeed, the DTD is higher for week days than week-end, likewise for peak than off-peak hours. In that regard, some authors used a correction factor to neglect impacts by assessing delay costs only for working days and then multiplying the results by the daily duration of peak hours. In a nutshell, we conclude that the time of the day is a key parameter for traffic delay costs and should be integrated in the assessment process. This will allow setting VOTs based on periods of the day and affecting them to DTD in circulation during that period.

2.3.2.2. Local economy disruption

Impacts on local economy were divided into six: municipal revenue loss, business income loss, property value loss, productivity loss, compensations and tax rebates as illustrated in Table 2.9.

Table 2.9: Assessment methods for local economy disruption

Indicators	Revealed preference methods
Municipal revenue loss	Benefit transfer
Business income loss	Benefit transfer
Property value loss	Benefit transfer; Trade-off
Productivity loss	Hedonic pricing
Compensations	Benefit transfer
Tax rebates	Benefit transfer

- *Municipal revenue loss*

Municipal revenue loss resulting from parking place reduction or suppression was divided into two: lost parking meter and ticket revenue (LPMR and LPTR). LPMR was commonly estimated as the product of three explanatory variables: lost metered spaces, daily parking space rate and project duration. Likewise, LPTR was assessed as the product of three variables: number of tickets per day, average fine amount and project duration. Yet, variables such as lost meter spaces and the number of tickets are random. In that regard, some authors proposed to multiply LPMR and LPTR respectively by a percent change of occupancy and of ticketing; thus, allowing dealing with uncertainties (Rahman, *et al*., 2004; Ormsby, 2009; Manuilova, *et al*., 2009; Matthews, 2015). LPRT is high in areas where average ticketing infractions are considerable. A correlation between LPRT and LPMR might exist because the loss of parking spaces could result in increased number of tickets given that some drivers would risk to park in restricted zones and thus willingly accepting to pay any fine for infraction (Ormsby, 2009). Existing assessment models for municipal revenue losses are illustrated in Table 2.10.

- *Business income loss*

Business income loss was commonly expressed as the difference between the changes in both revenue and total costs/expenses because reduced operating costs can offset decrease in revenue and thus mitigating losses. Some authors considered that in overall loss of sales in goods and services of one business owner could be offset by another's gain, except for specific shops with a lack of competition. Customers are simply transferred from one shop to another; therefore, the impacts are nil. However, business owners can incur losses in the form of damaged goods and delays of transported goods that might increase freight shipping as well.

- *Property value loss*

Property value loss was commonly estimated by transferring results from studies on depreciation of real estate due to highway traffic noise, which expresses the loss as a function of the noise depreciation index ranging from 0.4 to 0.65 percent of decrease in property value per decibel above the ambient noise level (Manuilova, et al., 2009). However, others found this method not adapted for non-recurrent noise related to works in urban areas as opposed to recurrent noise such as highway traffic noise. In fact, non-recurrent noise associated with the use of heavy machineries used for drilling, blasting and excavating, can hinder sales for a while because property owners can choose to postpone their sales after the completion of works. Therefore, property value loss was alternatively assessed as opportunity costs of missing sales during works (Ormsby, 2009).

- *Productivity loss*

Productivity loss at work place due to noise disturbance was commonly assessed through human capital approach, which expresses the loss as the product of the average hourly wage rate multiplied by the percentage of lost capital known as the productivity reduction factor (PRF). The common PRF values are illustrated in Figure 2.5 with respect to the noise level in decibels and the type of businesses (De Marcellis-Warin et al., 2013).

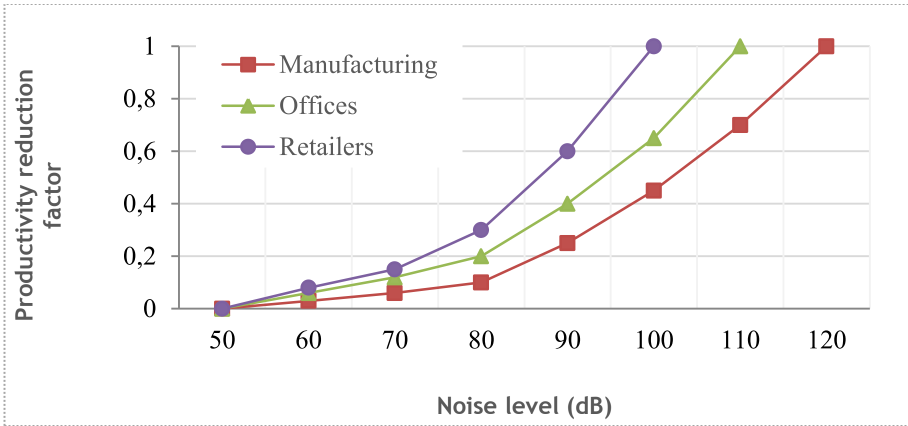

Figure 2.5: Productivity loss due to noise (De Marcellis-Warin et al., 2013)

- *Compensations and tax rebates*

Customers' tendency to avoid roads under construction results in losses of sales. However, work impacts on commercial tax revenue (in terms of goods and services tax/harmonized sales tax (GST/HST) and Quebec sales tax (QST)) can be neutral during the taxation year period given that the loss of potential customers in one shop would only transfer them to another shop within the area, except for specific shops with lack of competing actors. Specific shops will not necessarily suffer from permanent losses in sales because sales can simply be postponed and possible transfers of activities in both time and space can take place (Le Gauffre, et al., 2002). In the context of the City of Montreal, businesses that are closed during works are elligible for property tax rebates. Therefore, compensations in the form of tax rebates, compensatory payments/measures and legislative lenience such as temporary rights to use public spaces to enhance business sales are borne by the municipality; thus reducing sale/income losses for business owners (Ormsby, 2009).

Table 2.10: Parametric models for local economy disruption

Author	Social cost indicators	Abbr.	Detailed calculations
(b), (e)	Municipal revenue loss		LPMR + LPTR
(b), (e)		LPMR	NLMS × DPSR × PD
(b), (e)		LPTR	PCT × NTD × AFA × PD
(b), (e)		DPSR	HMR × DOH × PCO
(g)	Loss of parking spaces		LPMR + LPTR
(g)		LPMR	NLMS × DPSR × PD
(g)		LPTR	PLRZ × NTD × AFA × PD
(g)		DPSR	HMR × DOH × PCO
		PLRZ	$\frac{SLRZ}{TSRZ}$
(i)	Loss of parking revenue		LPMR + LPTR
(i)		LPMR	NLMS × DPSR × PCO × PD
(i)		LPTR	AFA × NTD × PD
(f), (h)	Lost parking meter revenue	LPMR	NLMS × DPSR × PD
(f)		PMRC	FPF + DPSOR × PD
(f), (h)	Lost parking ticket revenue	LPTR	PLRZ × NTD × AFA × PD
(f)		PLRZ	$\frac{SLRZ}{TSRZ}$
(f)	Compensation and tax rebates	TACM	
(a)	Business and trade loss	LCTR	AALOSTD × PD
(g)	Loss of income	LOBI	
(f)	Lost business income	LOBI	CIR – CITCE
		CIR	PCIR (%) × AER
		CITCE	PCITCE (%) × AETCE
(i)	Lost business revenue	LBR	IF × TW × PD
(f), (h)	Lost property value due to noise	$LPVN_{W}$	ΔdB(A) × NDI × TVOAP
(f)		TVOAP	$\frac{NAU}{TNUM} \times ANSD \times APP \times DNE$
(h)			$\sum_{i}^{n} VOAP_i \times AFP_i$
(e)	Noise and vibrations	$LPVN_{HT}$	ACOHN × L × DTD × PD

		ACOHN	$\frac{\mathrm{HDK}}{360} \times \frac{\mathrm{AHV}}{250{,}000} \times \frac{\mathrm{NDI}}{0.0062} \times (-0.018 + 0.0028 \ln(\mathrm{HTD}))$
(c)	Productivity reduction	LOP	$\mathrm{PD} \times \mathrm{PRF} \times \mathrm{NOAE} \times \mathrm{AHWR}$
(f)	Psychological / physical ailments	LOP	$\mathrm{PD} \times \mathrm{PRF} \times \mathrm{NOAE} \times \mathrm{AHWR}$
(h)	Noise and vibration	LOP	$\mathrm{PD} \times \sum_{k}^{n} \mathrm{PRF}_k \times \mathrm{NOAE}_k \times \mathrm{AHWR}_k$
(g)			$\mathrm{PD} \times \mathrm{PRF} \times \mathrm{NOAE} \times \mathrm{AHWR}$
(d)		LCTR_{gross}	$\mathrm{LCTR}_{net} - \mathrm{TACM}$

LPMR = lost parking meter revenue [$]
NLMS = number of lost metered spaces
DPSR = daily parking space rate [$/day]
PD = project duration [days]
HMR = hourly meter rate [$/hr]
DOH = daily operational hours [hr/day]
PCO = percent of change occupancy [%]
PMRC = parking meter revenue compensation [$]
FPF = fixed permit fee [$]
DPSOR = daily public space occupancy rate [$/day
LPTR = lost parking ticket revenue [$]
PLRZ = percent of lost restricted zone
NTD = number of tickets per day [ticket/day]
AFA = average fine amount [$]
SLRZ = surface of lost restricted zone [m^2]
TSRZ = total surface of restricted zone [m^2]
LCTR = lost commercial tax revenue [$]
AALOSTD = average amount loss of sales tax per day [$]
LCTR_{net} = net commercial tax revenue loss [$]
LCTR_{gross} = gross commercial tax revenue loss [$]
TACM = total amount of compensation measures [$]
PCIR = percent change in revenue [%]
AER = average expected revenue [$]
PCITCE = percent of change in total costs and expenses
AETCE = average expected total costs and expenses [$]
NDI = noise depreciation index, i.e. percent of reduction of the house price per dB(A) above the ambient noise [(%/dB(A)]

LPVN_W = lost property value due to work related noise
ΔdB(A) = increase in dB(A) relative to normal conditions
IF = impact factor
TW = turnover per week [$/week]
TVOAP = total value of affected properties [$]
NAU = number of affected units
TNUM = total number of units
ANSD = average number of sales per day
APP = Average Property Price [$]
DNE = duration of noise exposure [days]
VOAP = value of affected property [$]
AFP = adjustment factor for property
LPVN_{HT} = lost property value due to highway traffic related noise
ACOHN = average cost of highway noise [$/veh-km]
HDK = housing density per km^2
AHV = average house value [$]
HTD = hourly traffic density [veh/hr]
ANPV = average number of passenger per vehicle [per/veh]
ACOHN = average cost of highway noise [$/veh-km]
L = length of road [km]
DTD = daily traffic density [veh/day]
NOAE = number of affected employees
AHWR = average hourly wage rate [$/hr]
PRF = productivity reduction factor [%]

Where i =1 to n (total number of properties) and k=1 to m (total number of business types)

In a nutshell, different observations can be drawn from previous studies. First, impacts on businesses are difficult to estimate in part because business owners are not willing to divulge their accounting reports. Second, works can cause changes in customers' behaviours that make it difficult to bring them back to the place after works. Therefore, more studies should be done on business losses to consider the following elements for each business unit:

- The type of customer: regular or occasional; regular ones are usually loyal
- The type of shops: local or regional; local shops such as drugstores and groceries are not impacted by works, as opposed to regional shops which can suffer from deferring purchases
- The type of products: for example, beverage and clothing are very sensitive because they can be bought anywhere
- The type of units: shops scattered along a street or concentrated in trading complexes often with underground parking areas; the former suffers more losses

Second, the knowledge of local regulations in terms of compensatory measures is important to estimate net losses, which means gross losses minus compensations. For example, the City of Montreal offers mitigation measures such as marketing campaigns before and after works to increase customers and subsidies to renovate business properties during works. Third, works can also inhibit rental of business units because some business owners do not renew their lease in case of upcoming works. Fourth, the loss of parking spaces can generate parking relocation costs borne by businesses in order to provide parking areas to customers and employees.

2.3.2.3. Life quality loss

Impacts on life quality were divided into three: service interruption, insalubrity and health deterioration as illustrated in Table 2.11. Existing assessment models for life quality loss are illustrated in Table 2.12.

Table 2.11: Assessment methods for life quality loss

Indicators	Revealed preference methods
Service interruption	Preventive expenditure
Insalubrity	Trade-off
Health deterioration	

- *Service interruption*

Impacts of scheduled water service interruptions to block and reopen connections can be mitigated by the fact that the population is usually forewarned and can adjust their behaviour optimistically at no cost. However, some facilities such as dental care, restaurants, hotels and hospitals, are highly dependent on the service and might engage costs of adjustment. Therefore, costs of water interruptions were estimated as the monetary value of preventive behaviors (CERIU, 2010; Ormsby, 2009).

- *Insalubrity*

Heavy machineries such as jackhammer and backhoe equipped with back-up alarms and pneumatic equipment for earth moving, paving and demolition can be a great source of noise in urban areas (Gilchrist and Allouche, 2005). Even if one cannot ascertain a direct causal relationship between health deterioration and infrastructure projects, long-term exposure to noise can lead to negative health effects ranging from fatigue to permanent ear damage (Rahman, et al., 2005). Specifically, side-effects of noise can be physiological (hearing loss, sleep disturbance), psychological (irritability, tenseness) and social (communication interference); thus, leading to citizen discomfort and complaints. Given that people react differently to noise exposure, with some functioning with less productivity and others not coping with it, noise impacts were estimated as opportunity costs of time lost due to noise exposure (Najafi, 2004; Rahman et al., 2004).

In addition, dirt and dust resulting from construction activities can be harmful for human health. Depending on the nature and the degree of exposure and the people vulnerability, impacts can range from irritability and discomfort feeling to temporary problem of vision, allergies and respiration (Le Gauffre, et al., 2002). Costs of dirt and dust regarding life quality loss were expressed in the form of medical treatment costs (CERIU, 2010). The aspect of cleaning costs related to dirt and dust is discussed in the section 2.3.3.5 of urban landscape damage, and the aspect of air pollution in terms of particular matter (PM_{10}) in the section 2.3.3.7 of ecological environment damage.

- *Health and safety issues*

Health and safety were addressed in the form of human life loss and injury costs (Manuilova, et al., 2009; Ormsby, 2009). Human life loss is the largest component of accident costs (Manuilova, *et al*., 2009). It is highly associated with trenching-related activities (Najafi, 2004; Matthews, 2015). Although many people think that human life is priceless, methods referred as Value of Statistical Life attempt to give a price to life loss (see Figure 2.4). Injury costs cannot be neglected given that 20 % of traffic accidents directly related to construction works involve a member of the construction crew (Ormsby, 2009). However, in western countries, injuries are indemnified in most cases through health care systems by spreading out costs of health services to all beneficiaries. Therefore, benefits of health care offset medical costs borne by injured individuals, except for medical expenses not covered. Likewise, wage loss not compensated by insurance during convalescence should be taken into consideration. At this stage, family burden and activities forgone from injured individuals are unpredictable. Finally, costs of bypass installation are often neglected but constitute on their own social costs engaged in the bid to avoid any service interruption.

Table 2.12: Parametric models for life quality loss

Author	Social cost indicators	Abbr.	Detailed calculations
	Service interruption	USIC	
(f)	Water and wastewater service interruption	USIC	PC × RF × OAP × PD
(g)	Temporary service provision	USIC	PC × RF × OAP × PD
(c), (h)	Reduced quality of life		
(a), (b)	Noise disturbance	NEC	LTNED × NOAP × VOT × PD
(i)	Noise pollution costs	NPC	NOAP × PD × (NC_W - NC_P)
	Health and safety		
(f)	Accidental injury and death	AIDC	IC_{sofc} + IC_{nfip}
(g)		$AIDC_W$	IP × WAWD × PF × NAW × PD
(i)	Safety		IP × WAWH × PF × NAW × WHD × PD

USIC = utility service interruption costs
PC = preventive costs
RF = reduction factor [hr/day]
PD = project duration [days]
NEC = noise exposure cost
LTNED = lost time due to noise per day [hr/day]
NOAP = number of affected people [per]
VOT = value of time [$/hr-per]
NC_W = noise cost value for construction works [$/day]
NC_P = noise cost value prior to works [$/day]
AIDC = accidental injury and death costs
IC_{sofc} = Injury costs settled out from court
IC_{nfip} = injury costs neglected from insurance policies
$AIDC_W$ = worker accidental injury and death costs
IP = insurance prime ($/ $ of wage)
WAWD = worker average wage per day [$/hr]
WAWH = worker average wage per hour [$/hr]
PF = pain factor (multiplier for individual pain)
NAW = number of affected workers
WHD = working hours per day [hr/day]

2.3.2.4. Construction works

Additional construction works normally included in the bid such as overhead, reinstatement, emergency service and redundant system, can be accurately quantified after project completion (Rahman, et al., 2005). They are usually covered in the project cost contingency ranging from 5 to 20 % of total costs but could exceed it.

2.3.2.5. Urban landscape damage

Urban landscape damage results from dirt and dust deposits and hazardous use of heavy machineries. They were assessed in two forms: dirt and dust cleaning costs and property damage as illustrated in Table 2.13. Existing assessment models for urban landscape damage are illustrated in Table 2.14.

Table 2.13: Assessment methods for urban landscape damage

Indicators	Revealed preference methods
Dirt and dust cleaning costs	Preventive expenditure
Property damage	Asset valuation

- *Dirt and dust cleaning costs*

Dirt and dust is very critical in heavy urbanization areas (city center) and affects primarily residential, commercial and specific areas such as hospitals and schools (Rahman, et al., 2005). In addition to lowering aesthetic air quality, they can increase cleaning and maintenance costs particularly for building facades made of glass.

- *Property damage*

Excavations, inappropriate work planning and hazardous operations of heavy machineries can damage the urban landscape in an irreversible way; thus, leading to restoration costs for damaged structures of historical heritage and recreational facilities, and for ecosystem components such as parks, surface water and trees. Damage to structures can be mitigated by using proper techniques in shoring, underpinning, excavating and dewatering, to prevent uneven settlements and distresses (Najafi, 2004). Damage to ecosystem can take many decades to be restored to its original balance. Damage to structures can be seen immediately or detected after several months. Therefore, restoration costs can be borne by either owners or responsible parties after court settlement, or simply not restored but tolerated particularly if the damage is not immediately detected during and after works (Ormsby, 2009). They were often assessed by multiplying the likelihood of damage by its expected impacts in monetary terms.

Table 2.14: Parametric models for urban landscape damage

Author	Social cost indicators	Abbr.	Detailed calculations
(f)	Property damage	CPD	$LOD \times LCOD \times NDO$
(f)	Damage and lost amenity of recreational facilities	DLARF	$VOA \times PORA \times DODI$
(b), (g), (f)	Dirt and dust	DDCC	$ITCD \times CLCS \times PD$
		CLCS	$NOAU \times HPRU$
(i)	Cost of dust control	CDC	$ITCD \times CLCS \times PD$
			$2 \times LB \times HB \times W \times CF \times CCMS$

CPD = costs of property damage
LOD = likelihood of damage
LCOD = likely cost of damage
NDO = number of damage occurrences
DLARF = damage and loss of amenity of recreational facilities
VOA = value of the amenity [$]
PORA = percent in reduction of the amenity
DODI = duration of the damage impact
DDCC = dirt and dust cleaning costs
ITCD = increased time of cleaning per day [hr/day]
CLCS = cost of local cleaning services [$/hr]
PD = project duration [days]
NOAU = number of affected units
HPRU = hourly pay rate per unit
LB = length of building next to work zone [m]
HB = height of building next to work zone [m]
W = share of windows [%]
CF = correction factor
CCMS = costs of cleaning per meter square [$/m^2]

2.3.2.6. Adjacent utility damage

Impacts on adjacent utility damage can be divided into two: damage to road and pavement, and damage to buried utilities as illustrated in Table 2.15. Existing assessment models for adjacent utility damage are illustrated in Table 2.17.

Table 2.15: Assessment methods for adjacent utility damage

Indicators	Revealed preference methods
Damage to road and pavement	Asset valuation
Damage to buried utilities	Asset valuation

- *Damage to road and pavement*

Road damage induced by pavement cuts and trenches can take time to develop per the original pavement conditions (Ormsby, 2009). Likewise, pavement damages resulting from additional heavy traffic load on detoured roads not designed to support heavy traffic don't show up immediately and can also take many years to develop (Najafi, 2004). All this can lead to reduced pavement lifespan by up to 30 % (Matthews, 2015). Lifespan reduction is in part due to induced-soil differential settlement below the pavement leading to surface roughness, cracks and distresses, potholes, structural discontinuities and eventually to collapses (Najafi, 2004). Therefore, extra maintenance demands should be considered, in addition to reduction in travel comfort and safety, and accelerated vehicle deterioration due to bad road conditions. Pavement cuts in the first year of life can increase costs of maintenance of around \$150 per m^2 over a 30-year lifespan of the road structure (Ormsby, 2009).

There is still a lack of conclusive results about the effects of a utility cut on the pavement conditions (Ormsby, 2009). Many concurrent factors such as inappropriate backfill materials, poor sewerage drainage and poor patching procedures, can trigger the reduction of pavement service life. Non-linear pavement deterioration is used by the Transportation Department of the City of Montreal to simulate impacts on pavement condition in the first year of life (see Table 2.16).

Table 2.16: Pavement deterioration due to open-cut repairs (City of Montreal)

Number of repairs	Level of severity of surface repair		
	Low	Medium	High
1	99	98	96
2	98	96	93
3	97	93	89
4	96	91	85
5	95	89	82
6	94	87	78

- *Damage to buried utilities*

Damage to buried utilities can be caused by several factors: pavement collapse around the open-cut, loss of trench wall stability, poor excavation practices and inaccurate subsurface utility mapping during excavation. The latter can account for around 1.1% of project costs (Ormsby, 2009). Accidental water, electrical and gas main bursts during works can lead to severe impacts such as other project delays and business/resident evacuation with significant emergency costs (De Marcellis-Warin, *et al*., 2013). More research should be performed on such domino-effects of damage to buried utilities.

Table 2.17: Parametric models for utility damage

Author	Social cost indicators	Abbr.	Detailed calculations
	Accelerated road degradation		
(b), (e), (g)	Service life reduction	RSLRC	$RSLRC_q + RSLRC_d$
			PV_{OSL} - PV_{RSL}
(g)			PV_{BW} - PV_{AW}
(f)	Pavement service life reduction due to excavation	$RSLRC_q$	
(f)	Pavement service life reduction on alternate routes due to increased traffic	$RSLRC_d$	
(i)	Decreased road surface	DRS	$L\times ADRSV$ [\$/m]
		PV_{OSL}	$ICC \times \left(1 - \frac{RA}{RL}\right)$
		PV_{RSL}	$ICC \times \left(1 - \frac{RA}{0.3 \times RA + 0.7 \times RL}\right)$
(a)	Road and pavement damage	RPRC	$RCFS \times NIS$
	Damage to adjacent utilities		
(f)	Adjacent buried utility damage	BAUDC	$DCP \times AVCF \times ANC \times EVF$
		EVF	$\frac{EV}{EV_{ref}}$

RSLRC = road service life reduction costs
PV_{OSL} = present value of the original service life
PV_{RSL} = present value of the reduced service life
PV_{BW} = present value before works [\$]
PV_{AW} = present value after works [\$]
RSLRC = road service life reduction costs
ICC = initial costs of construction [\$]
RA = road age [year]
RL = road lifespan [year]
L = length of excavation [m]

ADRSV = average decreased road surface value (e.g., 110 \$/m)
RPRC = road and pavement restoration costs
DCP = direct costs of project
ACVF = average claim value factor (e.g., 1.1 %)
ANC = average number of claims (e.g., 1.2)
EVF Excavated Volume Factor
EV Excavated Volume during works in m^3
EV_{ref} reference Excavated Volume (e.g., 3,000 m^3)

Where q refers to road under works and d refers to alternate/detour roads

2.3.2.7. Ecological environment damage

Impacts on ecological environment were grouped into three: air pollution, groundwater/soil pollution and green amenity damage as illustrated in Table 2.18. Existing assessment models for ecological environment damage are illustrated in table 2.23.

Table 2.18: Assessment methods for ecological environment damage

Indicators	Revealed preference methods
Air pollution	Trade-Off
Soil and groundwater pollution	Delphi
Green amenity damage	Travel cost

- *Air pollution*

Air pollution resulting from fuel consumption is due to two factors: the use of heavy machineries and increased vehicle emissions (Manuilova, et al., 2009). Air pollutant gases emitted are the following toxic substances (MTQ, 2013): sulphur oxides (SO_x), nitrogen oxides (NO_x), volatile organic compounds (VOC_x), poly-aromatic hydrocarbons (PAH), carbon monoxide (CO), hydrocarbons (HC), particular matter ($PM_{2.5}$ and PM_{10}) and greenhouse gases (GHG) such as carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4). Their emissions are harmful to human health and ecological environment with depletion of the ozone layer. Air pollution costs from machineries were based on the volumetric emission cost (VEC) for each pollutant where GHGs can be converted to CO_2 equivalent (CO_{2eq}) units and thus simplifying calculations. Table 2.19 shows the VEC for air pollutant gases and GHGs used by the Ministry of Transportation of Quebec for benefit-cost analysis (MTQ, 2013). Air pollution costs from increased vehicle emissions were based on a passenger emission cost (PEC). Table 2.20 shows PEC values obtained from appropriate environmental studies (Manuilova, *et al*., 2009).

Table 2.19: Median costs of principal air pollutants and GHG (MTQ, 2013)

Unit cost	GHG	CO	HC	NO_x	SO_x	$PM_{2.5}$	PM_{10}
$ CAN 2011 / metric ton	81	1,742	6,339	8,086	6,747	30,822	8,655

Table 2.20: Passenger emission values (Manuilova, *et al*., 2009)

Types of vehicle	Valuation (2006)
Urban private	$0.001267 per p-km
Urban transit	$0.000454 per p-km
Freight transport (trucks)	$0.000589 per ton-km

Studies on social costs of carbon have been conducted given the increase of people's awareness on environmental pollution. In that regard, NASTT (North American Society for Trenchless Technology) developed a carbon calculator tool to assess CO_{2eq} tons generated by different renewal techniques with traffic controlled by a flag person for one lane closure on a two-lane road flowing in both directions. Table 2.21 shows results of the NASTT tool experiment for a 300-mm pipe, assuming a daily traffic density of 10,000 veh/day within 15 days and a unit cost of $3 per ton of CO_2 (CERIU, 2010).

Table 2.21: Results of NASTT carbon calculator (CERIU, 2010)

Technology	CO_2 tons	Total cost (2009)
Open-cut	252,07	$756,21
HDD	12,06	$36,18
Slip-lining	25,21	$75,63
CIPP	5,04	$15,12

CO_2 emissions are still controversial because they generate at the same time positive externalities for economic growth and negative externalities with pollution (Manuilova, *et al*., 2009). Available emission calculator tools can be used to assess pollution level associated with works despite their limitations such as bias issues (Ormsby, 2009).

- *Groundwater and soil pollution*

Groundwater and soil pollution highly results from accidental or constant leakage from machineries or exhaust fumes onto the ground. The magnitude of impacts depends on the types of groundwater and water uses which are illustrated in Table 2.22 (Werey, *et al*., 2005). Clear regulations and policies associated with pollution rights will enhance assessment of these impacts. Foreseen costs of removing, treating and disposing contaminated soils are normally included in the construction bid (Ormsby, 2009).

Table 2.22: Types of groundwater and water uses (Werey, *et al*., 2005)

Types of groundwater and water uses	Grade
Protected area for drinkable water production	100
Drinkable water production	80
Private domestic wells	60
Other sensitive water uses	30
Other water uses	10
No water use	5
No ground water	0

- *Green amenity damage*

Damage to historical trees, green and protected areas can increase the administrative burden (Najafi, 2004). Green amenity damage was assessed using replacement cost methods to restore the environment near to its original condition (CERIU, 2010).

Table 2.23: Parametric models for ecological environment damage

Author	Social cost indicators	Abbr.	Detailed calculations
	Air pollution		
(f), (g), (h)	Air pollutant and GHG emissions		$EC_{MEPG} + EC_{VEPG}$
(f), (g), (h)		EC_{MEPG}	$\sum_i VEC_i \times PEV_i$
(f), (g), (h)		EC_{VEPG}	$\sum_j PEC_j \times \Delta L_j \times ANPV_j$
(g)	Environmental impacts	ERC	

EC_{VEPG} = environmental costs from vehicle emitted pollutant gases

EC_{MEPG} = environmental costs from machinery emitted pollutant gases

PEC = Passenger Emission Cost [$/per-km]

ΔL = increased travel length (km)

ANPV = average number of passenger per vehicle

VEC = volumetric emission costs [$/metric tons]

PEV = pollutant emitted volume [metric tons]

Where i=1 to n (types of pollutant) and j=1 to m (types of vehicle)

2.3.2.8. *Litigation and legal fees*

Litigation and legal fees result from citizen complaints. They were assessed in two forms: the total amount of complaints and the labor costs dedicated to claim management (see Table 2.24).

Table 2.24: Parametric models for litigation and legal fees

Author	Social cost indicators	Abbr.	Detailed calculations
(a)	Property claims	LM	NC × AAC
(g)	Citizens' complaints	LAF	NEA × NHW × HWR

AAC = average amount of complaints

LM = litigation matters (resulting from vehicular wear due to potholes)

LAF = legal and administration fees

NC = number of complaints

NEA = number of employees affected

NHW = number of hours worked

HWR = hourly wage rate [$/hr-per]

2.3.3. Regression models

The regression models have never been used in the literature to estimate social costs. However, they offer a much simple way to assess social costs at a large scale. Regression models will predict social cost indicators of a new input X as Y, where X is the vector of predictors or independent variables and Y the expectation function or the dependant variable. A non-linear regression model can be written (Gordon, 2002)

$$\text{Equation 1} \qquad \mathbf{Y_i = f(X_i, \theta) + \varepsilon_i,} \qquad i = 1,\ldots, n$$

Where Y_i are the responses or social cost indicators, f is the known functions of the covariate vector $\mathbf{X_i=(X_{i1},\ldots,X_{ik})^T}$ and the parameter vector $\boldsymbol{\theta}=(\boldsymbol{\theta}_1,\ldots, \boldsymbol{\theta}_p)^T$, and $\boldsymbol{\varepsilon_i}$ are random errors. We designate by $\mathbf{Y_i}$ the prediction of $\mathbf{\hat{Y}_i}$ based on $\mathbf{X_i}$, which results from the first implementation of models designed in section 3.3.3. Therefore, the errors can be formulated as follows

$$\text{Equation 2} \qquad \boldsymbol{\varepsilon_i} = |\mathbf{Y_i} - \mathbf{\hat{Y}_i}| \qquad i = 1,\ldots, n$$

To design the regression functions, the relation between $\mathbf{Y_i}$ and each independent variable X_{i1} was studied. The unknown parameter vector $\boldsymbol{\theta}=(\boldsymbol{\theta}_1,\ldots, \boldsymbol{\theta}_p)^T$ is estimated by the method of least squares, which consists in minimizing the sum of the squares of the errors $SSE = \sum_i^n \varepsilon_i^2$. The least squares estimates of the unknown parameter vector are noted by $\boldsymbol{\theta}=(\boldsymbol{\theta}_1,\ldots, \boldsymbol{\theta}_p)^T$. The estimated value is $\mathbf{\hat{Y}_i = f(X_i, \theta)}$. The mean squared error MSE is given by SSE/(n-p) and the estimate σ by $\sqrt{MSE}$. In order to evaluate the non-linear regression, the F-test Two-sample for variances is used for the two populations $\mathbf{Y_i}$ **and** $\mathbf{\hat{Y}_i}$. We assume that the costs are normally distributed data. The hypotheses are:

- H_0: $\sigma_1 = \sigma_2$, variances are likely equal
- H_1: $\sigma_1 \neq \sigma_2$, variances are likely different

If $F \geq F_{0.05}$ (which is the critical value of F for the 0.05 significance level) we can reject H_0 and if $F < F_{0.05}$, we can not reject H_0. When H_0 is accepted, it means that on average the costs are spread out equally from their respective means. Now, in order to compare the two means (μ_1, μ_2) when the variances are known to be likely either equal or different, we can use the Two sample T-test assuming either equal ($\sigma_1 = \sigma_2$) or unequal variance ($\sigma_1 \neq \sigma_2$). The hypotheses are:

- H_0: $\mu_1 = \mu_2$, means are likely equal
- H_1: $\mu_1 \neq \mu_2$, means are likely different

If the p-value ≥ 0.05 (i.e. 5% chance there is no real difference between the two populations), we can not reject H_0 and if p-value < 0.05 we can reject H_0. When H_0 is accepted, it means that on average the two means are reliably the same. Therefore, we conclude that the regression function is validated.

2.4. LIMITATIONS IN EXISTING ASSESSMENT TECHNIQUES

Stated or revealed preference methods have been used to assess social cost indicators related to infrastructure works in various ways. Authors usually present parametric models for assessment with no precision on whether their methods are revealed or stated. For example, a parametric model used to estimate traffic delay costs is the product of four variables: the increment in travel time (hr), the value of time ($/hr), the daily traffic density (veh/day) and the project duration (day). We classify this model in the family of Trade-Off methods which are part of revealed preference methods. Since the value of time lost in traffic is set at the hourly wage rate, travel delay costs are considered as opportunity costs of forgone work activities. Therefore, each parametric model can be related to one single family of stated or revealed preference methods.

Limitations in existing parametric models can be outlined:

1) Contingent valuation methods such as Willingness-To-Pay (WTP) or Willingness-To-Accept-Compensation (WTAC) are barely used. However, these methods can be appropriate to estimate the value of time lost in traffic (VOT). The hourly wage rate, commonly used as VOT, fails to represent the value people placed on their time. Another fact is that people can adjust their behaviour to get on time at work. The VOT can be both tangible and intangible. The first case relates to business trips while the second relates to trips for leisure, commuting (home-work, school-home) or personal activities (sport, divertissement, etc.). Intangible costs are difficult to estimate.

2) Previous techniques failed to consider randomness in explanatory variables. For example, the duration of works is a random variable that may follow a normal distribution. Randomness implies that the social cost value is attached to a probability of occurrence. Also, uncertainty and

variability of explanatory variables were not comprehensively considered in available techniques. Uncertainty deals with variables whose possible values are associated to a random phenomenon, such as occupancy rates of parking spaces, road accidents and vehicle maintenance costs. Variability deals with variables that vary over time, such as vehicle density traffic which fluctuates per the time of the day and the day of the week.

3) The time of the day and the day of the week play a major role in social cost assessment. These variables were neglected in previous models, except for the use of a night factor to assess night-work social costs by multiplying the factor with day-work social costs (Werey, *et al.*, in 2005). This was done to consider the fact that conducting works at night greatly reduces impacts except for noise (Le Gauffre, et al., 2002).

4) No attention is given to compensations and tax rebates. From a municipal point of view, compensations are internal costs that neutralize or reduce impacts; whereas from a society point of view, they are transfer costs that should not be considered in the analysis because a transfer was made from one party (cost for municipality) to another (gain for businesses) within the society.

5) Assessments of social costs were studied only for one single road project and never at a larger scale for an entire road network. Case studies were proposed for single projects (often on one type of assets) of open-cut reconstruction or trenchless rehabilitation. There was also a lack in considering bundled projects resulting from coordination of works among various assets, such as combination of open-cut and trenchless techniques in the same renewal project. Moreover, road status during works whether partially or completely closed is not clearly defined in available techniques.

6)	No regression models had been used to estimate social costs. These models are simpler for assessing social costs at large scale such as an entire road network and are also easier to implement in a decision support system to optimize infrastructure programs.

A systematic approach to predict social costs is data intensive and implies a data protocol for collecting and processing information on different explanatory variables such as numbers of lanes, land use and road function. It also requires descriptions on types of works whether open-cut or trenchless and assumptions on traffic measures (see Table 2.25).

Table 2.25: Typical traffic measures for urban works

Description of traffic measures		Road closure
1)	A road narrowed by works but having two-way flows	Partial
2)	One-way lane closure of a dual two or three lane road	Partial
3)	A road closed in one direction with traffic detour	Partial
4)	A road completely closed in both directions with traffic detour	Complete

After all, social cost indicators should be valid. The validity is the ability of the social cost indicator to measure what it is intended to measure and nothing else. The social cost validity is challenged by the fact that the magnitude of impacts can be triggered by factors other than solely the presence of works in the street. For example, high business losses during works can result in part from constant poor management and thus fail to represent true social costs. At last, the main gap in municipal infrastructure research that was identified in literature is the lack of assessment models to assess social costs at macro scale, not at project level or micro-scale. This research fills this gap by standardizing social cost categorisation and by modeling them through non-linear regression analyses.

2.5. SOCIAL COST INTEGRATION USING SIMULATION IN INFRAMODEX ENVIRONMENT

This section deals with the integration of social costs in the decision support system (DSS), InfraModex. During the 2000s, significant advances were made in developing commercial DSS to assist municipal managers in decision-making processes for infrastructure asset renewals. Seven well-known systems had been discussed in the literature (Halfawy, et al, 2006): Synergen, Cityworks, MIMS, Hansen, RIVA, Infrastructure2000, and Harfan. The first four DSS include condition assessment and rating models. They focus on operational management aspects such as work orders and service requests, with no or little functionality to support long term renewal planning decision as well as the vast majority of existing systems that are absent in the literature such as MAXIMO. The last three DSS implement some level of support for long term renewal planning with modules for deterioration modelling, risk assessment, life cycle cost analysis, asset prioritization. However, the lack of considering social costs created significant inefficiencies in long-term work programs.

InfraModex had never been discussed in literature and was developed in 2004 to help municipal planners in long-term renewal programs. It is currently used in different canadian cities such as Hamilton, Montreal and Gatineau. Contrarily to previous decision support systems (DSS), InfraModex is a platform which offers decision support modules to automate different aspects of decision processes like to span multiple infrastructure assets as much as possible for coordination purposes. It is used in this research to integrate social costs related to works in order to compare long-term renewal policies for three linear municipal systems: water, sewer and road.

2.5.1. Automated modules for decision support

The use of InfraModex by Montreal Water Service's planners to support long-term programs for water and sewer distribution networks began in 2007. As part of the team, we developed various automated modules to implement renewal treatment scenarios. However, no attempt was done to integrate social costs in the analysis despite our awareness of their importance in the decision. In this research, social costs were incorporated for the first time. InfraModex parameterization involves six modules: (1) asset listing, (2) simulation parameters, (3) decision trees, (4) features, (5) costs and (6) clusters.

1) The asset listing is the screen view of all initial features of each type of assets before the analysis, given that InfraModex is a web-based tool with little interaction with the GIS.
2) Simulation parameters are of two types: general and financial. General parameters are the year of analysis, the reference year for costs, the number of iterations and the planning horizon, where the reference year for costs refers to the starting year when the inflation rate will be applied. Financial parameters are the inflation and interest rates. A distribution is normally assigned to the inflation rate and applied to both social and construction costs.
3) Decision trees are designed to model decision-making for infrastructure asset renewals. For each type of asset (water, sewer and road), one individual decision tree (IDT) is built with no consideration of adjacency with other types of asset. IDT consists in setting decision rules to select appropriate treatments based on condition states and selected criteria. Then, one coordination decision tree (CMD) is built to perform coordination of treatments resulting from the three IDTs over a planning horizon. A preselected treatment from an IDT can then be overthrown by another from the CMD; thus, enabling to advance and change treatments resulting from the IDTs throughout the planning horizon.

4) InfraModex also comprises two simulated features: progressive and non-progressive. Non-progressive features consist in physical characteristics such as diameter, material and installation date. Progressive features consist in state conditions of segments. For progressive features, automated modules to forecast their evolution should be programmed such as deterioration curves and break rate previsions. New initialization of some features is required for long-term planning simulation when treatments are carried on over time, for example a road reconstruction will bring the pavement condition index back to an excellent state.
5) The cost module in InfraModex is built in such a way that each treatment can be broken down into one or more cost items at the discretion of the user. For example, three cost items can be added to water segment replacement: pavement refection cost, pipe installation cost and repair cost of existing sidewalks. Therefore, a list of cost items and associated cost distributions are designed for each treatment per asset type and can vary accordingly to either diameter classes or road jurisdictions (local/arterial).
6) The clustering module simply helps to customize the presentation of results per assets. For instance, the user can decide to plot in the same graph, kilometers of assets scheduled for works and condition states. Also, the user can decide which type of costs (break repair, replacement, CIPP) should be presented in the investment profile throughout the horizon.

2.5.2. Social cost optimization

The need to integrate social costs in InfraModex was met in this research to support infrastructure long-term planning for the City of Montreal's Water Service. The complexity of integrating social costs in the past stems from the fact that they were difficult to assess at a macro level, and they were subject to cost variability due to the site vulnerability and the gravity of damage. Moreover, they needed flexible decision support systems which provide various generic functionalities and possibilities to customize build-in modules. In InfraModex, social cost indicators should be added as items for each work package (see Figure 2.6).

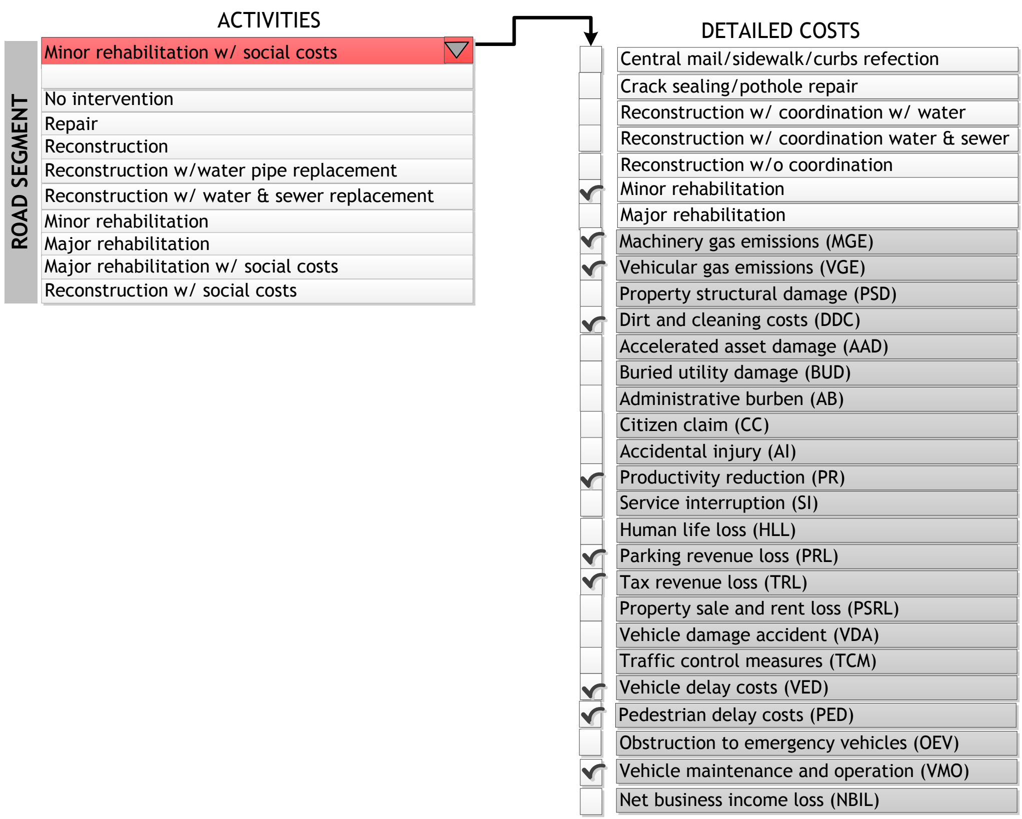

Figure 2.6: Example of cost items for road minor rehabilitation

Then the simulation was performed in InfraModex (see Figure 2.8). At the beginning, condition states are forecasted for each type of asset to feed in part decision tree criteria for treatment selection. Then, appropriate treatments will be proposed for each type of asset, resulting in three uncoordinated work programs. The resulting treatments are now criteria for the coordination decision tree to assess to propose one coordinated work program for all assets. This process is repeated many times due to the Monte-Carlo simulation (see Figure 2.7). The result of a scenario is not a single Present Value (PV) for investments but rather a distribution of PVs with their probability of occurrence.

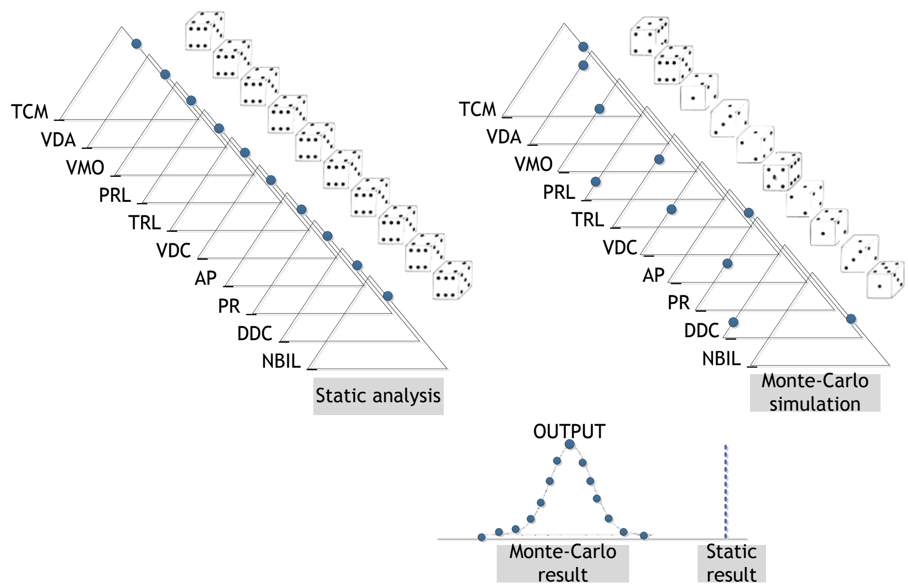

Figure 2.7: Social cost simulation versus static analysis

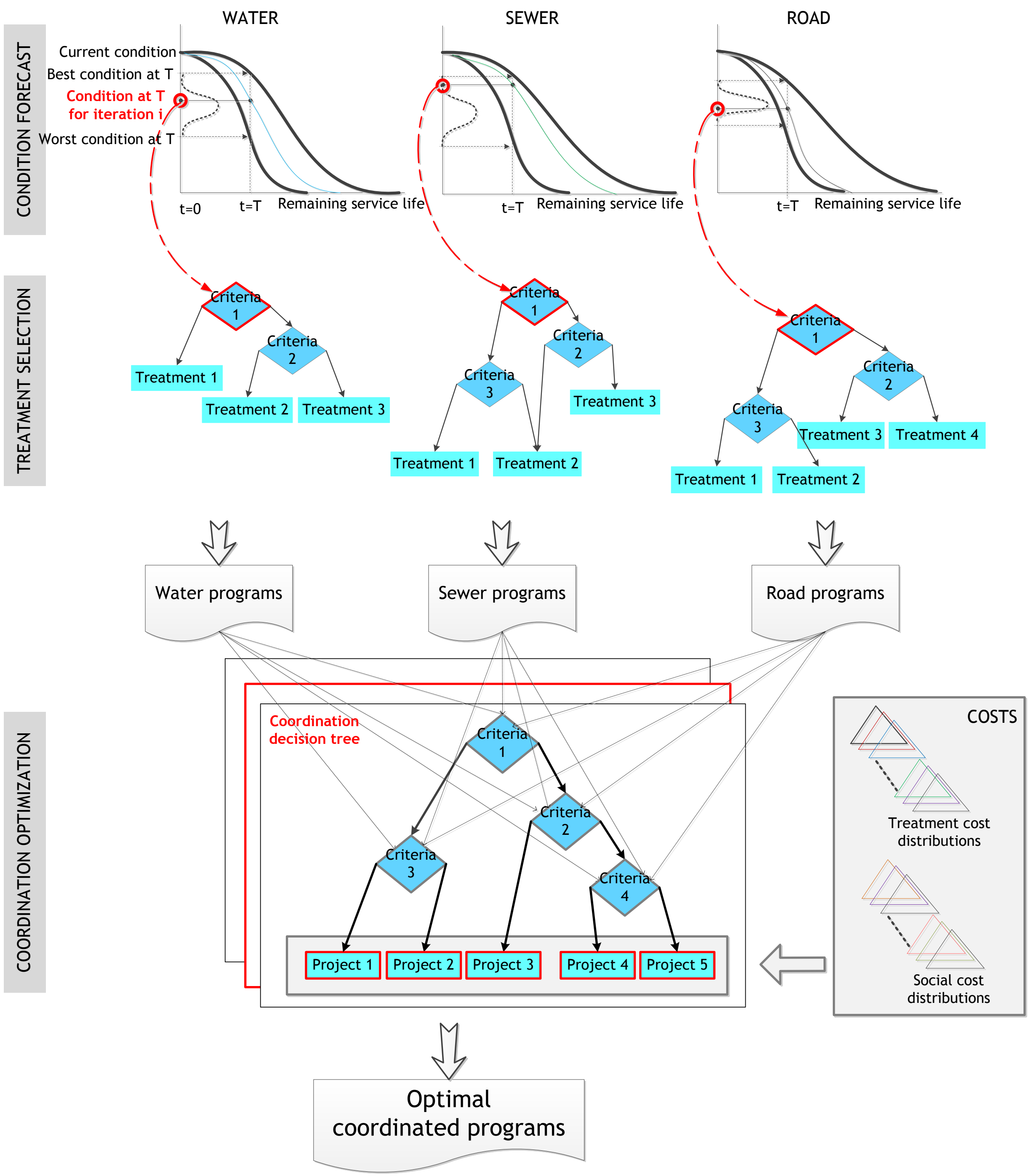

Figure 2.8: Optimization of renewal decisions

CHAPTER 3: RESEARCH METHODOLOGY

3.1. INTRODUCTION

Figure 3.1 shows the steps of research methodology: (3.2) specification of social cost indicators, (3.3) prediction of social cost variables, (3.4) non-linear regression modeling for social costs and (3.5) optimizing coordination strategies.

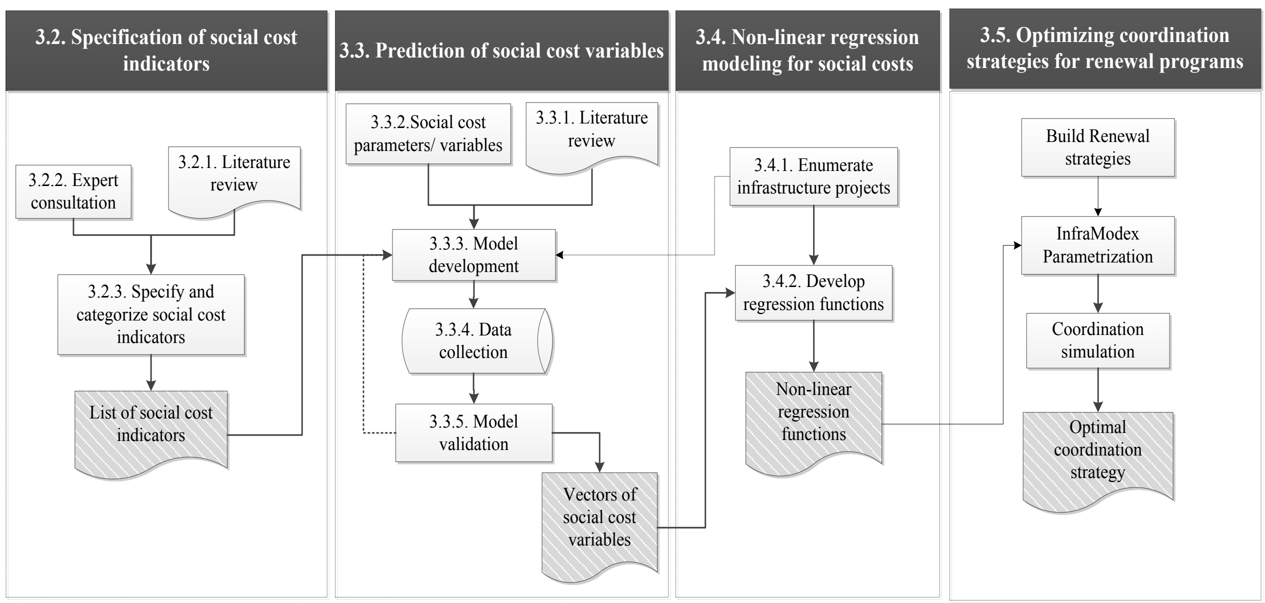

Figure 3.1: Research methodology

Social cost indicators were specified through extensive literature reviews and consultation with experts such as municipal officers, to specify and categorize social cost indicators. For each indicator in the resulting list of social cost indicators, an assessment model is develop through the upgrade of existing assessment methods from literature reviews and the identification of social cost parameters and variables. Data collection and processing are performed to run the developed models for one particular district of the City of Montreal. Once the models are validated, the resulting vectors of social cost variables are used as response variables in developing non-linear least squares regression models, to estimate the unknown parameters of the social cost regression functions. At this stage, the enumeration of infrastructure projects helps to assess the project durations that are used in the models. The developed non-linear regression functions enable to assess social costs at a large scale such an entire road network. Then social costs were integrated in the InfraModex decision support system. Three typical renewal strategies were built and tested in InfraModex. The results of the coordination simulation helped to select the strategy that would bring the best outcome for the society.

3.2. SPECIFICATION OF SOCIAL COST INDICATORS

This section deals with the specification of social cost indicators that is built upon extensive literature reviews and expert interviews. Each indicator should measure a specific impact that would not have been made in the absence of work. The specification process consists of three steps: (1) literature review, (2) expert consultation, (3) selection and categorization of social cost indicators.

3.2.1. Literature review

Chapter 2 describes the literature review which covers all the major disciplines necessary for this research and reveals discrepancies regarding both nomenclature and categorization of existing social cost indicators, in addition to a lack of cost breakdown analysis adapted for work-related impacts. The literature also supports the fact that social cost assessment is data-intensive. Even though it is a hard task to record necessary input data, the constraints, difficulties and challenges involved in data collection and processing are not discussed in literature, as well as issues of validity and reliability of indicators.

3.2.2. Expert consultation

Several interviews on impacts resulting from municipal works such as open-cut reconstruction and CIPP were conducted with a variety of stakeholders: engineers, white-collar employees and managers of the City of Montreal, managers of Montreal Public transport agency, business owners and spokesmen, police agents, insurance company agents, buildings' superintendents and human resource workers. Collected information about adverse impacts, cost parameters and work techniques was processed further in this research for the following purposes: to establish a list of selected indicators, to design a social cost data protocol and to develop new valuation methods.

3.2.3. Selection and categorization of social cost indicators

The selection of social cost indicators was performed gradually. First, a list of indicators was drawn from the literature review. Then, interviews were conducted in an attempt to clarify the cost composition of each indicator, thus resulting in twenty-seven indicators grouped into eight categories of domains affected by works (see Table 3.1).

Table 3.1: Social cost specification

I – ROAD TRAFFIC AND SAFETY		
Traffic control measures	TCM	Costs to ensure road traffic and safety such as administrative costs, inspection costs and signaling costs, plus costs of police presence
Vehicle accident damage	VAD	Average vehicle cost of insurance claim, plus permanent loss in an vehicle's market value due to its involvement in an accident if relevant
Vehicle delays	VED	Costs of travel delays for vehicles because of lengthening of travel route or increasing of travel time
Pedestrian delays	PED	Costs of travel delays for pedestrians because of lengthening of travel route or increasing of travel time
Vehicle maintenance and operations	VMO	Costs of additional fuel and non-fuel operations and vehicle maintenance because of lengthening of travel route or increasing of travel time
Obstruction to emergency vehicle	OEV	Costs of additional operations and maintenance because of lengthening of travel route or increasing of travel time

II – LOCAL ECONOMY		
Parking revenue loss	PRL	Losses of parking meter and ticket revenues plus costs of parking space relocation if applicable
Tax revenue loss	TRL	Municipal property tax rebates for vacancies plus reduction in tax revenues resulting from loss on sale for specific shops with lack of competition
Net business income loss	NBIL	Mitigation costs to boost customer sales before and after works or compensations that business owners are willing to accept
Property sale-and-rent loss	PSRL	Revenue losses related to difficulties to sale or rent properties
Productivity reduction	PR	Losses of productivity at work due to noise
III – LIFE QUALITY		
Human life loss	HLL	Statistical value of human life
Accidental injuries	AI	Costs of accidental injuries not compensated by insurance
Service interruption	SI	Costs of bypass installation plus damage costs resulting from unplanned or accidental interruptions
Resident noise discomfort	RND	Costs of noise disturbance preventing people for having a good sleep during night works
IV – URBAN LANDSCAPE		
Property structural damage	PSD	Restoration costs of property structural damage resulting from hazardous or improper work activities
Dirt and dust cleaning	DDC	Costs of cleaning resulting from dirt and dust pollution
V – ADJACENT UTILITY		
Buried utility damage	BUD	Costs of damage to accidental adjacent buried utility in terms of immediate repairs and lifespan reduction
Accelerated asset deterioration	AAD	Accelerated deterioration of assets due to increased traffic load on detoured roads not designed to support it
VI – ECOLOGICAL ENVIRONMENT		
Air pollution	AP	Environmental costs resulting from air pollution caused by fuel consumption and dust emissions
Soil/Groundwater pollution	SGP	Costs to mitigate soil and groundwater polluted by fuel leakage and spills from heavy machinery and exhaust fumes onto the ground
Green amenity suppression	GAS	Social compensations resulting from irreversible suppression of green or protected areas and trees
Ecosystem restoration	ER	Costs of restoring the ecosystem near to its original state

VII – CLAIM MANAGEMENT		
Administrative burden	AB	Increased service costs for public transport agency
Citizen claims	CC	Total amount of citizen claims related to works
VIII – CONSTRUCTION WORK		
Unforeseen work activities	UWA	Unforeseen construction and overhead costs related to activities normally included in the contract bid
Urban landscape reinstatement	ULR	Costs of pavement and landscape reinstatement often considered in the project cost or contingencies

In building the specification of social costs, it is important to notice that:

- In the City of Montreal, TCM costs are usually included in the contract bid, except for costs of police presence. However, police presence is required on major road construction sites although its cost can be high.
- Traffic accident impacts are usually broken down into two: material and personal (light, serious, fatal) damage. We consider it inaccurate to use a total cost for traffic accidents including both personal and material damage since value of human life is controversial. Therefore, we divided traffic accident impacts in three indicators: VDA costs for vehicle material damage, AI costs for light and serious personal damage and in HLL costs for fatal one. The last two also consider both public and site workers' personal damage.
- PRL costs are not only related to losses in parking meter and ticket revenues, but also additional costs of parking space relocation incurred by the municipality or enterprises, for example when the accessibility to public or private parking spots is denied.
- Ideally, NBIL should be assessed as the marginal loss of income revenues from losing businesses that cannot be recovered afterward and that are not offset by other gain of income revenues from winning businesses, minus potential compensations. The latter can be municipal funds to boost customer traffic and sales on commercial arteries before and

after works through marketing campaigns, or to renovate business properties during works. Yet, lack of information concerning business accounts leads us to compute NBIL as either mitigation measure costs or estimates of business owners' willingness to accept compensations. In fact, interviews with business owners reveal that they are willing to accept compensations from the municipality in the form of tax property rebates.

- SI costs of bypass installation are usually included in the contract bid. However, unplanned interruptions can affect some facilities such as food production plants, dental care and hospitals which are highly dependent on water service. Also, restaurants can be forced to close temporarily and are subject to risks of burns so as groceries to losses of goods / products when equipped with cooling water systems.
- DDC are critical for buildings in the city center made of glass and also for restaurants with a terrace and for retailers. Daily cleaning should be done in order to prevent losses of customers and to maintain good aesthetic quality of the urban environment.
- AB costs are limited to increased service costs for Public transport agency to maintain bus lines functional during works such as costs to provide additional bus lines and drivers.

At the first level, the categorization of social cost indicators is strongly based on whether the cost is tangible or not. So far, literature review was not clear on this matter. We propose a simple method to determine the tangibility of a social cost (see Fig. 3.2). At a second level, both indicators can be separated into direct or indirect costs, and at a third level into fixed or variable costs; thus, resulting in a 3-level social cost hierarchy (see Fig.3.4). Firstly, let us discuss about how indicators can be tangible or intangible. Each indicator is defined in such a way that only one type of resource whether income, time or good is directly consumed because of works. Time resource can be divided in two: work and non-work such as personal, care and free time. Loss of work time is tangible and can be assessed based upon the salary wage whereas loss of personal or free time is more complex to assess and thus intangible. Fig.3.3 illustrates non-work time use by individuals which is an average of 16.5 h per day. Likewise, goods can be divided into several groups: environmental goods (air, surface water, and green), real properties, consumer goods (beverage, food, and vehicle), infrastructure amenities, human health and life. Some goods are marketed such as real property, food and vehicles, whereas others are not such as air quality, rivers and greens. Some are even considered to be priceless such as human life and health, even though they can be marketed to some extent in terms of health and life insurance. In nutshell, losses of income, work time and goods with market price, are tangible. Intangible costs can consist of both tangible and intangible cost objects.

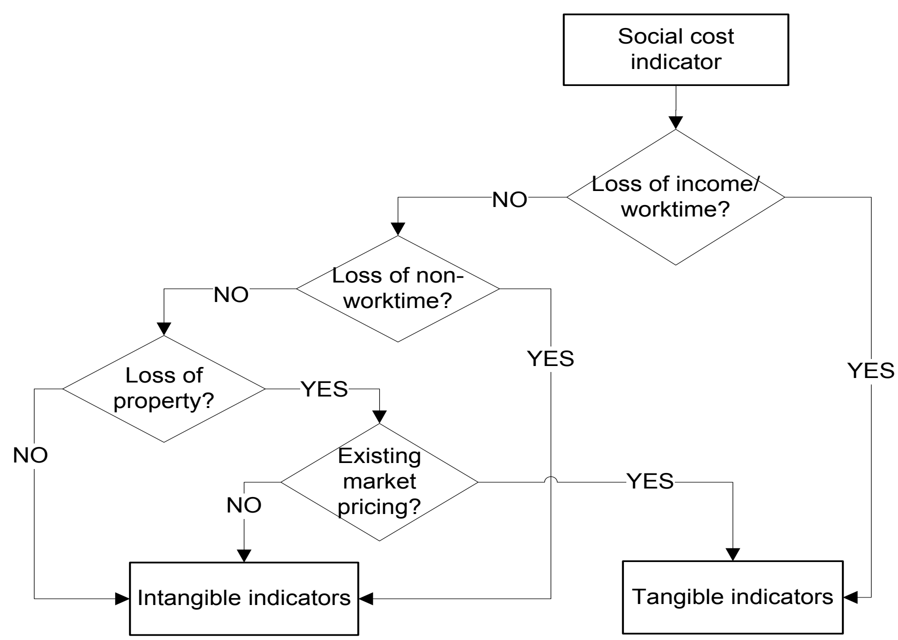

Figure 3.2: Scheme to determine the cost tangibility

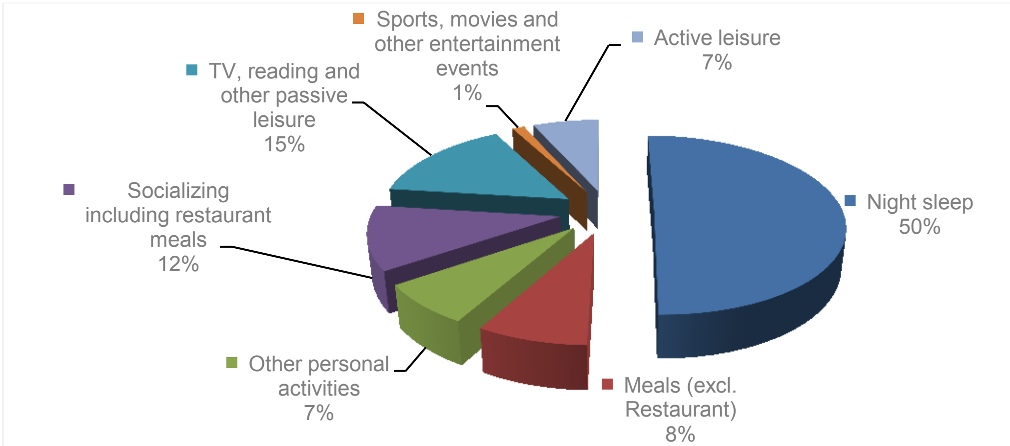

Figure 3.3: Average time use for non-worked hours (based on North American behaviour)

Secondly, indicators can be separated into direct and indirect costs. Direct costs are solely attributable to works and nothing else; thus, could never be made in the absence of works and are easily traceable such as TCM. Indirect costs are not solely attributable to works but also to other uncontrollable sources, for example VAD which can be triggered by various factors such as drivers' conditions, poor traffic control or signage, and pavement surface distresses. Indirect costs can consist of both direct and indirect cost objects. Thirdly, indicators can be separated into fixed and variable costs. Fixed costs are independent of the output which is chosen to be the number of days; thus, do not change with an increase or decrease in the duration of works such as ULR. On the contrary, variable costs such VED rise as the duration increases. Variable costs can consist of both fixed and variable cost objects. At a fourth level, indicators can be separated into certain or uncertain costs, where certainty refers to impacts that will unquestionably occur if works take place such as VED while uncertainty to impacts that might or not occur such as VAD.

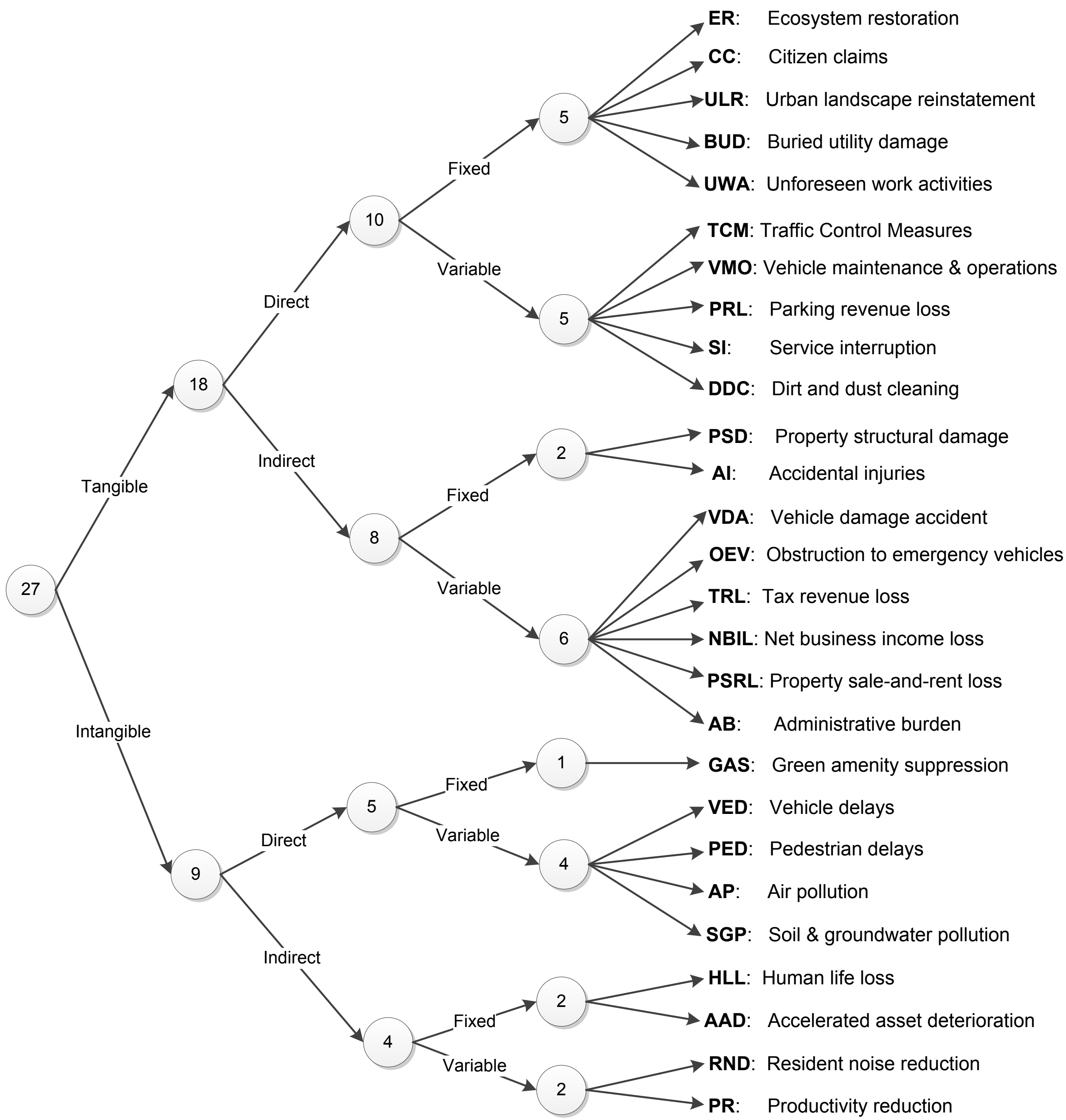

Figure 3.4: Social cost hierarchy

3.3. PREDICTION OF SOCIAL COST VARIABLES

This section deals with the prediction of social cost variables that constitute response variables for the regression functions that are explained in the next section. The development of models used for the prediction of social cost variables was achieved in five steps: (1) literature review on existing assessment techniques, (2) determination of social cost parameters and variables, (3) design of models, (4) data collection, and (5) model validation.

3.3.1. Literature review on existing assessment techniques

Existing assessment techniques are presented in section 2.3. Models were provided for some indicators and applied to case studies on a specific road segment. However, they were subject to some limitations, to name a few: time parameters such as the time of the day and the day of the week were not integrated even though social costs highly depend on them, contingent valuation methods such as Willingness-to-pay or Willingness-to-accept compensation were barely used, and no attention was given to municipal compensations or tax rebates (see Section 2.4). Therefore, these existing techniques were used as a foundation and upgraded to achieve a high level of confidence in social cost prediction.

3.3.2. Social cost parameters and variables

Ten key parameters were identified for social cost assessment (see Table 3.2) based on literature review. Some of these parameters such as the time of the day and the day of the week were not used in existing assessment techniques. This research proposes an approach to include these parameters in social cost prediction.

Table 3.2: Social cost input parameters

Parameters	Value domains
Time of the day	Night, morning, morning peak hours, midday, afternoon peak hours, evening
Day of the week	Week days, Saturday, Sunday
Season of work	Summer, winter, spring, fall
Type of work	35 scenarios[†]
Land use	Commercial, industrial, residential
Road classification	Local, arterial
Transportation mode	Bus, light truck, heavy truck, automobile
Traffic density	Annual average density traffic (AADT)
Duration of works	Number of days
Type of road closure	Partial, complete

[†] see Appendix M

- The *Time of the day* and the *Day of the week* should be taken into consideration in equation models if traffic pattern records reveal a variability of the vehicle density according to them and also if works are performed at night in order to mitigate social costs except for noise.
- The *Type of work* and the *Season of work* are related to some extent because open-cut works are usually performed in summer. For buried pipe renewals, two main types of works are considered: open-cut and trenchless techniques. For road segment, three types of works are retained: minor and major rehabilitation, and reconstruction. Furthermore, given that major events such as festivals, sidewalk / street sales can take place during summertime, a detailed study of work impacts on these activities should be addressed specifically.
- The *Land use* and the *Road classification* are important for customer traffic because commercial arteries with retailers and restaurants scattered along the road will

unquestionably suffer sales' losses during works. In fact, restaurant owners can be prevented from using their terraces because of noise and dust pollution. Road classification is important in case of complete road closure because vehicles especially trucks and buses circulating on arterial roads are detoured on other arterial roads to keep the same level of service and so it is for local roads.

- The *Transportation mode* and the *Traffic density* are associated by default using the modal shares of vehicle volume in circulation.
- The *Duration of works* and the *type of road closure* are also significant parameters because many indicators vary per them. The duration of works depends on the type of works. Two status of road neutralization is considered: partially or completely closed.

In the next section, social cost variables that are used for each equation are described whether probabilistic or deterministic. The probabilistic ones should be assigned with probability distributions. Given the large number of variables required, a lot of effort is needed to process, to save and to update information in databases. Table 3.3 illustrates the full list of social cost variables collected in this research.

Table 3.3: Social cost variables in alphabetical order

AC:	amount of claim
ACPK:	annual cost of service per kilometer
AHOR:	average household occupancy rate
AHW:	average hourly wage
AIHP:	annual increase in house price
AMR:	average monthly rent
ASC:	area of the surface to be cleaned
CR:	cost of repair
CM:	compensation measures
CLPG:	costs of lost products and goods
DI:	duration of interruption
ΔT:	additional travel time
ΔL:	additional travel distance
DN:	duration of noise
DOH:	daily operational hour
DPTIK:	daily parking ticket infractions per km
f:	miles-to-acre conversion factor
FC	fuel cost
FCB:	frequency of cleaning buildings per day
FVHOR:	fire vehicle hourly operating rate
HMR:	hourly meter rate
HWR:	hourly wage rate
IOE:	increased operating expenses
IPD:	insurance payouts for deaths
L:	road length
L_a:	length of the asset
LCC:	local cleaning cost per m^2
MR:	mortgage rate
NBA:	number of buildings affected
NDFNW:	number of week days following night works
NEA:	number of employee affected
NHA:	number of housing affected
NHW:	number of hours worked in a day
NLH:	number of lost hours in a day
NLPS:	number of lost parking space
NPO:	number of police officers
NRTR:	non-residential tax rate
NTP:	number of trips per day
NPV:	number of police vehicles
OC:	operating costs
OR:	occupancy rate
PAL:	% of average loss in residual value
PC:	preventing costs
PD:	project duration
PDCC:	property damage claim compensation
PFR:	pedestrian flow rate
PIMV:	% of increase due to market value
PNRU:	% of non-residential units
PVHOR:	police vehicle hourly operating rate
PRC:	parking relocation cost
PRF:	productivity reduction factor
PTR:	parking ticket rate
RF:	reduction factor
RTP:	transition period
RTR:	residential tax rate
SW:	sidewalk width
TNRH:	total number of rental housing
TTCC:	temporary traffic control cost
TUTV:	total unit taxable value
TVPM:	total value of properties in the market
VAC:	variable ambulance costs
VDFE:	victim discounted future earnings
VEC:	volumetric emission cost
VOR:	vehicle occupancy rate
VOT:	value of time
VPEK:	volume of pollutant emitted per km-driven
VTD:	vehicle traffic density
VRV:	vehicle residual value before accident
VR:	vacancy rate

3.3.3 Model Development

To build models that capture in the best possible way the adverse impacts of municipal works on population, economy, ecosystems, etc., they were designed in such a way that they often contain summations. Table 3.3 and Table 3.4 represent the models used respectively for tangible and intangible indicators, which are labelled as either "new" (if absent in literature) or "upgraded" (from literature and expert opinions). Not all indicators are assessed through models, some result directly from statistical analyses of costs collected: from project contract bids (such as UWA-Unforeseen work activities, URL-Urban reinstatement landscape and TCM-Traffic control measures), from municipal Litigation services (such as CC-Citizen claim and PSD-Property structural damage) and from Insurance companies (such as AI-Accidental injury); thus, they should be applicable solely to the municipality context.

One major upgrade in this research is the integration of social parameters such as time of the day, day of the week and land use for social cost prediction. Other parameters such as transportation mode, traffic density and work duration, were already studied in literature. Modeling steps to predict social costs is illustrated in Figure 3.5. The vector of social cost variables is $Y_i=(y_1, y_2, \ldots, y_n)$ where i represents one specific road and y_i is the estimate of social costs from implementing a specific project under specific road conditions (partial or complete closure).

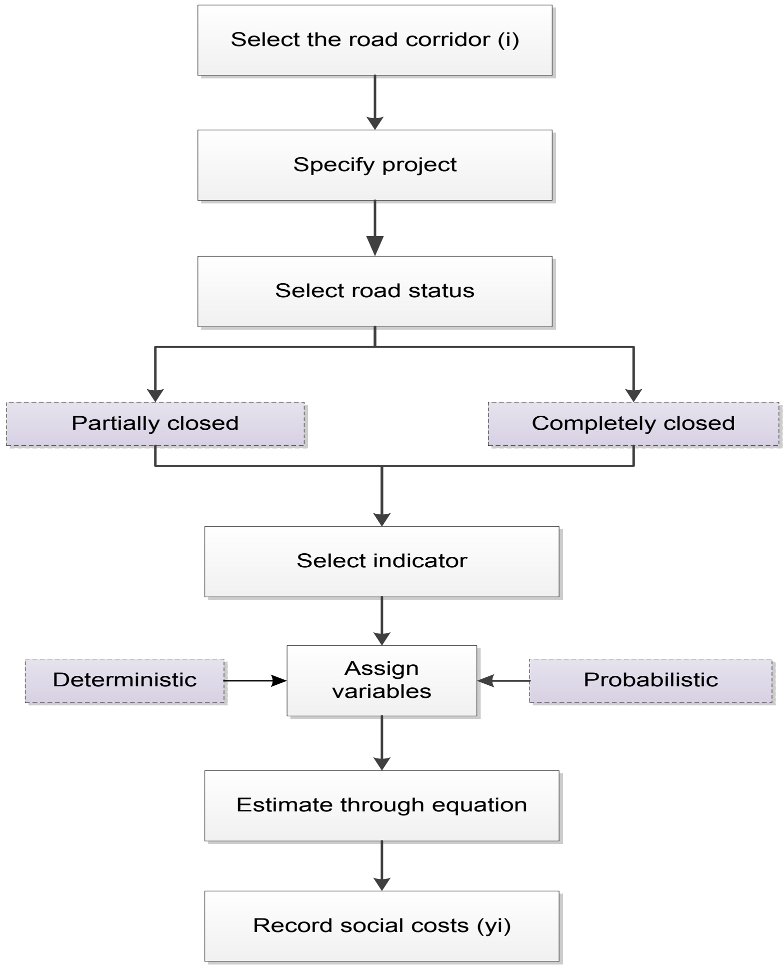

Figure 3.5 : Modeling steps for social cost prediction

In a nutshell, each social cost indicator generates its vector of social cost variables. Given that infrastructure projects mainly differ in their duration, the social cost vector Y_i can comprise N (number of roads) times the number of infrastructure projects. The social cost vector is used as a response variable to estimate the unknown parameters of the regression function associated to the social cost indicator.

Table 3.4: Models for tangible indicators

1-TCM: Traffic control measures	*NEW*
Probabilistic variables	HWR, PVHOR, PD
Deterministic variables	TTCC, NPV, NPO

$$\mathrm{TCM} = \mathrm{TTCC} + (\mathrm{NPV} \times \mathrm{PVHOR} + \mathrm{NPO} \times \mathrm{HWR}) \times \mathrm{NHW} \times \mathrm{PD} \quad [1.a]$$

TCM costs are new in terms of costs of police presence. They are divided in two items: TTCC normally included in the contract bid as a lump sum and costs of police presence which do not form part of the contract bid. In the City of Montreal, the police presence is obligatory on major work sites and mostly during rush hours. Based on the information gathered from interviews, retired police staff is hired at an HWR of 83.81 $/h and PVHOR amounts to 21.33 $/h. We solely consider police presence costs for open-cut activities on arterial roads, with an average of 1 police vehicle at each end of work zone and of 2 policemen per vehicle, for a total of 4 working hours.

2-VDA: Vehicle damage accident	*NEW*
Probabilistic variables	PAL, VRV
Deterministic variables	

$$\mathrm{VDA}_{accidented\ vehicle} = \mathrm{PAL} \times \mathrm{VRV} \quad [2.a]$$

For each vehicle involved in an accident, VDA costs are estimated solely in tangible terms of decreased automobile value, which represent the permanent loss in an automobile's market value due to its involvement in an accident and that which are not compensated by insurance policy. Damage of personal and commercial goods not covered by any kind of insurance policy are overshadowed. Given that not all work sites lead to car accidents and that accidents can be trigger by other factors such as the driver's behaviour, we do not assess this indicator in this research. An average claim amount can also be applied.

3-VMO: Vehicle maintenance and operations	*UPGRADED*
Probabilistic variables	PD, OC
Deterministic variables	ΔL, VTD

$$\mathrm{VMO}_{\text{partial closure, for vehicles going through the work zone}} = \sum_{i=1}^{3} \mathrm{PD_i} \times \left(\sum_{j=1}^{6} \Delta \mathrm{L_{ij\ equivalent}} \times \left(\sum_{k=1}^{4} \mathrm{OC_k} \times \mathrm{VTD_{ijk}} \right) \right) \quad [3.a]$$

$$\mathrm{VMO}_{\text{complete closure, for vehicles that are detoured}} = \sum_{i=1}^{3} \mathrm{PD_i} \times \left(\sum_{j=1}^{6} \left(\Delta \mathrm{L_{ij\ equivalent}} + \Delta \mathrm{L_{ij\ congestion}} \right) \times \left(\sum_{k=1}^{4} \mathrm{OC_k} \times \mathrm{VTD_{ijk}} \right) \right) [3.b]$$

$$\mathrm{VMO}_{\text{complete closure, for vehicles that are normally in circulation on alternate roads}} = \sum_{i=1}^{3} \mathrm{PD_i} \times \left(\sum_{j=1}^{6} \Delta \mathrm{L_{ij\ congestion}} \times \left(\sum_{k=1}^{4} \mathrm{OC_k} \times \mathrm{VTD_{ijk}} \right) \right) \quad [3.c]$$

VMO costs are upgraded with the incorporation of the time of the day in order to reflect among others the difference in fuel consumption during each period; where *i=the day of the week=(Weekday, Saturday, Sunday)*, *j=the time of the day=(Night, Morning, Morning peak hours, Midday, Afternoon peak hour, Evening)* and *k=the type of vehicle=(Automobile, Light truck, Heavy truck, Bus)*. The assessment of ΔL, the additional road length, is illustrated in Appendix G for all cases. In case of partial closure allowing vehicle to go through the work zone, the additional travel time due to works can be translated into an equivalent ΔL. The total vehicle traffic density (VTD) on alternate roads is expressed as twice the VTD that are detoured. In case of complete road closure, the detoured vehicles and the ones normally circulating in the detour road will experience additional VMO costs.

4-OEV: Obstruction to emergency vehicles	*UPGRADED*
Probabilistic variables	PD
Deterministic variables	ΔT, FVHOR, NTP
$\mathrm{OEV_{fire}} = \Delta T \times \mathrm{FVHOR} \times \mathrm{NTP} \times \mathrm{PD}$ [4.a]	
Probabilistic variables	PD
Deterministic variables	ΔT, PVHOR, NTP
$\mathrm{OEV_{police}} = \Delta T \times \mathrm{PVHOR} \times \mathrm{NTP} \times \mathrm{PD}$ [4.b]	
Probabilistic variables	PD, ΔL, NTP
Deterministic variables	VAC
$\mathrm{OEV_{ambulance}} = \Delta L \times \mathrm{VAC} \times \mathrm{NTP} \times \mathrm{PD}$ [4.c]	

Three types of emergency vehicles are considered: fire, police and ambulance. Costs of Obstruction to emergency (OEV) vehicles are upgraded with the addition of variable costs per km-driven for ambulances. Ambulance costs are in the charge of residents in Quebec and amount to a fix cost of 125$ plus a variable cost per km-driven (VAC) of 1.75$/km. Solely the impact of additional travel length (ΔL) will be considered. For the first two, costs of relocation incurred when works can hinder entrances and exits of vehicles, are neglected; whereas costs of additional specific control measures (e.g., construction of a temporary route) should be added. Moreover, interviews conducted in 2015 with both police and fire agents in the frame of this research reveal that construction works have not yet been critical for achieving the response delay in emergency cases. Therefore, solely the impacts on vehicle operating rate will be considered for fire and police vehicles considering additional time (ΔT).

5-PRL: Parking revenue loss	*UPGRADED*
Probabilistic variables	PRC, NLPS, PD, OR
Deterministic variables	HMR, DOH
$\mathrm{PMRL} = \mathrm{PRC} + \mathrm{NLPS} \times \mathrm{HMR} \times \mathrm{OR} \times \sum_{i=1}^{3} \mathrm{PD_i} \times \mathrm{DOH_i}$ [5.a]	
Probabilistic variables	PTR, PD, DPTIK
Deterministic variables	L
$\mathrm{PTRL} = \mathrm{L} \times \mathrm{DPTIK} \times \mathrm{PD} \times \mathrm{PTR}$ [5.b]	

Parking revenue loss (PRL) is upgraded with the incorporation of the day of the week (i) to consider different operational hours and is assessed as the sum of three cost items: Parking relocation cost (PRC), Parking meter revenue loss (PMRL) and Parking ticket revenue loss (PTRL). PRC are incurred whenever works hinder entrances and exits of private parking lots for residents or businesses. For instance, a Jean-Coutu drugstore owner in the City of Montreal engaged 3,000 $ to relocate parking places for its staff because of 2-month construction works on Saint-Mathieu St in 2014. PRC are project-specific and cannot be assessed in a systematic way. PMRL can be expressed as a function of the Daily operation hour (DOH). In the City of Montreal, DOHs varies according to the day of the week (i), where *i=(Weekday, Saturday, Sunday)*. PTRL is expressed as a function of the daily parking ticket infractions per km (DPTIK). In 2010: 1,241,694 infractions were issued in Montreal (SPVM, 2010). Therefore, given a total network length of 4,021 km, DPTIK is computed as follows:

$$\text{DPTIK}\,(2010) = \frac{1{,}241{,}694}{365 \text{ days} \times 4{,}021 \text{ km}} = 0.85$$

For PTRL assessment, L should be by default the length of the road under works. If possible, lengths of upstream and downstream roads neutralized for work mobilization should be added. Thus, L should be equivalent to the total length of road segments neutralized by the works. Note that a road closure can also increase parking infractions in the neighbourhood because of reduced number of available parking spaces; however, this effect is neglected in this research.

6-TRL: Tax revenue loss	*NEW*
Probabilistic variables	PD
Deterministic variables	TUTV, RTR, NRTR, PNRU

$$\text{TRL} = \sum_{\text{unit}=\text{u}} \text{TUTV}_{\text{u}} \times (\text{RTR}_{\text{u}} \times (1 - \text{PNRU}_{\text{u}}) + \text{NRTR}_{\text{u}} \times \text{PNRU}_{\text{u}}) \times \frac{\text{PD}}{365 \text{ days}} \qquad [6.a]$$

Property tax rebates for vacancies are offered by the City of Montreal to businesses that are closed during works even though in most cases, businesses remain open during works. In 2014, surveys conducted with business owners in the frame of this research, reveal that they are willing to accept the cancellation of their tax payments as compensations for work's sake. In a society point of view, TRL can be consider as a transfer cost because it is a loss for the municipality and a gain for business owners.

7-PSRL: Property sale-and-rent loss	*NEW*
Probabilistic variables	PD, PIMV
Deterministic variables	MR, AIHP, TVPM

$$\text{PSRL}_{\text{sale}} = \sum_{t=1}^{\text{int}\left(\frac{\text{PD}}{365 \text{ days}}\right)} \text{PIMV} \times \text{TVPM} \times \left(1 - \frac{(1+\text{AIHP})^{\text{t}}}{(1+\text{MR})^{\text{t}}}\right) \qquad [7.\text{a}]$$

Probabilistic variables	PD, TNRH, AMR
Deterministic variables	VR

$$\text{PSRL}_{\text{rent}} = \text{VR} \times \text{TNRH} \times \text{AMR} \times \frac{\text{PD}}{30 \text{ days}} \qquad [7.\text{b}]$$

Property sale-and-rent loss is new in terms of adverse impacts on renting or selling a unit. In fact, construction works can temporarily inhibit property sale and rent for residents and businesses. PSRL solely for sale is assessed as an opportunity cost which is the expected return forgone whenever the project duration (PD) exceeds one year. The average monthly rent (AMR) is about 840 $ in Montreal.

8-NBIL: Net business income loss	
Probabilistic variables	NBIL
Deterministic variables	

Ideally, business income loss (BIL) due to works consists of marginal loss of net operating income revenues from losing businesses that cannot be recovered afterward and that are not offset by marginal gain of net operating income revenues from winning businesses. BIL before and during works should be assessed per business's types. Some businesses can minimize BIL by reducing operating and production expenses. BIL for grocery stores and drugstores is assessed in the form of costs of lost products and goods (CLPG) and additional increased operating expenses (IOE) such as extra freight shipping costs. Moreover, possible compensation measures (CM) given by municipality in order to enhance business sales can be used to mitigate business losses; thus, the net business income loss (NBIL) should be assessed considering any other forms of compensation. In the City of Montreal, subsidies are provided to businesses that are closing during works to upgrade their property. In this research, we propose to use contingent valuation in the form of Willingness-to-accept compensation to estimate NBIL. Therefore, Business losses can be computed in terms of Tax revenue loss (TRL) or subsidies granted by the municipality.

9-AI: Accidental injury	
Probabilistic variables	
Deterministic variables	NLH, HWR

$$\mathrm{AI} = \sum_{\mathrm{Employee=e}} \mathrm{HWR_e} \times \mathrm{NLH_e} \qquad [9.\mathrm{a}]$$

NLH can be computed from two points of view. From the employee view, NLH is calculated from the date of accident to the date of return to work. From the employer's view, NHL is set from the date of accident to the date when another employee takes over the work. Injuries and diseases are indemnified in most cases by health care systems by spreading out costs of health services including staff time, medical supplies and treatment to all beneficiaries. In the same line, insurance covers among others costs of lost wages during convalescence. As such, only uncovered medical expenses or wage losses should be taken into consideration even though it is very difficult to quantify them. In addition, family members of injured individuals can also bear extra costs in terms of pain, suffering and activities forgone, which are neglected in this study. An average compensation amount can also be used to estimate AI. The municipality can also engage costs of compensation (avg≈7700$, max≈11000$ for Montreal).

10-SI: Service interruption	*UPGRADED*
Probabilistic variables	NEA, HWR, DI, RF
Deterministic variables	

$PL_{business} = \sum_{business\ (b)} DI \times NEA_b \times HWR_b \times RF_b \qquad [10.a]$	
Probabilistic variables	DI, NHA, AHOR, PC
Deterministic variables	
$PC_{household} = DI \times NHA \times AHOR \times PC \qquad [10.b]$	

SI costs are divided into three: Bypass installation cost (BIC), preventive costs (PC) for each household (h) and productivity loss (PL) for each business (b). BIC is included in the contract bid. PC and PL are engaged if service interruption is involved for any reason such reopening of laterals, etc. When water main renewals are performed, a bypass installation is provided for temporary service provision; but connections should be blocked and reopened twice at the beginning and the end of works, which lead to preventive costs for forewarned residents. Some facilities such as dental care, restaurants and hospitals are very critical because they are highly dependent on water service. Facilities equipped with cooling water systems or compressors are subject to risks of burns in case of unscheduled water interruptions. For instance, PC can be equal to the cost of 1 liter water bottle per individual in a household per 8 hours of interruption. However, PL is neglected in this study.

11-PSD: Property structural damage	
Probabilistic variables	PDCC
Deterministic variables	
$PSD = \sum_{Claim\ (c)} PDCC_c \qquad [11.a]$	

PSD claims can be obtained from municipality records (avg≈3800$, max≈25000$); leaving aside side-effects of vibrations that remain unclaimed. In fact, vibrations from works are rarely a direct cause of property damage but rather contribute to the process of deterioration from other causes (CNRC, 2000).

12-DDC: Dirt and dust cleaning	
Probabilistic variables	FCB, PD
Deterministic variables	LCC, ASC
$DDC = LCC \times PD \times \sum_{Building\ (b)} FCB_b \times ASC_b \qquad [12.a]$	

Buildings with large windows are subject to daily cleaning costs during works and are mostly non-residential edifices. Therefore, DD cleaning costs for non-residential buildings will be assessed assuming a daily cleaning frequency rather than normally once a week for residential buildings. ASC is set to be 2-meter long multiplied by the width of the frontage. In this study, we set LCC at a local rate of 1.5 $/m^2.

13-AB: Administrative burden	
Probabilistic variables	ACS, NLH
Deterministic variables	NEA, HWR
$AB = NEA \times HWR \times NLH + ACS$	

AB costs are related to time burnt in meetings, on the phone and elsewhere to resolve work-related incoming matters such as complaints and traffic issues. In the City of Montreal, these costs can be very high. We also added the additional costs of service (ACS) suffered by Public transport agency. However, AB costs for municipality can be neglected.

14-CC: Citizen claim	
Probabilistic variables	CC
Deterministic variables	

$$CC = \sum_{Claim=c} AC_c$$

Citizen claim amounts are those being settled out of court and borne by the municipality (avg≈3500$, max≈10000$). Parties affected by work/business deferrals can address complaints to the municipality through insurance companies.

15-URL: Urban reinstatement landscape	
Probabilistic variables	URL
Deterministic variables	

Urban landscape reinstatement (ULR) encompasses costs of pavement and landscape reinstatement, and provision for costs of adjacent utilities that are normally included in the contract bid.

16-UWA: Unforeseen work activities	
Probabilistic variables	UWA
Deterministic variables	

Unforeseen work activities (UWA) encompass unforeseen construction and overhead costs related to activities normally included in the contract bid. Because the nature of infrastructure works is not without risks, UWA costs are often incorporated in project contingency cost; thus, UWA costs are assessed as contingency costs plus potential additional UWA costs claimed by the contractor.

17-Ecosystem restoration	

Ecosystem restoration (ER) deals with money invested to bring green environment to nearly its original state, for example re-planting trees. ER is different from the indicator of green amenity suppression (GAS) dealing with the impossibility to restore the green environment.

18-BUD: Buried utility damage	

$$BUD = \sum_{Damage\ (d)} CR_d$$

Studies conducted by University of Toronto shows that inaccurate subsurface utility information can result into damages accounting for around 1.1% of project costs (Ormsby, 2009). Damage cost records can be obtained from municipal records.

Table 3.5: Models for intangible indicators

1-VED: Vehicle delays	*UPGRADED*
Probabilistic variables	PD, VTD
Deterministic variables	VOR, VOT, ΔT

$$\mathrm{VED}_{\text{partial closure, for vehicles going through the work zone}} = \sum_{i=1}^{3} \mathrm{PD_i} \times \left(\sum_{j=1}^{6} \Delta \mathrm{T_{ij}} \times \left(\sum_{k=1}^{4} \mathrm{VOR_k} \times \sum_{l=1}^{2} \left(\mathrm{VTD_{ijkl}} \times \mathrm{VOT_{ijkl}} \right) \right) \right) \quad [1.a']$$

$$\mathrm{VED}_{\text{complete closure, for vehicles that are detoured}} = \sum_{i=1}^{3} \mathrm{PD_i} \times \left(\sum_{j=1}^{6} \left(\Delta \mathrm{T_{ij}} + \Delta \mathrm{T_{ij\ congestion}} \right) \times \left(\sum_{k=1}^{4} \mathrm{VOR_k} \times \sum_{l=1}^{2} \left(\mathrm{VTD_{ijkl}} \times \mathrm{VOT_{ijkl}} \right) \right) \right) \quad [1.b']$$

$$\mathrm{VED}_{\text{complete closure, for vehicles that are normally in circulation on alternate roads}} = \sum_{i=1}^{3} \mathrm{PD_i} \times \left(\sum_{j=1}^{6} \Delta \mathrm{T_{ij\ congestion}} \times \left(\sum_{k=1}^{4} \mathrm{VOR_k} \times \sum_{l=1}^{2} \left(\mathrm{VTD_{ijkl}} \times \mathrm{VOT_{ijkl}} \right) \right) \right) \quad [1.c']$$

VED is discretized according to the day of week (*i= Weekday, Saturday, Sunday*), the time of day (*j= Night, Morning, Morning peak hours, Midday, Afternoon peak hour, Evening*), the type of vehicle (*k=automobile, bus, light truck, heavy truck*) and the type of trips (*l=business-trip, non-business trip*). Then VDT should also be collected accordingly either manually or through a radar traffic counter. We first experiment a VOT value (17.6 $/p-hr) based on the average HWR of the province of Quebec. This demonstrates very high social costs related to vehicle delays. Knowing that one cannot ascertain that each driver is willing to pay 17.6 $ to avoid one hour of delay, we propose to use on one hand a VOT based on HWR around 17 $ for business trips and on the other hand a VOT based on the price of a cup of coffee about 1.5$ for non-business trips. However, VOT is set at 0 $ for non-business trips during off-peak hours and during nighttime for all trips.

If the road is partially closed thus allowing vehicles to go through or to bypass the work zone area, travel times ΔT should ideally be collected 20 days after the beginning of works because a 20-day period is often necessary for driver's adjustments to the point where ΔT to go through the work zone area is the same as to bypass it (De Marcellis-Warin, et al., 2013). If a road is completely closed, the increment in length ΔL is computed as the difference between the normal and detour road length; so ΔT is evaluated as ΔL divided by the vehicle speed. Furthermore, traffic detours can lead to increased congestions on alternate roads if the road under work is completely closed. This effect should also be considered by estimating the difference between congestion time delays (ΔCTD) prior to work and during work for a selected alternate road. For example, if free-flow vehicle speed (VS_{ff}) =50 km/h, L=5 km, actual vehicle speed (VS_a) =40 km/h, then the congestion time delay (CTD = $L/VS_a - L/VS_{ff}$) is 1.5 min. If the difference ΔCTD is not significant then congestion impacts should be neglected; otherwise greater number of vehicles should be impacted. Even though it is complex to forecast drivers' choices, optimal alternative routes should be proposed in case of complete road closure using traffic modeling tools if possible.

2-PED: Pedestrian delays	*UPGRADED*
Probabilistic variables	PD, SW
Deterministic variables	ΔT, VOT, PFR

$$\mathrm{PED} = \mathrm{SW} \times \left(\sum_{i=1}^{3} \mathrm{PD_i} \times \left(\sum_{j=1}^{6} \Delta\mathrm{T_{ij}} \times \mathrm{VOT_{ij}} \times \mathrm{PFR_{ij}}\right)\right) \qquad [2.a']$$

PED is discretized according to the time of the day (i= *Weekday, Saturday, Sunday*) and the day of the week (j= *Night, Morning, Morning peak hours, Midday, Afternoon peak hour, Evening*). The pedestrion flow rate (PFR) are expressed in ppmm (pesdestrian per min per meter of sidewalk width). The assessment of ΔT for each period is achieved for two cases: complete closure of one sidewalk leaving the other open and partial closure of both sidewalks.

3-PR: Productivity reduction	*UPGRADED*
Probabilistic variables	
Deterministic variables	PRF, DN, NEA, HWR

$$\mathrm{PR} = \mathrm{HWR} \times \sum_{t=1}^{3} \mathrm{NEA_t} \times \sum_{h=1}^{DN} \mathrm{PRF_{ht}} \qquad [3.c']$$

PR related to noise depends on the renewal technique and the noise duration. It is discretized per the type of building (t=*institutional, commercial, industrial*). For each hour (h) of the noise duration (DN), the productivity reduction factor (PRF) corresponds to the dBA level produced by machinery per the type of building. PRF used in this study is illustrated in Figure 2.4.

4-RND: resident noise discomfort	*NEW*
Probabilistic variables	DNFNW
Deterministic variables	NHL, VOT, AHOR, NHA

$$\mathrm{RND} = \mathrm{NDFNW} \times \mathrm{NHL} \times \mathrm{NHA} \times \mathrm{AHOR} \times \mathrm{VOT}$$

Sleep disturbances resulting from noise exposure at night are related to personality traits and subjective noise sensitivity, and they are symptomized by tiredness after sleep (Jakovljevic, et al, 2006) leading to negative work outcomes in terms of decreased productivity, lost work time due to sleepiness and cognitive/mood-related misbehaviours (Swanson, et al., 2011). Therefore, RND is assessed in terms of decreased productivity on the day following night works.

5-HLL: Human life loss	
Probabilistic variables	
Deterministic variables	VDFE, IPD

$$\mathrm{HLL} = \sum_{victim=v} \text{Maximum of} \{\mathrm{VDFE_v}\ ;\ \mathrm{IPD_v}\}$$

For each victim, statistical analysis for IPD should be performed and presented as mean value. VDFE can be assessed based on the mean age of local population, the average annual wage and the time elapsed before retirement age.

6-AAD: Accelerated asset deterioration	*NEW*
Probabilistic variables	L, ACPK
Deterministic variables	RTP

$$\mathrm{AAD} = \sum_{\mathrm{Asset\ (a)}} \mathrm{RTP_a} \times \mathrm{ACPK_a} \times \mathrm{L_a}$$

Accelerated asset deterioration (AAD) related to reduced service life is assessed in terms of loss in pre-paid cost of service provision. RTP is based on condition grade reduction by one level.

7-AP: Air pollution	*UPGRADED*
Probabilistic variables	VEC, PD, FC
Deterministic variables	L, f

$$\mathrm{MGE} = \mathrm{VEC_{PM_{10}}} \times \left(0.42\frac{\mathrm{tons}}{\mathrm{acre}}/\mathrm{month}\right) \times \mathrm{L} \times \mathrm{f} \times \mathrm{PD} + \mathrm{VEC_{GHG}} \times (0.0101\ \mathrm{tons}\ /\mathrm{gallon}) \times \mathrm{FC}$$

Probabilistic variables	VEC, PD
Deterministic variables	ΔL, VTD, VPEK, L

$$\mathrm{VGE} = \sum_{i} \mathrm{PD_i} \times \sum_{j} \Delta \mathrm{L_{ij}} \times \sum_{k} \mathrm{VTD_{ijk}} \times \sum_{\mathrm{pollutant}=p} \mathrm{VEC_p} \times \mathrm{VPEK_{ijkp}}$$

$$\mathrm{VGE} = \mathrm{L} \times \sum_{i} \mathrm{PD_i} \times \sum_{\mathrm{pollutant}=p} \mathrm{VEC_p} \times \sum_{j}\sum_{k} \mathrm{VTD_{ijk}} \times \left(\mathrm{VPEK_{ijkp,\ normal}} - \mathrm{VPEK_{ijkp,\ work}}\right)$$

The valuation of volume of pollutant emitted for CO_2 and PM_{10} are performed respectively to convert fuel consumption of construction machinery into kg of CO_2 using 10.1 kg of CO_2 for each gallon of diesel fuel used (Rehan and Knight, 2007), and to estimate soil-related particles released into the air during construction activities (Qi, et al., 2013). VGE is discretized according to the day of week (*i= Weekday, Saturday, Sunday*), the time of day (*j= Night, Morning, Morning peak hours, Midday, Afternoon peak hour, Evening*), the type of vehicle (*k=automobile, bus, light truck, heavy truck*) and the type of pollutant (*p=GES, CO, HC,* NO_x, SO_x, $PM_{2.5}$, PM_{10}). Two ways of assessing VEG are provided. Results of both methods are similar.

8-SGP: Soil/groundwater pollution	

No assessment techniques for valuating SGP costs is proposed given the complexity of the matter; however, it should be assessed through Delphi method after the completion of works, which consists in an evaluation through a consensus of different expert's view.

9-GAS: Green amenity suppression	

Green amenity suppression (GAS) as opposed to ER deals with the permanent removal of green plants and recreational areas. No assessment techniques for valuating GAS cost is proposed; however, this should be assessed through contingent valuation in terms of how much residents are willing to accept for compensation to capture in the best way possible the value that people place on it.

3.3.4 Data collection

Figure 3.6 gives the information sources for each indicator. For further details, a complete description of data collection can be found in Chapter 4. Various individuals or parties were contacted by phone calls, emails or one-on-one interviews to collect information, which was given in different formats: Excel, Word and PDF files, ESRI shape files, hand notes and Access database. Then the information was processed to extract input variables for social cost prediction. A lot of effort in time was devoted in data collection and treatment as explained in Chapter 4.

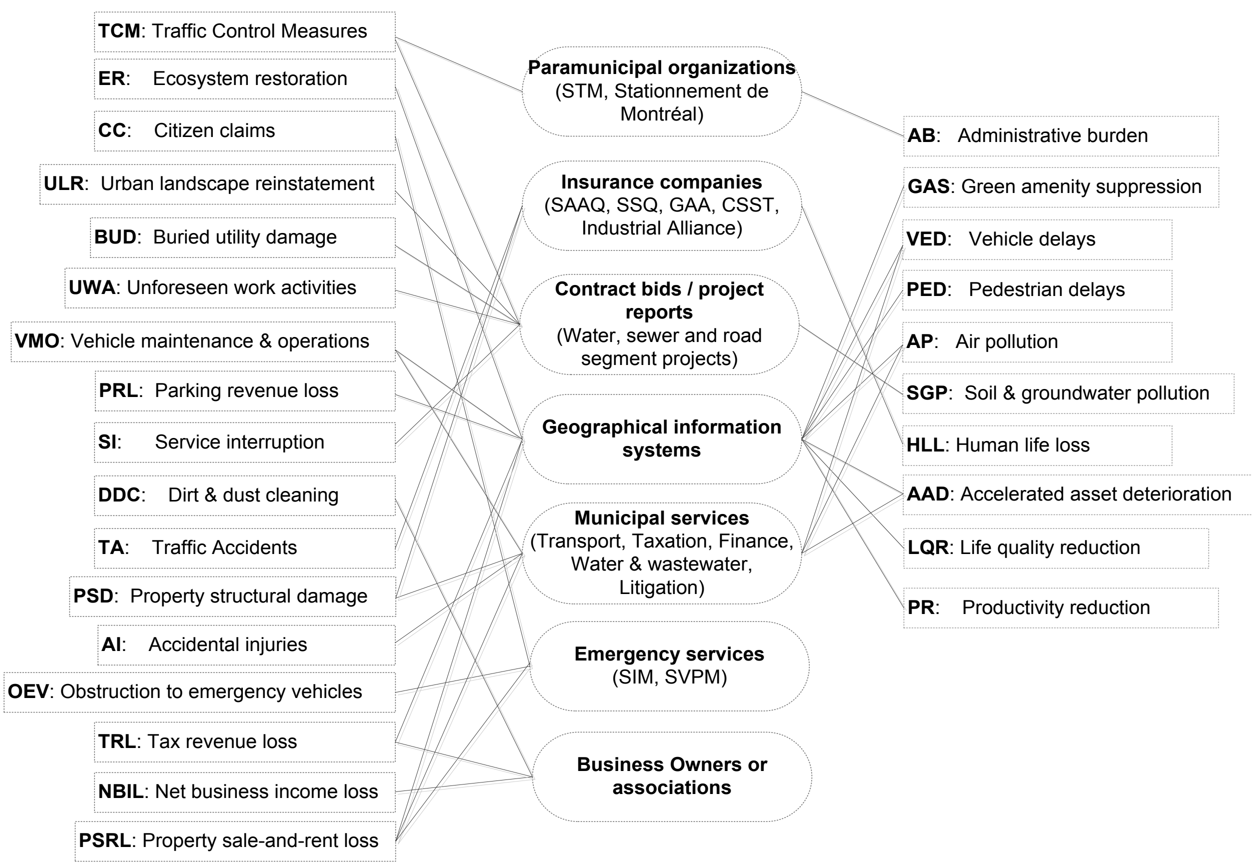

Figure 3.6 : Data sources for social cost indicators

3.3.5 Model validation

The valuation of social cost indicators may enclose different levels of abstraction, requiring different levels of validity to demonstrate that developed models are reasonable representation of work-related impacts. In this study, the validation of models was achieved by three means: expert opinions, real cost collection whenever possible and comparison of results from two different methods. The first consists in presenting the results to another person or a group of people. Even though they might not understand all computational details, they can raise potential issues related to results such as cost incoherence and questionable assumptions. The second consists in asking affected parties the estimation of their losses after the completion of works. This validation is the most reliable even though people tend to overestimate their losses, especially business owners. In practice, it was hard to validate real losses exclusively related to works because of other competing factors, to name a few: hidden causes of losses, deferrals of some impacts over a long run, and spread of damage among many protagonists; thus, making it too expensive to collect information. The third consists in assessing costs with two different parametric models using different experimental data from different sources, to compare results. If results remain in the same order of magnitude, we can assume that costs are valid; otherwise, models should be revised. The following ten indicators were validated: VED, PED, VMO, PRL, TRL, PSRL, PR, SI, DDC and AP. TRL were validated with the second method, by collecting property taxes of different buildings in Montreal. Our estimates were closed to the collected property taxes. AP costs were validated with the third method, and the results of the two different models were quite similar. The remaining indicators were validated with the first method, but with very little in-depth questioning from respondents.

3.4 NON-LINEAR REGRESSION MODELING

As shown in section 3.3.3, the implementation of the developed models is fastidious at macro level for an entire network. There was therefore a need to develop regression functions for social cost indicators to ease the prediction of social costs at macro level. A linear regression modeling was first experimented, but the results were not satisfactory even though the R^2, measuring the goodness-of-fit of linear regression, was acceptable. Estimated costs from linear regression were often negative because of a high negative value for the coefficient associated with a constant/intercept. Therefore, a shift to non-linear regression modeling was achieved in three steps: the enumeration of infrastructure projects, the development of regression functions and the estimation of unknown regression parameters.

3.4.1 Enumeration of infrastructure projects

Social cost prediction is associated to the type of projects as we all know that trenchless works on buried pipes don't have the same impacts than open-cut works. It is therefore important to enumerate the different kinds of infrastructure projects upon which social costs are predicted. The enumeration of infrastructure projects was achieved in two steps. The first was to determine all the possible combinations of treatments among water, sewer and road lines within the same road corridor. The second was to eliminate combinations that are neither feasible in practice nor realistic. For that purpose, phone interviews or face-to-face discussions were carried out with asset managers; thus, reducing the number of combinations of treatments from thirty-five to eighteen. Finally, solely eighteen types of infrastructure projects are retained for this research (see Table 3.6).

Two types of treatments for water and sewer lines are considered: open-cut reconstruction (OCR) and Cured-In-Place-Pipe lining (CIPP). For road lines, three types of treatments are retained: open-cut reconstruction (OCR), major rehabilitation techniques such as pulverization (OCP) and minor rehabilitation techniques such as surfacing treatment (TST). Therefore, a list of thirty-five potential projects on a corridor was originally enumerated. Then, the preceding list of thirty-five projects was submitted to managers. Given the context of Montreal where nearly 80 % of sewer and water segments are buried in the same trench under road segments (see Figure 3.7), municipal planners in order to reduce risks recommend that sewer pipe OCR induces both water pipe and road OCR and likewise water pipe OCR induces road OCR; thus, leaving only eighteen potential projects that are feasible in practice. Table 3.6 illustrates the eighteen projects plus one extra renewal decision which corresponds to a status quo that is no intervention on the three types of assets. In Table 3.6, the number 5 means that a minor rehabilitation for the roadway and CIPP works for both water and sewer pipes are bundled in one infrastructure project. Likewise, the number 19 means a status quo.

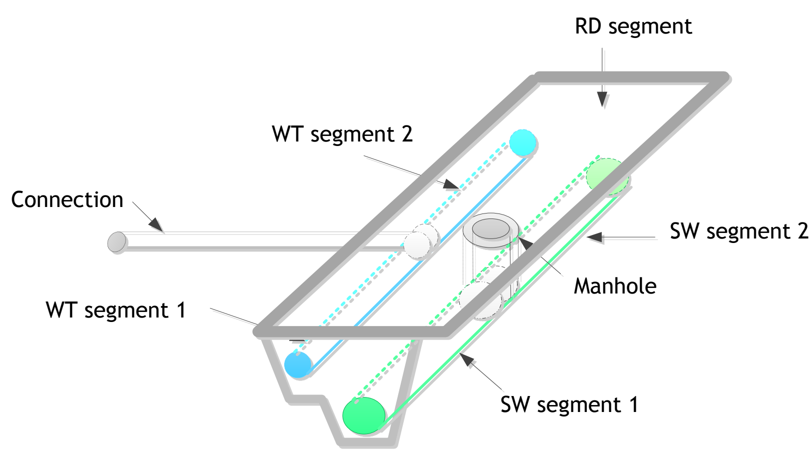

Figure 3.7 : Example of a typical trench

Table 3.6 : Identification number for work packages on a road corridor

	Sewer (SW_)	∅	∅	∅	CIPP	CIPP	CIPP	OCR	OCR	OCR
	Water (WT_)	∅	CIPP	OCR	∅	CIPP	OCR	∅	CIPP	OCR
Road (RD_)	∅	19	15		10	6				
	TST	18	14		9	5				
	OCP	17	13		8	4				
	OCR	16	12	11	7	3	2			1

Once the enumeration of infrastructure projects was achieved, the next step was to assess the project duration because social costs are associated that. A methodology of estimating the project duration was developed by the City of Montreal and was adapted in this research to assess the duration of the eighteen types of projects. Table 3.7 illustrates results of standard duration of projects for a sample of more than a thousand roads in the City of Montreal. For illustration purposes in Table 3.7, the predicted work durations are expressed in terms of the mean and the maximum value of the sample. We notice that water main CIPP lasts longer than sewer CIPP. Also, when the three types of assets are involved, the duration of project is substantially the same regardless the type of works whether trenchless or open-cut.

Table 3.7 : Duration of work - (mean; max) days

	Sewer	∅	∅	∅	CIPP	CIPP	CIPP	OCR	OCR	OCR
	Water	∅	CIPP	OCR	∅	CIPP	OCR	∅	CIPP	OCR
Road	∅		(21;135)		(8;26)	(30;150)				
	TST	(8;20)	(30;150)		(17;46)	(40;170)				
	OCP	(10;38)	(30;160)		(20;60)	(40;180)				
	OCR	(10;38)	(30;160)	(30;160)	(20;60)	(40;180)	(40;180)			(40;180)

3.4.2 Development of regression functions

Linear regression models were first tried in this study and they fail to match social costs because some coefficients or the constant (intercept) was often negative. A negative coefficient means for every unit increase in the variable, a unit decrease in cost is expected; this was counter-intuitive because the increase in all variables (such as Project duration and Vehicle traffic density) should lead to the increase of social costs. A negative constant was also a concern because it can lead to negative costs. Then non-linear regression models were chosen. For all indicators, the Project duration follows an exponential law, the Length of the road follows a power law and the Vehicle traffic density follows a linear law. Then, the regression functions were developed upon these observations solely for ten indicators: VED-Vehicle delays, PED-Pedestrian delays, VMO-Vehicle maintenance and operations, PRL-Parking revenue loss, TRL-Tax revenue loss, PSRL-Property sale-and-rent loss, PR-Productivity reduction, SI-Service Interruption, DDC-Dirt and dust cleaning, and AP-Air pollution. The remaining indicators did not bear a significant weight in the social costs and consequently no regression functions were developed for their assessment. Table 3.8 illustrates the modeled regression functions. The least-square method was applied to estimate the unknown parameters of the regression functions as explained in section 2.3.3. Given the hardship in data collection and processing, the regression functions allow assessing social costs at a large scale with a few key variables; thus reducing the amount of data needed to assess social costs. For example, the first prediction of VED costs was based on the following data: PD_i, ΔT_{ij}, VOR_k, VTD_{ijkl}, and VOT_{ijkl}, which were collected per the day of the week (i), the time of day (j), the type of vehicle (k) and the type of trips (l). The estimation of ΔT_{ij} required additional variables such as the vehicle speed and the road length. In a nutshell, it takes time! Now, VED costs can easily be assessed by a regression function using three key variables: VTD, L and PD, considering that the other variables and assumptions remain unchanged.

Table 3.8 : Regression functions

Indicator	Equation models
VED	$\left(\left(a.\mathrm{VTD}_{auto} + b.\mathrm{VTD}_{light\ truck} + c.\mathrm{VTD}_{heavy\ truck} + d.\mathrm{VTD}_{bus}\right).e^{e.\mathrm{Road\ length}}\right).\mathrm{Project\ duration}^{f}$
PED	$a.\mathrm{Number\ of\ pedestrians\ per\ day}.e^{b.\mathrm{Sidewalk\ width}}.\mathrm{Project\ duration}^{c}$
VMO	$\left(\left(a.\mathrm{VTD}_{auto} + b.\mathrm{VTD}_{light\ truck} + c.\mathrm{VTD}_{heavy\ truck} + d.\mathrm{VTD}_{bus}\right).e^{e.\mathrm{Road\ length}}\right).\mathrm{Project\ duration}^{f}$
PRL	$a.\mathrm{Number\ of\ on\ street\ paid\ parking\ spaces}.\mathrm{Project\ duration}^{b}$
TRL	$\left(\left(\sum_{residential}\mathrm{Property\ value}\right)^{a} + \sum_{i=1}^{12}\left(\sum_{\mathrm{Class}\ b_i}\mathrm{Property\ value}\right)^{b_i}\right).\mathrm{Project\ duration}^{c}$
PSRL	$a.\mathrm{Number\ of\ apartments\ for\ rent}.\mathrm{Project\ duration}^{b}$
PR	$a.\mathrm{Number\ of\ employees}.\mathrm{Noise\ duration}^{b}$
SI	$a.\mathrm{Number\ of\ households}.\mathrm{Duration\ of\ interruption}^{b}$
DDC	$(a.\mathrm{Number\ of\ commercial\ buildings} + b.\mathrm{Number\ of\ non\ commercial\ buildings}).e^{c.\sum_{building}\mathrm{Facade\ width}}.\mathrm{Project\ duration}^{d}$
$AP_{vehicle}$	$\left(\left(a.\mathrm{VTD}_{auto} + b.\mathrm{VTD}_{light\ truck} + c.\mathrm{VTD}_{heavy\ truck} + d.\mathrm{VTD}_{bus}\right).e^{e.\mathrm{Road\ length}}\right).\mathrm{Project\ duration}^{f}$
$AP_{machinery}$	$(a.\mathrm{WT\ CIPP} + b.\mathrm{WT\ Open\ cut} + c.\mathrm{SW\ CIPP} + d.\mathrm{SW\ Open\ cut} + e.\mathrm{RD\ Minor\ rehab} + f.\mathrm{RD\ Major\ rehab} + g.\mathrm{RD\ Open\ cut}).\mathrm{Road\ Length}$

3.5 OPTIMIZING COORDINATION STRATEGIES USING SOCIAL COSTS

Infrastructure planners in the City of Montreal are attempting to coordinate interventions among different types of assets solely when open-cut works are involved. Considering that roads and buried pipes are managed with different departments, municipal planners are pondering how they should engage open-cut works within a road corridor from one intersection to another: should road reconstruction await pipe replacement? Or should pipe replacement await road reconstruction? These first two renewal scenarios were studied: 1) Performing road open-cut techniques only when pipes are scheduled for replacement, and 2) Performing pipe replacement only when road is scheduled for open-cut works. Figure 3.8 and 3.9 illustrate the coordination decision tree respectively for scenario 1 and 2. If the road reconstruction is due while pipes are not, the road can be resurfaced meantime in scenario 1, while pipes can be repaired meantime in scenario 2. A third scenario that is a combination of the first two was built as illustrated in Figure 3.10.

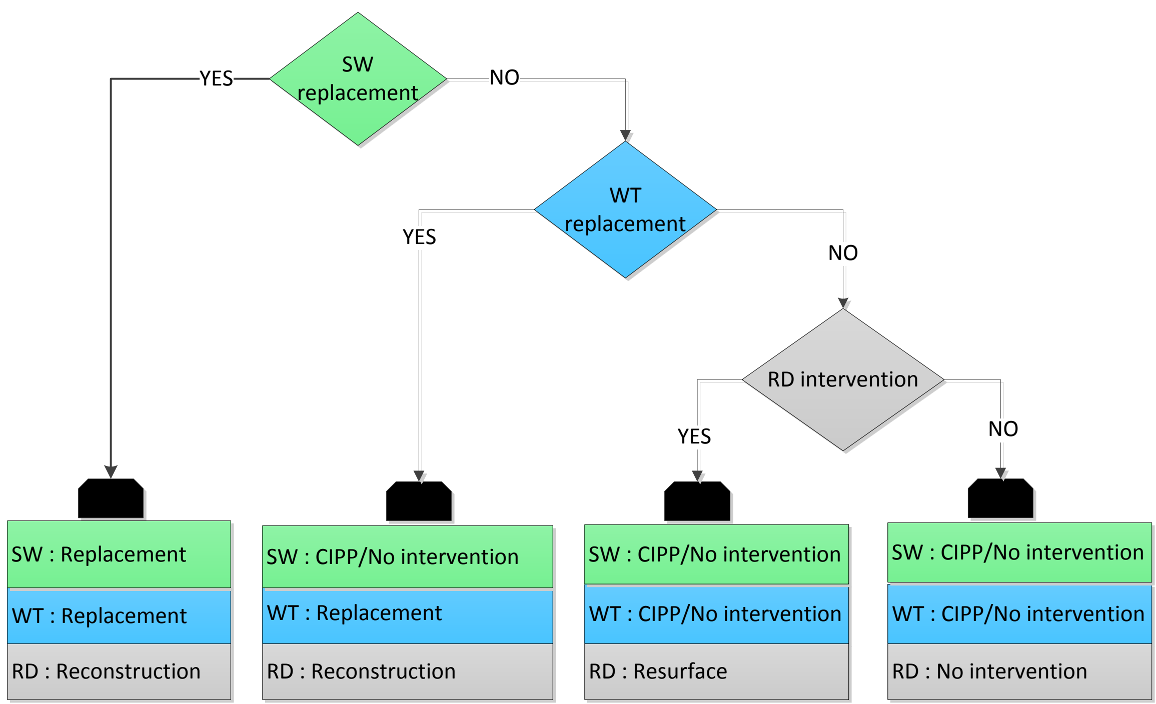

Figure 3.8 : Scenario 1 - Road reconstruction if water or sewer pipe is replaced

Social costs are assessed for all types of work packages in both scenarios. Social cost items already included in the contract bid such as service interruption (SI) in terms of bypass installation, and traffic control measures (TCM) are excluded, except for costs for police surveillance. By default, all remaining social cost indicators are considered for open-cut works, and some of them are not retained for CIPP or road rehabilitation such as buried utility damage (BUD). However, the full amount of social costs to different types of works was added for: CIPP, open-cut reconstruction, minor and major road rehabilitation. The amount of social costs differs with the road jurisdiction whether local or arterial.

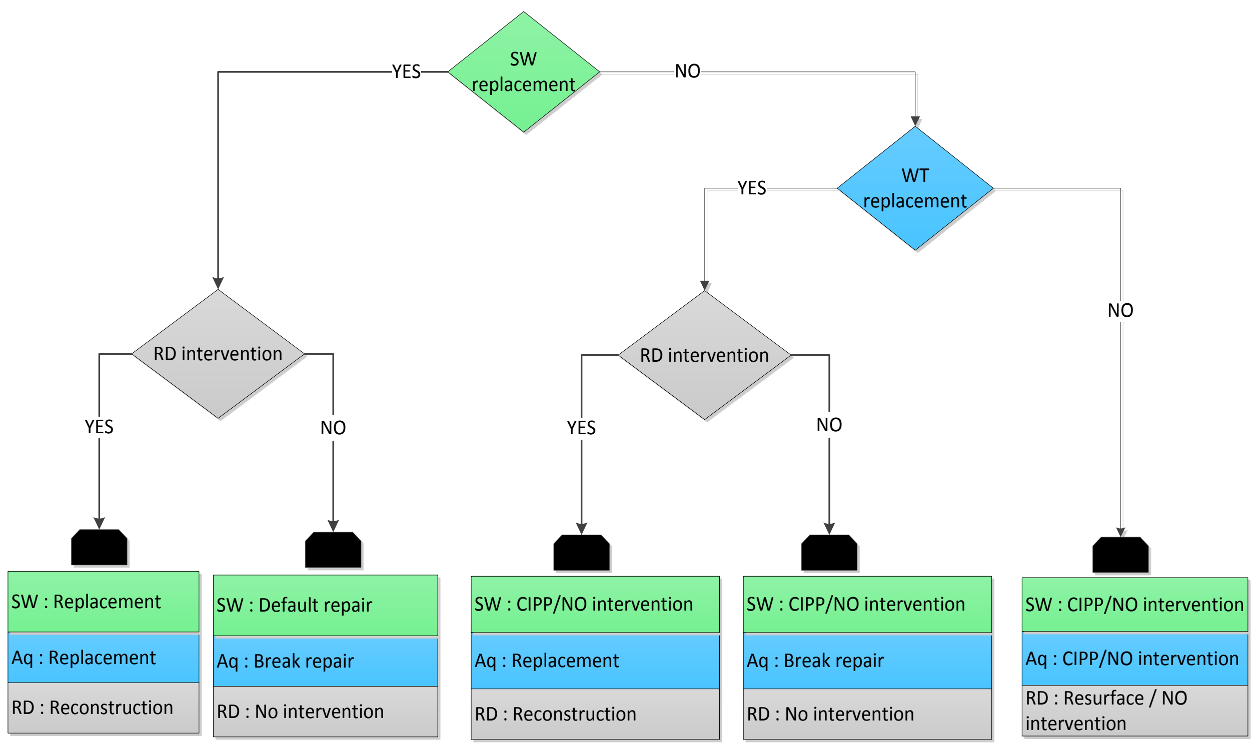

Figure 3.9 : Scenario 2 – Water or sewer pipe replacement if road is reconstructed

Scenario 3 is like scenario 1 (i.e., performing road open-cut techniques only when pipes are scheduled for replacement), except that when sewer is scheduled for replacement, in case of no intervention on water, we wait for road open cut works to replace the sewer. We will run the three scenarios in InfraModex and analyze results based on social costs, total costs (social costs plus construction costs) and the levels of service. The optimization will be to select the least cost strategy of coordination in terms of total costs.

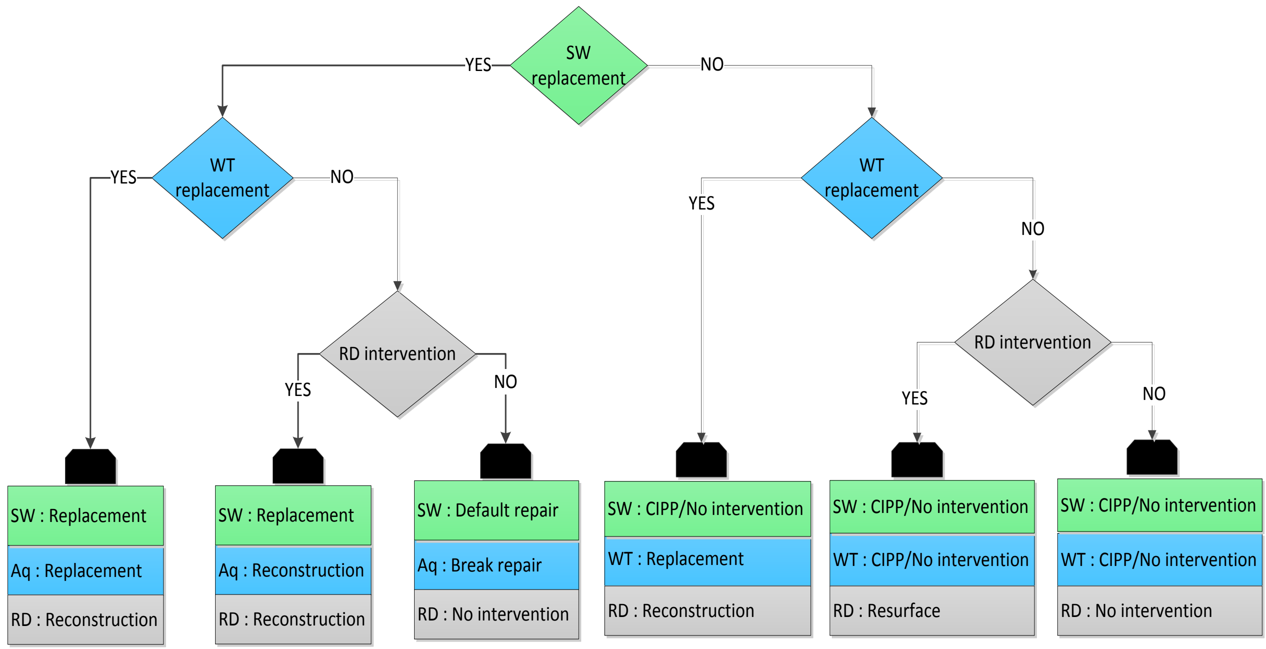

Figure 3.10 : Scenario 3 – Mixed strategies

The three proposed scenarios are implemented in a Monte-Carlo-based decision support system, InfraModex. The simulation runs over a horizon of 150 years. There is no constraint on budget allocation. The Levels of service (LOS) are set to a specific target for the three types of assets: water, sewer and road lines. In a first step, a silo approach is performed for each network: the LOS are examined each year for all assets of the network and whenever the threshold is reached for an asset, an appropriate treatment is proposed; resulting in three individual programs of works for each network: water, sewer and road. In the second step, a coordinated approach is performed for all types of assets per road corridor: individual treatments for each type of assets are examined every year through the coordination decision tree so individual treatments can be either maintained, changed or delayed for coordination' sake; resulting in a coordinated program of work per road corridor (see Figure 2.8).

CHAPTER 4: DATA COLLECTION

4.1. INTRODUCTION

This chapter deals with data used for social cost prediction. The collection of data was fastidious given the large volume of information processed to feed assessment models. In the following sections, the data source, treatment and storage are explained. Problems that were experience in data collection and analysis are summarized as well.

4.2. DATA SOURCES

The assessment of social cost indicators related to municipal works is data-intensive. A large amount of data was extracted from the **SIGS**, which is the Geographical Information System of the City of Montreal (see Figure 4.1), and from the City website. In fact, most departments or services of the City publish their statistics on a website, which is called “Montréal en Statistiques” (**M-Stat**). For further information that was not available through **SIGS** or **M-Stat**, the following departments or services were contacted:

- **SVPM** : Service de Police de la Ville de Montréal (*Montreal Police Service*)
- **SIVT** : Service des Infrastructures, de la Voirie et des Transports de la Ville de Montréal (*Montreal Transport Infrastructure Service*)
- **PM** : Arrondissement du Plateau Mont-Royal (*Plateau Mont-Royal borough*)
- **SIM** : Service de sécurité Incendie de la Ville de Montréal (*Montreal Fire Department*)
- **SÉFVM** : Service d’évaluation foncière de la Ville de Montréal (*Montreal Property Valuation Department*)
- **BRVM** : Bureau des réclamations de la Ville de Montréal (*Montreal Complaints Office*)
- **SEVM** : Service de l’eau de la Ville de Montréal (*Montreal Water Department*)

The rest of data was collected from the following enterprises, agencies and associations:

- **STM**: Société de transport de Montréal (*Montreal Public Transport Agency*)
- **SM**: Stationnement de Montreal (*Montreal Parking Agency*)
- **SA**: Sociétés d'assurances (*Insurance companies*), namely SAAQ, SSQ, GAA, CSST and Industrial Alliance
- **SCHL** : Société canadienne d'hypothèques et de logement (*Canada Mortgage and Housing Corporation*)
- **USQ** : Urgence-Santé Québec (*Health Emergency Quebec*)
- **CREA**: Canadian Real Estate Association

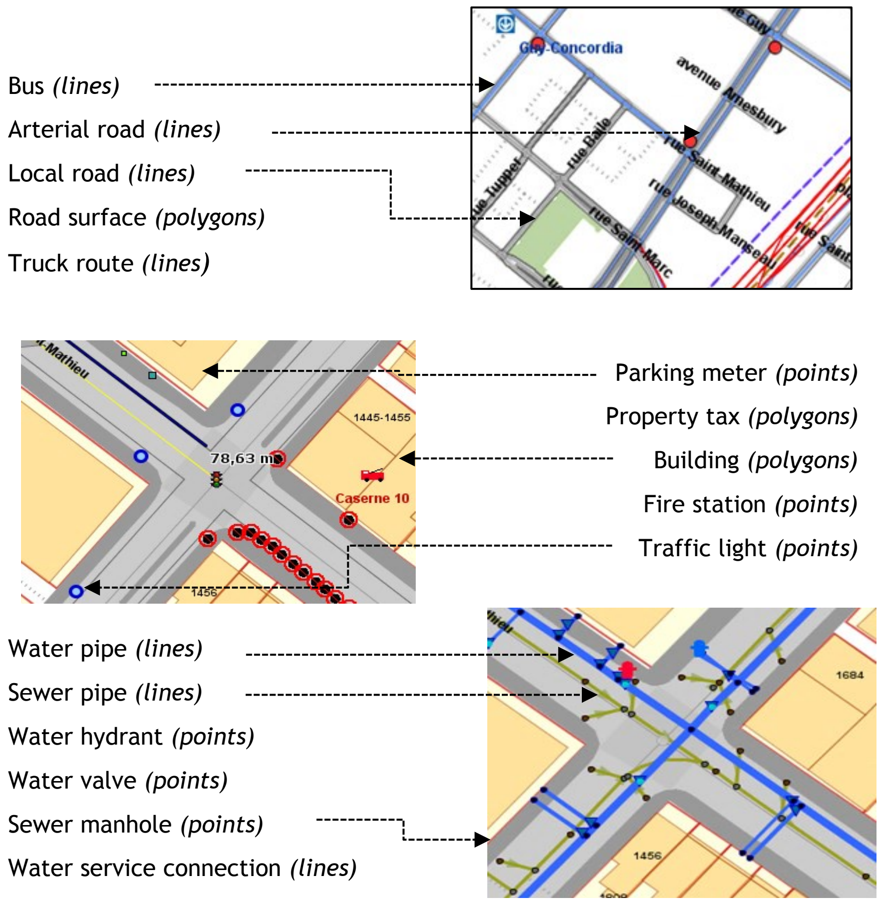

Figure 4.1 : Example of data collected from Montreal GIS

4.2.1. Data spatial requests

The GIS database system of the City of Montreal is composed of several GIS data layers related to municipal infrastructure assets such as roads and bridges, potable water, storm and wastewater assets, buildings, parks, etc. Unfortunately, these database tables have no field in common. Given that social cost indicators are assessed for each road corridor, spatial data from different GIS layers had to be integrated to the road corridor layer using ArcGIS spatial analysis tools. The reason is that up to the date of this study, nearly all GIS layers do not contain the road identification number as an attribute. Therefore, for example, attributes from the building layer such as number of apartments or from the parking meter layer such as number of parking spaces, should be affixed to the road layer. These spatial requests were time-consuming, so we suggest that the road identification number should be included in each database or layer for the future.

4.2.2. Data dictionary

Given the large amount of data collected, a data dictionary (in alphabetical order) is proposed to recall all data used in the social cost models. For each type of data, the dictionary provides the following information: glossary for abbreviations, unit, possible range of values and sources. It should be noted that the estimation of one data in Table 4.1 might require other extra data that are not illustrated in this table. For example, the additional travel time ΔT is a result of an in-house valuation using data such as the vehicle speeds before and during works. The mention "**In-house**" in Table 4.1 refers to data resulting from our in-house valuation.

Table 4.1 : Data dictionary for social cost indicators

Data	Description	Unit	Format	Value	Sources
AC	Amount of claims from residents	$	Numeric	≥ 0	**BRVM**
ACPK	Annual cost of water service per km	$/km	Numeric	≥ 0	**In-house**
AHOR	Average household occupancy rate	per/app	Float	≥ 0	**M-Stat**
AHW	Average hourly wage	$/h	Numeric	≥ 0	**In-house**
AIHP	Annual increase in house price	%	Float	[0-100 %]	**CREA**
AMR	Average monthly rent	$	Numeric	≥ 0	**M-Stat**
ASC	Area of the surface to be cleaned	m^2	Numeric	≥ 0	**In-house**
CR	Cost of repair	$	Numeric	≥ 0	**SEVM/SIVT**
CM	Compensation measures	$	Numeric	≥ 0	**-**
CLPG	Costs of lost products and goods	$	Numeric	≥ 0	**-**
DI	Duration of interruption	hr	Integer	≥ 0	**In-house**
DN	Duration of noise	hr	Float	≥ 0	**In-house**
ΔT	Additional travel time	hr	Float	≥ 0	**In-house**
ΔL	Additional travel distance	km	Float	≥ 0	**In-house**
DOH	Daily operational hour	hr/day	Integer	≥ 0	**SM**
DPTIK	Daily parking ticket infractions per km	$/day-km	Numeric	≥ 0	**VM**
f	Miles-to-acre conversion factor		Float	7.9	**Qi, et al. 2013**
FC	Fuel cost	$	Numeric	≥ 0	**CAA 2014**
FCB	Frequency of cleaning building per day	/day	Integer	≥ 0	**In-house**
FVHOR	Fire vehicle hourly operating rate	$/hr	Numeric	≥ 0	**SIM**
HMR	Hourly meter rate	$/hr	Numeric	≥ 0	**SSM**
HWR	Hourly wage rate	$/hr-per	Numeric	≥ 0	**In-house**
IOE	Increased operating expenses	$	Numeric	≥ 0	**-**
IPD	Insurance payouts for deaths	$	Numeric	≥ 0	**-**
L	Length of road	m	Float	≥ 0	**SIGS**
L_a	Length of the pipe asset	m	Float	≥ 0	**SIGS**
LCC	Local cleaning cost per meter square	$\$/m^2$	Float	≥ 0	**Local rate**
MR	Mortgage rate	%	Float	[0-100 %]	**SCHL**
NDFNW	Number of business days following a noisy night	day	Integer	≥ 0	**In-house**
NEA	Number of employee affected	per	Integer	≥ 0	**SIGS**
NHA	Number of housing affected	house	Integer	≥ 0	**SIGS**
NLH	Number of lost hours in a day	hr/day	Integer	≥ 0	**-**
NLPS	Number of lost parking space	space	Integer	≥ 0	**SIGS**
NPO	Number of police officers	per	Integer	≥ 0	**SVPM**

NTP	Number of trips per day	trip	Integer	≥ 0	**In-house**
NPV	Number of police vehicles	veh	Integer	≥ 0	**SVPM**
NRTR	Non-residential tax rate	%	Float	[0-100%]	**SÉFVM**
OC	Operating costs for vehicles	$/km	Numeric	≥ 0	**CAA 2014**
OR	Occupancy rate	%	Float	[0-100%]	**-**
PAL	Percent of average loss in vehicle value	%	Float	[0-100%]	**-**
PC	Preventing costs	$/hr	Numeric	≥ 0	**In-house**
PD	Project duration	days	Integer	≥ 0	**In-house/SIVT**
PDCC	Property damage claim compensation	$	Numeric	≥ 0	**BRVM**
PFR	Pedestrian flow rate			≥ 0	**HCM 2000**
PIMV	Percent increase due to market value	%	Float	[0-100 %]	**-**
PNRU	Percent of non-residential units	%	Float	[0-100 %]	**SÉFVM**
PVHOR	Police vehicle hourly operating rate	$/hr	Numeric	≥ 0	**SVPM**
PRC	Parking relocation costs	$	Numeric	≥ 0	**-**
PRF	Productivity reduction factor	%	Float	[0-100 %]	**De Marcellis 2013**
PTR	Parking ticket rate	$/hr-infraction	Numeric	≥ 0	**SSM**
RF	Reduction factor	%	Float	[0-100 %]	**-**
RTP	Transition period			≥ 0	**In-house**
RTR	Residential tax rate	$/100$	Numeric	≥ 0	**SÉFVM**
SW	Sidewalk width	m	Float	≥ 0	**-**
TNRH	Total number of rental housing	app	Integer	≥ 0	**SÉFVM/GIS**
TTCC	Temporary traffic control cost	$	Numeric	≥ 0	**-**
TUTV	Total unit taxable value	$	Numeric	≥ 0	**SÉPVM**
TVPM	Total value of properties in the market			≥ 0	**-**
VAC	Variable ambulance costs	$	Numeric	1.75$/km	**USQ**
VDFE	Victim discounted future earnings	$	Numeric	≥ 0	**-**
VEC	Volumetric emission cost	$	Numeric	≥ 0	**MTQ 2013**
VOR	Vehicle occupancy rate	per/veh	Float	≥ 0	**-**
VOT	Value of lost time	$/hr-per	Numeric	≥ 0	**In-house**
VPEK	Tons of pollutant emitted per km-driven	tons/km		≥ 0	**MTQ 2013**
VTD	Vehicle traffic density	veh/day	Integer	≥ 0	**SIVT**
VRV	Vehicle residual value before accident	$	Numeric	≥ 0	**-**
VR	Vacancy rate	%	Float	≥ 0	**-**

4.2.3. Data model

The data model should be built as illustrated in Table 4.2. It provides a view of all attributes per indicator for each type of works. For example, the prediction of TCM costs requires filling seven attribute fields. The road identification number ID_TRC is the common and primary key for all tables except for PR, AAD_ASSET and DDC, which have two primary keys.

Table 4.2 : Data model

TCM
ID_TRC
HWR
NPO
NPV
PD
PVHOR
TTCC

VMO
ID_TRC
OC
ΔL
VDT
PD

RND
ID_TRC
DNFNW
NLH
NHA
VOT
AHOR

CC
ID_TRC
AC

VDA
ID_TRC
PAL
VRV

TRL
ID_TRC
PD
TUTV
RTR
NRTR
PNRU

HLL
VDFE
IPD

AP
ID_TRC
VEC
PD
VTD
L
f
ΔL

OEV_F
ID_TRC
PD
ΔT
FVHOR
NTP

PMRL
ID_TRC
PD
HMR
DOH
PRC
NLPS
OR

AB
ID_TRC
NEA
NLH
HWR
ACS

BUD
ID_TRC
CR

OEV_P
ID_TRC
PD
ΔT
PVHOR
NTP

PTRL
ID_TRC
PD
DPTIK
PTR
L

AI
IDTRC
HWR
NHL

AAD_A
ID_TRC
ID_ASSET
ACPK
L
RTP

OEV_A
ID_TRC
PD
ΔL
VAC
NTP

PSRL_S
ID_TRC
TVPM
PD
AIHP
MR
PIMV

VED
ID_TRC
PD
VTD
VOR
VOT
ΔL

PD
ID_TRC
PDCC

NBIL
ID_TRC
TRL

PSRL_R
ID_TRC
VR
PD
TNRH
AMR

PED
ID_TRC
PD
SW
VOT
PFR
ΔT

DDC
ID_TRC
ID_BLDG
PD
FCB
ASC
LCC

SI_H
ID_TRC
NHA
PC
AHOR

SI_B
ID_TRC
PD
NEA
HWR
RF
DI

PR
ID_TRC
ID_BLDG
DN
NEA
HWR
PRF

4.3. PROBLEMS OF DATA COLLECTION AND ANALYSIS

As explained earlier in section 4.2, data integration was the major issue because spatial data layers from different sources did not have a common key identifier. Therefore, massive efforts were invested on linking all layers to the corridor layer in order to facilitate further data analysis. An average of 90 % of linkage was done automatically against 10 % manually. Once data integration completed, there was a need to develop data dictionary and model to schematize the organization and relationships of the indicators' databases. Data used in assessment models can be classified in three major groups:

- Hard data that are straightforwardly collected from different data repositories, such as parking meter spaces, number of buildings, annual average density traffic, road surface and length.
- Data that are obtained through literature, interviews and reports such as pollutant emission costs, claim amounts, costs of the police presence on work site, vehicle maintenance and operation costs.
- Soft data that are computed on basis of assumptions such as durations (for work, noise exposure and machinery utilization), likelihood of damage and value of time lost (VOT) in traffic delays. This required state-of-the-art and reliable assessment processes for different kind of information.

Some data available in the SIGS were not be updated such as the number of employees per business unit. They had to be validated with other sources wherever possible. Challenges in updating all developed models each year can easily be anticipated if the municipality does not put in place a data management program for social cost assessment.

CHAPTER 5: IMPLEMENTATION OF SOCIAL COST MODELS

5.1. INTRODUCTION

This chapter deals with the implementation of assessment models. More than a thousand road corridors of the City of Montreal were selected for the case study. Regression models provide social cost values for each road corridor and for every type of work. These costs can be used as input data in decision support systems to run different renewal strategies and analyze them. The incorporation of social costs in decision-making processes for infrastructure asset renewals ultimately helps to select renewal strategies that bring the best outcome to the society.

5.2. PLATEAU MONT-ROYAL ROADS

The district of the City of Montreal named The Plateau Mont-Royal was selected for the case study. The Plateau Mont-Royal offers a variety in road corridor types such as residential, commercial, arterial and local roads. It has the highest rate of density of people per square meter in Canada. It is composed of 1351 road corridors totalling 145 km with two North-South transit routes of Saint-Laurent Blvd. and Saint Denis St. and two East-West transit routes of Mount Royal Ave. and Sherbrooke St. Up to now, social cost indicators related to municipal works had never been assessed at a strategic/large level, but rather they were addressed at a project/micro level in part due to the complexity of their assessment. Now the regression models proposed in this study will enable to assess social costs for an entire road network.

5.3. RESULTS ON REGRESSION ANALYSES

This section deals with characteristics and results of the regression models built for social cost indicators for the 1351 road corridors in The Plateau Mont-Royal district. Social cost regression functions are standard cost curves for work-related impacts and can be applicable to

Canadian roads under similar conditions. Out of the twenty-seven (27) social cost indicators specified in Table 3.1, solely ten (10) indicators were relevant to perform regression analysis: Vehicle delays (VED), Pedestrian delays (PED), Vehicle maintenance and operations (VMO), Parking revenue loss (PRL), Tax revenue loss (TRL), Property sale and rent loss (PSRL), Productivity reduction (PR), Service interruption (SI), Dirt and dust cleaning (DDC) and Air pollution (AP). The next sections present the results for these top ten (10) indicators.

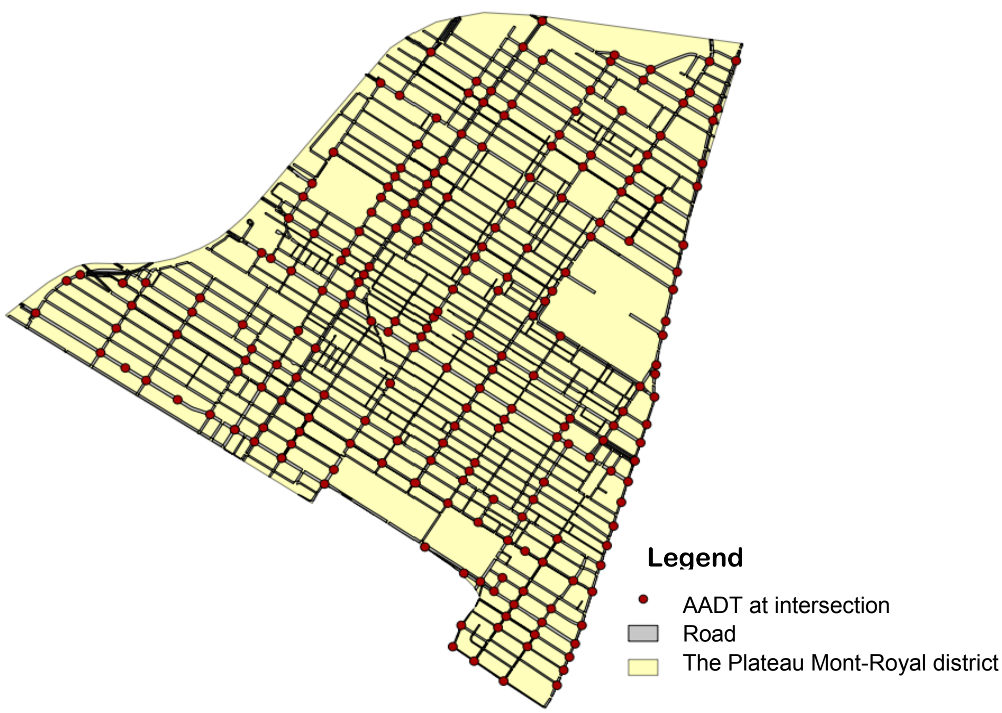

Figure 5.1 : Case study area in Montreal

5.3.1. Vehicle delays

Vehicle delay (VED) costs represent the costs of travel delays borne by vehicle passengers because of increased travel route or time. In table 3.5, variables needed to predict VED costs are the project duration (PD_i), the increased travel time (ΔT_{ij}), the vehicle traffic density (VTD_{ijkl}), the value of time lost in traffic (VOT_{ijkl}) and vehicle occupancy rate (VOR_k), where i is the day of the week, j is the time of the day, k is the type of vehicle and l is the type of trips.

5.3.1.1 Methodology for vehicle delays

The traffic volume pattern in the City of Montreal reveals that the average annual daily traffic (AADT) varies per the day of the week (see Figure 5.2) and the time of the day (Figure 5.3). In this study, three periods for the day of the week (Monday-Friday, Saturday and Sunday) and six periods for the time of the week were chosen as illustrated in Table 5.1.

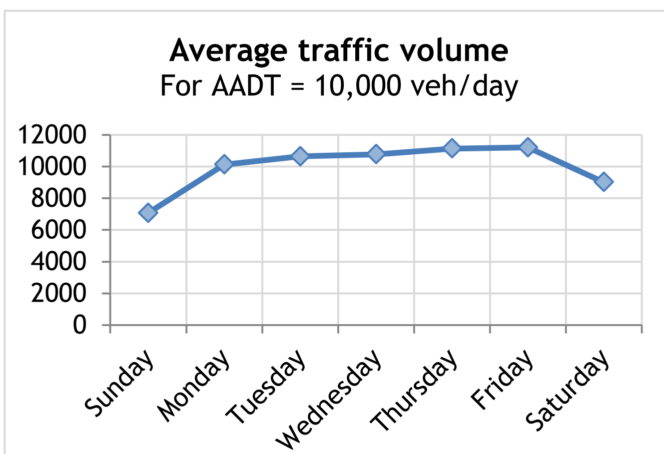

Figure 5.2 : Montreal traffic volume pattern per the day of the week (City of Montreal)

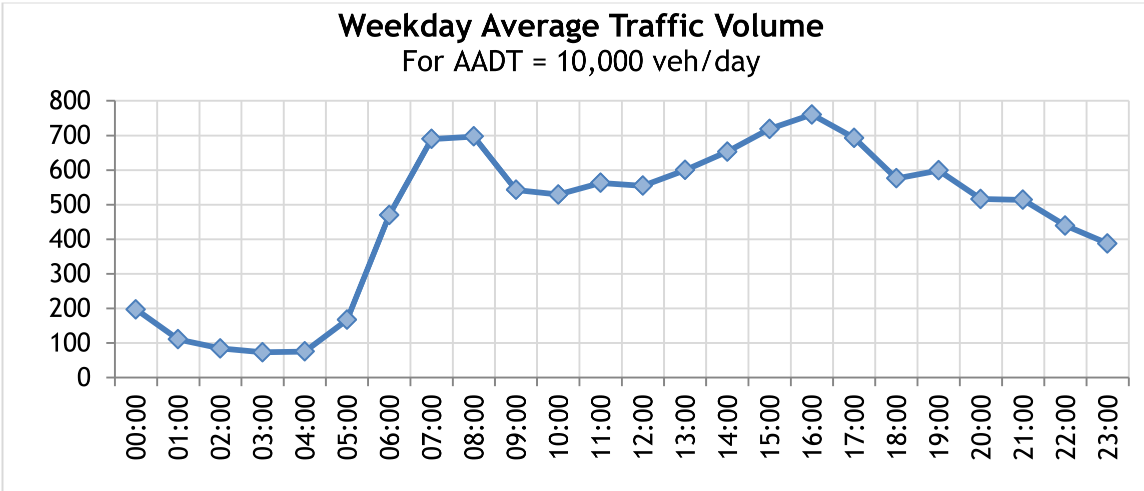

Figure 5.3 : Montreal traffic volume pattern per the time of the day (City of Montreal)

Table 5.1 : Discretization of the time of the day

j=	Night	Morning	Morning peak hours	Midday	Afternoon peak hours	Evening
From	00:00 a.m.	06:00 a.m.	07:00 a.m.	09:00 a.m.	04:00 p.m.	06:00 p.m.
To	05:59 a.m.	06:59 a.m	08:59 a.m.	03:59 p.m.	05:59 p.m.	11:59 p.m.
Total	6 hours	1 hour	2 hours	7 hours	2 hours	6 hours

The average annual daily traffic (AADT), which was collected from the Montreal Department of Transportation, should be factored to consider weekly and daily variations of traffic volumes (see Appendix A). At this stage monthly variations are neglected. Therefore, the resulting traffic volume factors used in our models are illustrated in Table 5.2. For example, the vehicle traffic density (VTD_{ij}) during morning peak hours on Saturday is expressed as 0.1237 x AADT.

Table 5.2 : Traffic Volume Factors

	Weekday	Saturday	Sunday
Night	0.0572	0.0477	0.0374
Morning	0.0495	0.0414	0.0325
Morning peak hours	0.1476	0.1237	0.0970
Midday	0.4019	0.3365	0.2641
Afternoon peak hours	0.1468	0.1229	0.0964
Evening	0.2752	0.2297	0.1803

In other to assess the VTD for each type of vehicle (automobile, bus, light truck and heavy truck) and for each type of trips (business, non-business), the statistics on vehicle volumes authorized to circulate on Montreal Island jurisdiction were used. They are computed by the SAAQ (see Appendix B). Table 5.3 summarizes the modal shares of vehicle volumes used in this study. For example, the vehicle traffic density (VTD_{ijkl}) during morning peak hours on Saturday for automobiles in business trips is expressed as 0.1237 x 4.97 % x AADT.

Table 5.3 : Modal Shares of vehicle volumes in circulation

	Non-business	Business
Automobile	60.67 %	4.97 %
Light truck	23.84 %	7.31 %
Heavy truck		2.82 %
Bus	0.39 %	

The traffic delay ΔT_{ij} is assessed for partial and complete closure of the road. For partial closure, ΔT is expressed as the sum of ΔT_d due to deceleration of vehicle arriving at the work zone and of ΔT_{sr} due to the speed reduction when going through the work zone (see Appendix C). For a complete closure, ΔT is expressed as the difference between travel times on normal and detour routes (see Appendix C). To automate the processes, the vehicle speeds in normal and work conditions on both alternate and normal roads were defined as a level of service (LOS) (see

Figure 5.4). The values of LOS are presented in Table 5.4. The LOS of the class IV are used in this study when the vehicle free-flow speed ranges from 40 to 55 km. The LOS are assigned to the road per the time of the day in a systematic way presented in Table 5.5.

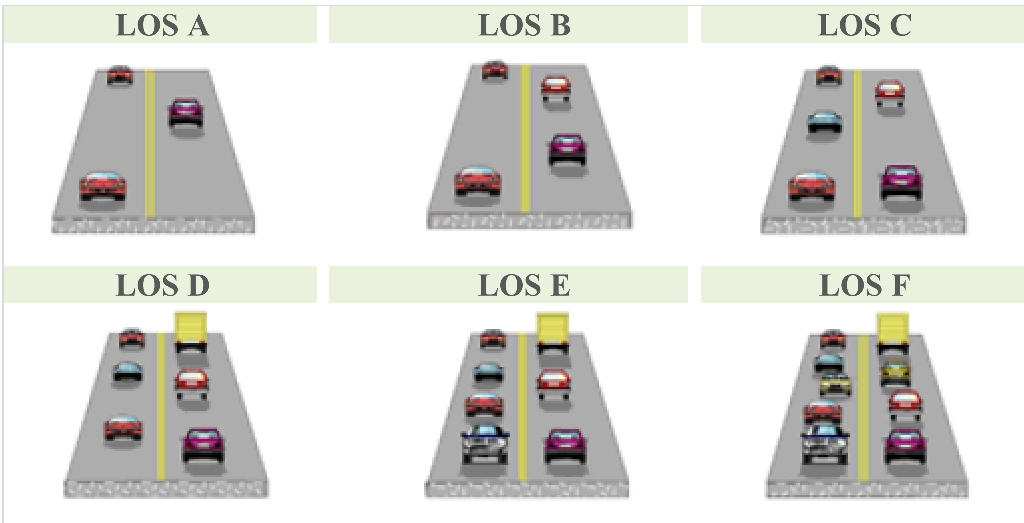

Figure 5.4 : Level of service for road segments (Courtesy of Montreal Polytechnic School)

Table 5.4 : LOS for urban streets (HCM, 2000)

Urban street class	I	II	III	IV
Free-flow speed range (FFS)	70 – 90 km/h	55 – 70 km/h	50 – 55 km/h	40 – 55 km/h
Typical FFS	80 km/h	65 km/h	55 km/h	45 km/h
LOS	Average travel speed (km/h)			
A	> 72	> 59	> 50	> 41
B	> 56-72	> 46-59	> 39-50	> 32-41
C	> 40-56	> 33-46	> 28-39	> 23-32
D	> 32-40	> 26-33	> 22-28	> 18-23
E	> 26-32	> 21-26	> 17-22	> 14-18
F	≤ 26	≤ 21	≤ 17	≤ 14

Table 5.5 : Systematic selection of LOS

Flow conditions	Normal	Work	
Road	**Normal**	**Normal**	**Alternate**
Road closure status		Partial	Complete
	V_n	V_w	V_d
Night	A	A	B
Morning	C	E	D
A.M. peak hours	D	F	E
Midday	B	D	C
P.M. peak hours	D	F	E
Evening	B	D	C

Therefore, travel delays ΔT_{ij} for each period can be assessed. The same LOS for week and weekend days are used. The vehicle speed on detoured road (V_d) are set at one level lower than the vehicle speed in normal conditions (V_n). In case of partial closure, some vehicles normally going through the work zone can take detours. In this research, delays are assessed as if all vehicles are passing through work zone. In case of complete closure, vehicles are normally detoured on an alternative road of at least the same capacity. Therefore the original vehicle speed on the detour route is set at V_n and its vehicle traffic density similar to VTD. The additional demand that is placed on the alternative route can result in exceeding the available capacity and thus in delays due to congestion borne by vehicles normally circulating on the alternative route. However, vehicles normally going through the road under works will bear delays due to congestion plus delays due to lengthening of route (see Appendix G).

The value of time lost in traffic (VOT) is critical factor in evaluating delay costs and should be assessed as the passenger's willingness-to-pay (WTP) to reduce travel time (see Appendix D). The VOT_{ijkl} are illustrated in Table 5.6. For vehicles in business trips, VOT is set at the local average wage rate and for vehicles in non-business trips at the price of a cup of coffee as a WTP for waiting time. However, VOT is zero for all trips at night and evening periods. Especially for non-business trips at morning and midday VOT is also zero. The impacts of works for these cases were neglected. At last, the vehicle occupancy rate VOR_k, which the average number of passengers, is shown in Table 5.7.

Table 5.6 : Value of time

	Non-business trips			**Business trips**		
	Weekday	Saturday	Sunday	Weekday	Saturday	Sunday
Night	0	0	0	0	0	0
Morning	0	0	0	17.6	17.6	17.6
Morning peak hours	1.5	1.5	1.5	17.6	17.6	17.6
Midday	0	0	0	17.6	17.6	17.6
Afternoon peak hours	1.5	1.5	1.5	17.6	17.6	17.6
Evening	0	0	0	0	0	0

Table 5.7 : Average vehicle occupancy rate

Automobile	Bus	Light truck	Heavy truck
1.3	65	1.3	2.3

5.3.1.2 Regression functions for vehicle delays

Once the Vehicle delay (VED) costs were predicted through models for both partial and complete road closures, the regression functions were built in a way to find the relationship between predicted VED costs (in $), VDT (in veh.), Road length (in meter) and Project duration (in days).

Equation 3

$$\text{VED costs} = \Big(\big(a.\text{VTD}_{\text{auto}} + b.\text{VTD}_{\text{light truck}} + c.\text{VTD}_{\text{heavy truck}} + d.\text{VTD}_{\text{bus}}\big).e^{e.\text{Road length}}\Big).\text{Project duration}^{f}$$

Values of coefficients are presented in Table 5.8. The regression was performed by minimising the sum of the squares of the errors, i.e. differences between modeled and measured values.

Table 5.8: Regression coefficients for VED

		Road closure	
Variables	Coefficients	Partial	Complete
VTD_{auto}	a	0.0124	0.0873
$VTD_{light\ truck}$	b	0.0074	0.0076
$VTD_{heavy\ truck}$	c	0.1122	0.6335
VTD_{bus}	d	0.0001	0.0001
Road length	e	0.0040	0.0040
Project duration	f	1.0306	1.0306

The statistical tests, F-Test and T-Test, were performed per work package. The results for work package 17 (see Table 3.6) for complete road closure are illustrated in the tables 5.8a and 5.8b. The variable 1 is the vector $V_{i=1\ to\ 1349}$ of social costs assessed with the developed models, where i represents each road segment. The variable 2 is the vector of social costs assessed with regression functions. F-statistic = 1.01 < $F_{0.05}$ = 1.09; so H_0 ($\sigma_1 = \sigma_2$) is accepted. The t-test assuming equal variances has a p-value = 0.56, so H_0 ($\mu_1 = \mu_2$) is accepted. The regression function for complete closure is validated.

Table 5.8a: F-Test Two-Sample for variances

	Variable 1	*Variable 2*
Mean	26685.93088	28870.01439
Variance	9656297088	9536178696
Observations	1349	1349
df	1348	1348
F	1.012596072	
P(F<=f) one-tail	0.409144738	
F Critical one-tail	1.093772246	

Table 5.8b: T-Test Two-Sample Assuming Equal Variance

	Variable 1	*Variable 2*
Mean	26685.93088	28870.01439
Variance	9656297088	9536178696
Observations	1349	1349
Pooled Variance	9596237892	
Hypothesized Mean Difference	0	
df	2696	
t Stat	-0.57904153	
P(T<=t) one-tail	0.281304763	
t Critical one-tail	1.645419019	
P(T<=t) two-tail	0.562609525	
t Critical two-tail	1.960844296	

For the partial closure (work package #13 in Table 3.6), the F-statistic = 1.02 < $F_{0.05}$ = 1.09; therefore H_0 ($\sigma_1 = \sigma_2$) is accepted. The t-test assuming equal variances has a p-value = 0.44, so H_0 ($\mu_1 = \mu_2$) is validated. So, the regression function for partial closure is also adequate. Note that the results can be slightly different per the kind of work packages illustrated in Table 3.6. Figure 5.5 illustrates VED costs for a complete road closure in case of reconstruction of all assets (water, sewer and road). It shows rightly that where VTD is high, VED costs is also high.

Figure 5.5 : VED cost visualization

Note that in the following sections of this chapter, for each social cost indicators, solely the F-statistic value and the p-value of the T-test to validate developed regression models are commented.

5.3.2. Pedestrian delays

Pedestrian delay (PED) costs represent the costs of travel delays borne by pedestrians because of increased travel route or time. In table 3.5, variables needed to predict PED costs are the project duration (PD_i), the increased travel time (ΔT_{ij}), the pedestrian flow rate (PFR_{ij}), the value of time lost in traffic (VOT_{ij}) and the sidewalk width (SW), where i is the day of the week and j is the time of the day. Two cases were studied: partial closure of both sidewalks or complete closure of one sidewalk leaving the opposite sidewalk open.

5.3.2.1 Methodology for pedestrian delays

First, the character of each street is determined: commercial, industrial, residential and institutional. Then, the levels of service (LOS) are set for each street per the time of the day and the day of the week. Table 5.9 illustrates the different LOS used in this study. The LOS are expressed in terms of pedestrian flow rate (PFR) and associated pedestrian walking speed (PWS). PFR is the number of pedestrian crossing effective sidewalk width each minute (ppmm). A neperian logarithmic relationship between PFR and PWS was demonstrated (see Appendix J). Figure 5.6 illustrates the effective width on a sidewalk and Figure 5.7 typical LOS for sidewalks.

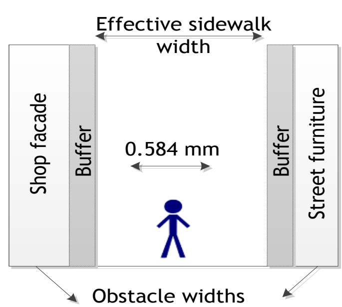

Figure 5.6 : Effective width on a sidewalk (Finch, 2010)

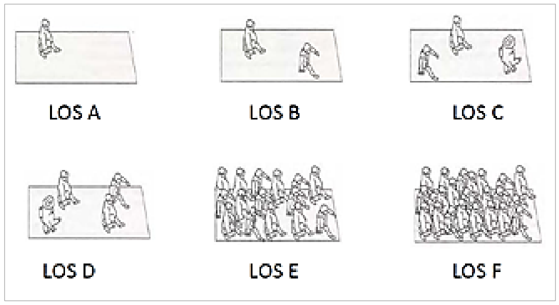

Figure 5.7 : Levels of service for sidewalks (HCM, 2000)

Table 5.9: Levels of service for sidewalks

LOS	PFR (ppmm)	PWS (m/s)
A+	0.09	1.33
	0.1	1.33
	0.2	1.33
	0.3	1.33
	0.4	1.33
A	3	1.33
A-	6	1.33
B+	9	1.33
B	12	1.33
B-	15	1.33
C+	19	1.26
C	22	1.19
C-	25	1.14
D	31	1.03
E	35	0.98
F	49	0.83

Both sidewalks are considered to have the same LOS and length. In case of partial closure, 50 % of sidewalk reduction is assumed on each sidewalk. In case of complete closure of one sidewalk, the PFR on the opposite sidewalk is doubled and the crossing time is neglected. The number of pedestrian crossing the sidewalk (PFR_{ij}) for each period is assessed as the PFR in ppmm multiplied by the time length of each period and the sidewalk width. The corresponding PWS_{normal} under normal conditions can be found in Table 5.9. The increased travel time (ΔT_{ij}) is assessed for two cases: partial and complete closure of sidewalks (see Appendix J). Before and during works, the same number of pedestrians crossing the sidewalk is assumed. So, the PWS_{work} under work conditions leads to the PFR_{work}. In both cases of partial and complete closure, the PFR_{work} increases because pedestrians will have reduced personal space. The complete closure of both sidewalks is not studied because the City of Montreal never allows it. Table 5.10 illustrates the value of time lost (VOT_{ij}) for pedestrians used in this study. The VOT is set at about the price of coffee as willingness-to-pay for lost time.

Table 5.10: Value of time lost for pedestrians

	Weekday	Saturday	Sunday
Night	0	0	0
Morning	1	0	0
Morning peak hours	2	0	0
Midday	0	0.25	0.25
Afternoon peak hours	2	0.25	0.25
Evening	0	0	0

5.3.2.2 Regression functions for pedestrian delays

Once the Pedestrian delay (PED) costs were predicted through models for both partial and complete sidewalk closures, the regression functions were built in a way to find the relationship between predicted PED costs (in \$), Number of pedestrians per day (ped/day) and effective Sidewalk width (m).

Equation 4 $$\text{PED costs} = \text{a. Number of pedestrians per day. } e^{\text{b.Sidewalk width}} \text{. Project duration}^{c}$$

Values of coefficients are presented in Table 5.11. The regression was performed by minimising the sum of the squares of the errors, i.e. differences between modeled and measured values.

Table 5.11: Regression coefficients for PED

		Sidewalk closure	
Variables	Coefficients	Partial	Complete
Number of pedestrians per day	a	0.0013	0.0009
Sidewalk width	b	0.0826	0.2079
Project duration	c	1.5313	1.7335

For the complete closure (work package #17 in Table 3.6), the F-statistic = 1.34 > $F_{0.05}$ = 1.16; therefore H_0 ($\sigma_1 = \sigma_2$) is rejected. The t-test assuming unequal variances has a p-value = 0.27, so H_0 ($\mu_1 = \mu_2$) is accepted. So, the regression function for complete closure is validated. For the partial closure (work package #1 in Table 3.6), the F-statistic = 1.92 > $F_{0.05}$ = 1.03; therefore H_0 ($\sigma_1 = \sigma_2$) is rejected. The t-test assuming unequal variances has a p-value = 0.96, so H_0 ($\mu_1 = \mu_2$) is accepted. So, the regression function for partial closure is validated. Note that the results can be slightly different per the kind of work packages illustrated in Table 3.6.

5.3.3. Vehicle maintenance and operations

Vehicle maintenance and operations (VMO) costs represent the costs of additional fuel and non-fuel operations and vehicle maintenance. In table 3.4, variables needed to predict VMO costs are the project duration (PD_i), the increased travel route (ΔL_{ij}), the vehicle traffic density (VTD_{ijkl}), the operational costs (OC_k), where i is the day of the week, j is the time of the day and k is the type of vehicle.

5.3.3.1 Methodology for VMO

The travel delays (ΔT_{ij}) are used as explained in section 5.3.1. Therefore, the ΔL_{ij} equivalent is assessed for both partial and complete road closures (see Appendix G). Table 5.12 illustrates the vehicle operating costs per the local market.

Table 5.12: Vehicle operating costs

Type of vehicle	Costs
Automobile	0.16 $/km
Light truck	0.42 $/km
Heavy truck	1.12 $/km
Bus	1.12 $/km

5.3.3.2 Regression functions for VMO

Once the Vehicle maintenance and operations (VMO) costs were predicted through models for both partial and complete road closures, the regression functions were built in a way to find the relationship between predicted VMO costs (in $), VDT (in veh.), Road length (in meter) and Project duration (in days).

Equation 5

$$\text{VMO costs} = \Big(\big(\text{a.VTD}_{\text{auto}} + \text{b.VTD}_{\text{light truck}} + \text{c.VTD}_{\text{heavy truck}} + \text{d.VTD}_{\text{bus}}\big).\, \text{e}^{\text{e.Road length}}\Big).\, \text{Project duration}^{\text{f}}$$

Values of coefficients are presented in Table 5.13. The regression was performed by minimising the sum of the squares of the errors, i.e. differences between modeled and measured values.

Table 5.13: Regression coefficients for VMO

Variables	Coefficients	Road closure	
		Partial	Complete
VTD_{auto}	a	0.0230	0.1373
$VTD_{light\ truck}$	b	0.0072	0.0073
$VTD_{heavy\ truck}$	c	0.0440	0.3205
VTD_{bus}	d	0.3546	0.4067
Road length	e	0.0040	0.0040
Project duration	f	1.0256	1.0325

For the complete closure (work package #17 in Table 3.6), the F-statistic = 1.01 < $F_{0.05}$ = 1.09; therefore H_0 ($\sigma_1 = \sigma_2$) is accepted. The t-test assuming equal variances has a p-value = 0.54, so H_0 ($\mu_1 = \mu_2$) is accepted. So, the regression function for complete closure is validated. For the partial closure (work package #13 in Table 3.6), the F-statistic = 1.01 < $F_{0.05}$ = 1.09; therefore H_0 ($\sigma_1 = \sigma_2$) is accepted. The t-test assuming unequal variances has a p-value = 0.54, so H_0 ($\mu_1 = \mu_2$) is accepted. So, the regression function for partial closure is also validated. Note that the results can be slightly different per the kind of work packages illustrated in Table 3.6.

5.3.4. Parking revenue loss

Parking revenue losses (PRL) represent the losses of parking meter and ticketing revenues, plus the costs of parking space relocation if applicable. In table 3.4, variables needed to predict PRL are the project duration (PD_i), the daily operational hour (DOH_i), the occupancy rate (OC), the hourly meter rate (HMR), the number of lost parking spaces (NLPS), the road length (L), the parking ticket rate (PTR) and the daily parking ticket infractions per km (DPTIK); where i is the day of the week.

5.3.4.1 Methodology for PRL

Table 5.14 and Table 5.15 illustrate respectively, the different existing tariff zones for Montreal city and the daily operational hours. The average PTR is set at around 50 $ in Montreal.

Table 5.14: Hourly meter rates

Tariff zones	Hourly meter rate
Zone 1	3 $/h
Zone 2	2.5 $/h
Zone 3	2 $/h
Zone 4	1.5 $/h

Table 5.15: Parking meter operational hours

Day of week (i)	Monday to Friday	Saturday	Sunday
Operational hours	12 h	9 h	5 h

5.3.4.2 Regression functions for PRL

Once the Parking meter revenue losses (PRL) were predicted through models, the regression functions were built in a way to find the relationship between predicted PRL (in $), the number of on street paid parking spaces and Project duration (in days).

Equation 6 $$\text{PRL} = \text{a. Number of on street paid parking spaces. Project duration}^{\text{b}}$$

Values of coefficients are presented in Table 5.16. The regression was performed by minimising the sum of the squares of the errors, i.e. differences between modeled and measured values.

Table 5.16: Regression coefficients for PRL

Tariff zones	a	b
Zone 1 (3 $)	26.9195	0.9879
Zone 2 (2,5 $)	22.4323	0.9879
Zone 3 (2 $)	17.9501	0.9879
Zone 4 (1,5 $)	13.4623	0.9879

The statistical analyses were performed for all kinds together of work packages illustrated in Table 3.6. For zone 1, the F-statistic = 1.0 < $F_{0.05}$ = 1.04; therefore H_0 ($\sigma_1 = \sigma_2$) is accepted. The t-test assuming equal variances has a p-value = 0.99, so H_0 ($\mu_1 = \mu_2$) is accepted. The regression function is validated. For zone 2, the F-statistic = 1.0 < $F_{0.05}$ = 1.3; therefore H_0 ($\sigma_1 = \sigma_2$) is accepted. The t-test assuming equal variances has a p-value = 0.99, so H_0 ($\mu_1 = \mu_2$) is accepted. The regression function is validated. For zones 3 and 4, the F-statistic = 1.0 < $F_{0.05}$ = 1.2; therefore H_0 ($\sigma_1 = \sigma_2$) is accepted. The t-test assuming equal variances has a p-value = 0.98, so H_0 ($\mu_1 = \mu_2$) is accepted. The regression functions are validated. Figure 5.8 illustrates PRL for a complete reconstruction of all assets.

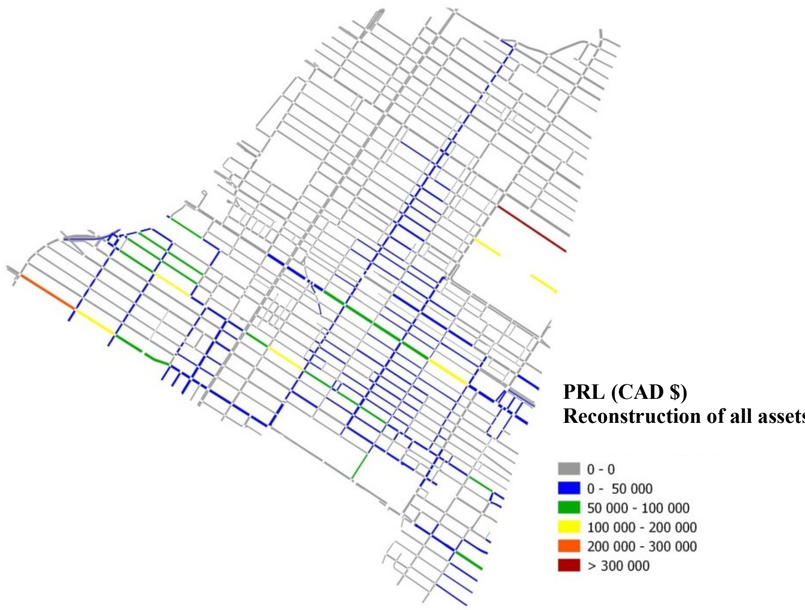

Figure 5.8 : PRL visualization

5.3.5. Tax revenue loss

The Tax revenue losses (TRL) represent the municipal property tax rebates for vacancies, plus reduction in tax revenues resulting from loss on sale for specific shops with lack of completion that cannot be recovered (if applicable). In table 3.4, variables needed to predict TRL costs are the project duration (PD), the total value of taxable units (TUTV), the residential tax rate (RTR), the non-residential tax rate (NRTR) and the percent of non-residential units (PNRU).

5.3.5.1 Methodology for TRL

Property units are classified in twelve classes per the percent of non-residential units. As illustrated in Table 5.17, the residential tax rate (RTR) is the basic rate and the non-residential tax rate (NRTR) varies accordingly to the number of residential or dwelling units. Table 5.18 illustrates the different classes, for example a unit of class 2 means that the percent of non-residential unit (PNRU) is only 3 %. The tax rate is expressed in dollar per 100 $ of the total value of taxable unit (see Appendix L).

Table 5.17: Tax rate applicable in Montreal (City of Montreal)

Type of immovables	Abbr.	Tax rate
Basic rate	BR	3.272
Non-residential immovables and 5 or less dwelling units	NRTR	0.6812
Non-residential immovables and 6 and more dwelling units	NRTR	0.7143

Table 5.18: Property unit classes (City of Montreal)

Classes	% of tax rate
1	0.5 %
2	3 %
3	6 %
4	12 %
5	22 %
6	40 %
7	60 %
8	85 %
9	100 %
10	100 %
11	100 %
12	100 %

5.3.5.2 Regression functions for TRL

Once the Tax revenue losses (TRL) were predicted through models, the regression function is built in a way to find the relationship between the predicted TRL (in $), the property value of each unit (in $) per its kind, and the Project duration (in days).

Equation 7

$$\mathrm{TRL} = \left(\left(\sum_{\mathrm{residential}} \text{Property value}\right)^{a} + \sum_{i=1}^{12}\left(\sum_{\mathrm{Class}\ b_i} \text{Property value}\right)^{b_i}\right) . \text{Project duration}^{c}$$

Values of coefficients are presented in Table 5.19. The regression was performed by minimising the sum of the squares of the errors, i.e. differences between modeled and measured values.

Table 5.19: Regression coefficients for TRL

Variables		Coefficients	Variables		Coefficients
Residential	a	0.2029	Class 7	b_7	0.2279
Class 1	b_1	0.0009	Class 8	b_8	0.2159
Class 2	b_2	0.2747	Class 9	b_9	0.00002
Class 3	b_3	0.0003	Class 10	b_{10}	0.0336
Class 4	b_4	0.0203	Class 11	b_{11}	0.0224
Class 5	b_5	0.00002	Class 12	b_{12}	0.3898
Class 6	b_6	0.1259	Project duration	c	1.3585

The statistical analyses were performed for all kinds together of work packages illustrated in Table 3.6. The F-statistic = 1.07 > $F_{0.05}$ = 1.02; therefore H_0 ($\sigma_1 = \sigma_2$) is rejected. The t-test assuming unequal variances has a p-value = 0.001, so H_0 ($\mu_1 = \mu_2$) is rejected. The regression function cannot be validated. Figure 5.9 shows the Google street classification in 2016.

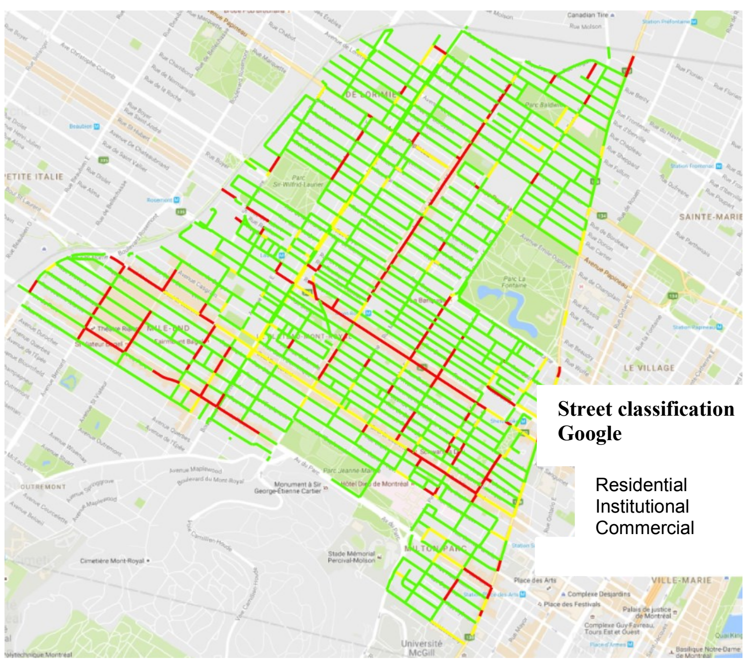

Figure 5.9 : Google street classification (Google 2016)

Figure 5.10 illustrates the TRL results for a complete reconstruction of all assets. Given that TRL can be used as willingness-to-pay for business losses, it shows rightly that commercial streets bear higher losses than residential or institutional streets. In future research, regression functions should be done per street classification.

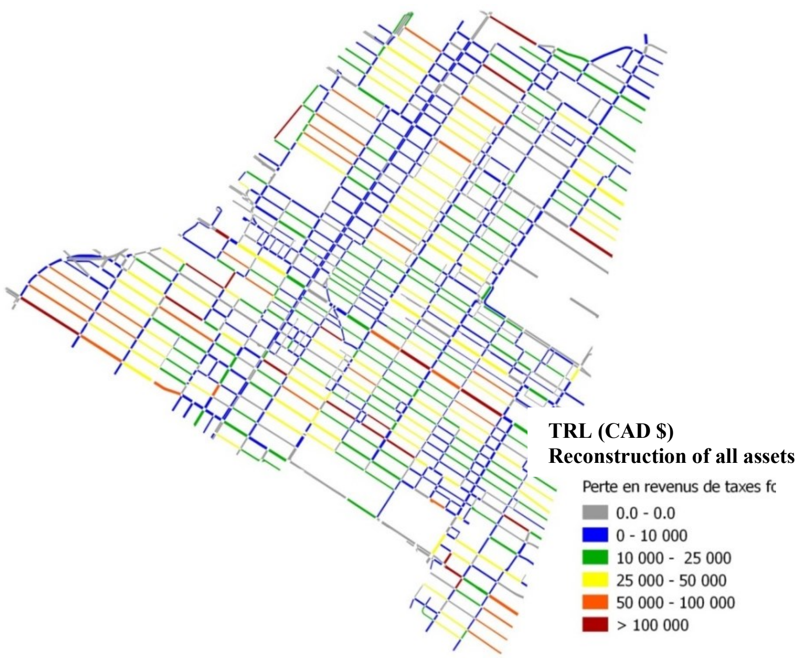

Figure 5.10 : TRL visualization

5.3.6. Property sale and rent loss

Property sale and rent losses (PSRL) represent revenue losses related to difficulties to sale and rent properties during works. In table 3.4, variables needed to predict PSRL are the project duration (PD), the percent of increase due to market value (PIMV), the mortgage rate (MR), the annual increase in house price (AIHP), the total value of properties in the market (TVPM), the total number of rental housing (TNRH), the vacancy rate (VR) and the average monthly rent (AMR). PRSL were solely assessed for rent losses because the project duration is usually less than a year. The average monthly rent was set at 850 $ and the vacancy rate at 3.5 %. Once the Property sale and rent losses (PSRL) were predicted through models, the regression function is built in a way to find the relationship between predicted PSRL (in $), the number of apartment for rent and the Project duration (in days).

Equation 8 $$\mathrm{PSRL} = \mathrm{a.\,Number\ of\ apartments\ for\ rent\,.\,Project\ duration^{b}}$$

Values of coefficients are presented in Table 6.6. The regression was performed by minimising the sum of the squares of the errors, i.e. differences between modeled and measured values.

Table 5.20: Regression coefficients for PSRL

Variables	Coefficients	
Number of apartment for rent	a	0.9920
Project duration	b	0.9999

The statistical analyses were performed for all kinds together of work packages illustrated in Table 3.6. The F-statistic = 1.0 < $F_{0.05}$ = 1.01; therefore H_0 ($\sigma_1 = \sigma_2$) is accepted. The t-test assuming equal variances has a p-value = 0.99, so H_0 ($\mu_1 = \mu_2$) is accepted. The regression function is validated.

5.3.7. Productivity reduction

Productivity reduction (PR) costs represent the costs of productivity loss at work due to noise. In table 3.5, variables needed to predict PR costs are the duration of noise (DN), the number of employees affected (NEA), the productivity reduction factor (PFR) and the hourly wage rate (HWR). Productivity reduction (PR) was assessed in terms of lost work hours.

5.3.7.1 Methodology for PR

For each type of works, machines are described according to the duration and the decibel as illustrated in Figure 5.11 for road minor rehabilitation. Then the Gantt Diagram was performed by reporting each hour of use and associated decibel regarding the work steps. The noise duration was used instead of the project duration that is usually longer. So, for each hour of use, if two or more machines are operating at the same time, the resulting decibel for that hour should equal the highest decibel plus 3 dBA. Then the productivity reduction factor (PFR) was associated to the corresponding dBA level in accordance with the type of building (institutional, commercial and industrial) as illustrated in Figure 4. The noise duration for all types of works is described in Appendix K.

Type of work	Work steps	Type of machine	# of machines	Duration (hour)	Machine Decibel
Road minor rehab	Mobilization	Truck	2	4	85
		Truck Ford 450	3	2	55
		Truck	8	2	85
	Resurface	Motor scraper	1	2	85
	Crack sealing	Mechanic broom	1	2	85
	Bitumen binder	Truck Colle	1	2	85
		Asphalt Compactor	2	5	80
		Asphalt Paver	2	5	85
	Evacuation des débris	Backhoe	1	9	80

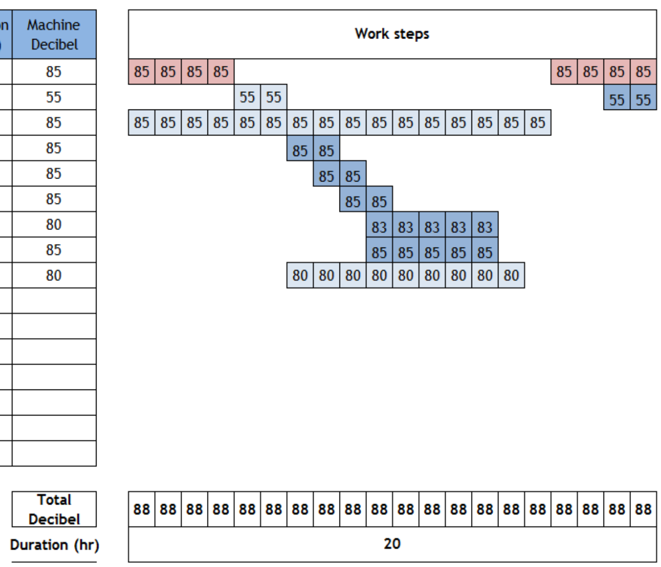

Figure 5.11 : Noise duration diagram for road minor rehabilitation

5.3.7.2 Regression functions for PR

Once the Productivity reduction (PR) costs were predicted through models, the regression function is built in a way to find the relationship between predicted PR costs (in $), the number of employees affected and the noise duration (in hours).

Equation 9 $$\mathrm{PR} = \mathrm{a.\,Number\ of\ employees\ .\,Noise\ duration}^{\mathrm{b}}$$

Values of coefficients are presented in Table 5.21. The regression was performed by minimising the sum of the squares of the errors, i.e. differences between modeled and measured values.

Table 5.21: Regression coefficients for PR

Variables	Coefficients	
Number of employees	a	5.0864
Noise duration	b	1.0735

The statistical analyses were performed for all kinds together of work packages illustrated in Table 3.6. The F-statistic = 1.03 > $F_{0.05}$ = 1.02; therefore H_0 ($\sigma_1 = \sigma_2$) is rejected. The t-test assuming unequal variances has a p-value = 0.26, so H_0 ($\mu_1 = \mu_2$) is accepted. The regression function is validated. Figure 5.12 illustrates the results of PR costs for a complete reconstruction of all assets. Commercial and institutional streets bear higher costs than residential ones.

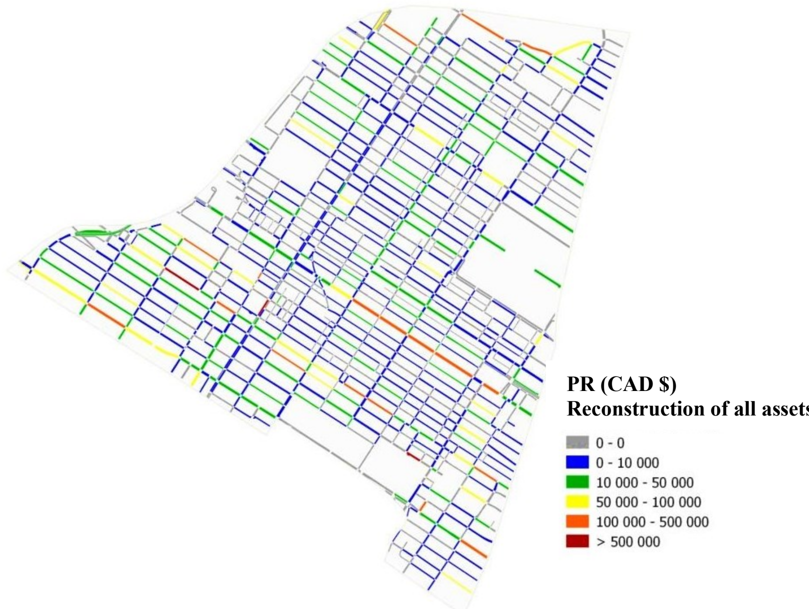

Figure 5.12 : PR cost visualization

5.3.8. Service interruption

Service interruption (SI) costs represent the costs of bypass installation, plus damage costs resulting unplanned or accidental interruptions. In table 3.4, variables needed to predict SI costs are the duration of interruption (DI), the number of employees affected (NEA), the hourly wage rate (HWR), the reduction factor (RF), the number of housing affected (NHA), the average household occupancy rate (AHOR) and the preventing costs (PC). Given that SI costs related to bypass installation are normally included in the construction contract bid, SI costs were assessed solely for forewarned residents in terms of preventive costs. SI costs related to accidental failures during works were neglected. Once the SI costs were predicted, the regression function is built in a way to find the relationship between predicted SI costs (in $), the number of households and the duration of interruption (in days).

Equation 10 $$\text{SI} = \text{a}.\text{Number of households} \,.\, \text{Duration of interruption}^{\text{b}}$$

Values of coefficients are presented in Table 5.22. The regression was performed by minimising the sum of the squares of the errors, i.e. differences between modeled and measured values.

Table 5.22: Regression coefficients for SI

Variables	Coefficients	
Number of households	a	38.8841
Duration of interruption	b	0.9999

The statistical analyses were performed for all kinds together of work packages illustrated in Table 3.6. The F-statistic = 1.0 < $F_{0.05}$ = 1.03; therefore H_0 ($\sigma_1 = \sigma_2$) is accepted. The t-test assuming equal variances has a p-value = 0.99, so H_0 ($\mu_1 = \mu_2$) is accepted. The regression function is validated.

5.3.9. Dirt and dust cleaning

Dirt and dust cleaning (DDC) costs represent the costs of cleaning resulting from dirt and dust generated by works. In table 3.5, variables needed to predict DDC costs are the project duration (PD), the local cleaning costs (LCC), the frequency of cleaning a building per day (FCB) and the area (m^2) of the building surface to be cleaned (ASC). Once the dirt and dust cleaning (DDC) costs were predicted through models, the regression function is built in a way to find the relationship between predicted DDC costs (in $), the number of commercial buildings, the number of non-commercial buildings, the total area of all buildings (m^2) to be cleaned and the project duration (in days).

Equation 11

$$\text{DDC} = (\text{a. Number of commercial buildings} + \text{b. Number of non-commercial buildings}) . e^{c.\sum_{\text{building}} \text{Facade width}} . \text{Project duration}^{d}$$

Values of coefficients are presented in Table 5.23. The regression was performed by minimising the sum of the squares of the errors, i.e. differences between modeled and measured values.

Table 5.23: Regression coefficients for DDC

Variables	Coefficients	
Number of commercial buildings	a	19.0069
Number of non-commercial buildings	b	2.5769
Building facade width	c	0.0002
Project duration	d	1.0867

The statistical analyses were performed for all kinds together of work packages illustrated in Table 3.6. The F-statistic = 1.01 < $F_{0.05}$ = 1.02; therefore H_0 ($\sigma_1 = \sigma_2$) is accepted. The t-test assuming equal variances has a p-value = 0.99, so H_0 ($\mu_1 = \mu_2$) is accepted. The regression function is validated. Figure 5.13 illustrates the DDC costs for reconstruction of all assets. Commercial and institutional streets bear higher costs than residential ones.

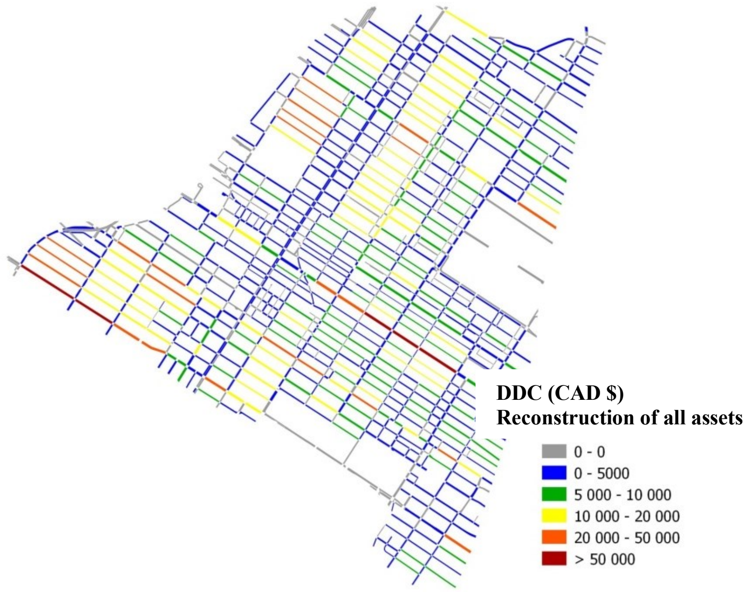

Figure 5.13 : DDC cost visualization

5.3.10. Air pollution

Air pollution (AP) costs were divided into two categories: $AP_{vehicle}$ costs from vehicle emissions and $AP_{machine}$ costs from heavy machinery use. AP costs represent environmental costs resulting from air pollution caused by fuel consumption and dust emissions. In table 3.5, variables needed to predict AP costs from machine are the project duration (PD), the miles-to-acre conversion factor (f), the road length (L), the fuel cost (FC), and the volumetric emission costs (VEC in \$/ton) for GHG and PM_{10}. Variables needed to predict AP costs from vehicle are the project duration (PD_i in days), the increased travel route (ΔL_{ij} in km), the vehicle traffic density (VTD_{ijk} in veh/day), the volume of pollutant emitted per km-driven ($VPEK_{ijkp}$ in ton/veh-km) and the volumetric emission costs (VEC_p in \$/ton), where i is the day of the week, j is the time of the day, k is the type of vehicle and p is the type of pollutant.

5.3.10.1 Methodology for vehicle AP

Two valid assessment methods for $AP_{vehicle}$ are proposed in Table 3.5. The VEC for each pollutant is illustrated in Table 5.24. Given the levels of service (LOS) during normal and work conditions for each period ij (see section 5.3.1); $VPEK_{ijkp}$ are estimated through emissions-speed tables for each type of vehicle (see Appendix E). For example, Table 5.25 illustrates the emissions-speed table for automobile.

Table 5.24: Vehicle emission costs (MTQ, 2013)

$ CAN 2011 per metric ton	GES (g/km)	CO (g/km)	HC (g/km)	NO_x (g/km)	SO_x (g/km)	$PM_{2,5}$ (g/km)	PM_{10} (g/km)
	81	1 742	6 339	8 086	6 747	30 822	8 655

Table 5.25: Volumetric pollutant emissions per kilometer for automobiles (MTQ, 2013)

V (km/h)	GES (g/km)	CO (g/km)	HC (g/km)	NO_x (g/km)	SO_x (g/km)	$PM_{2,5}$ (g/km)	PM10 (g/km)	Fuel (l/km)
5	898	17.406	0.765	0.689	0.004	0.008	0.016	0.369
10	450	9.699	0.452	0.552	0.004	0.008	0.016	0.185
15	344	6.945	0.316	0.446	0.004	0.008	0.016	0.142
20	284	5.681	0.24	0.376	0.004	0.008	0.016	0.117
25	251	5.008	0.196	0.338	0.004	0.008	0.016	0.103
30	231	4.797	0.179	0.343	0.004	0.008	0.016	0.095
35	219	4.646	0.168	0.346	0.004	0.008	0.016	0.09
40	208	4.532	0.159	0.349	0.004	0.008	0.016	0.085
45	199	4.441	0.152	0.351	0.004	0.008	0.016	0.082
50	190	4.392	0.145	0.353	0.004	0.008	0.016	0.078
55	182	4.393	0.137	0.353	0.004	0.008	0.016	0.075
60	180	4.512	0.132	0.356	0.004	0.008	0.016	0.074
65	177	4.66	0.129	0.36	0.004	0.008	0.016	0.073
70	175	4.822	0.126	0.366	0.004	0.008	0.016	0.072
75	171	4.982	0.124	0.372	0.004	0.008	0.016	0.07

5.3.10.2 Regression functions for vehicle AP

Once the Air pollution (AP) costs from vehicles were predicted through models for both partial and complete road closures, the regression function were built in a way to find the relationship between predicted $AP_{vehicle}$ costs (in \$), VDT (in veh.), the road length (in meter) and the project duration (in days).

Equation 12

$$\text{AP}_{\text{vehicle}}\text{costs} = \left(\left(\text{a.VTD}_{\text{auto}} + \text{b.VTD}_{\text{light truck}} + \text{c.VTD}_{\text{heavy truck}} + \text{d.VTD}_{\text{bus}}\right).\, e^{\text{e.Road length}}\right).\text{Project duration}^{\text{f}}$$

Values of coefficients are presented in Table 5.26. The regression was performed by minimising the sum of the squares of the errors, i.e. differences between modeled and measured values.

Table 5.26: Regression coefficients for AP from vehicle emissions

		Road closure	
Variables	Coefficients	Partial	Complete
VTD_{auto}	a	0.0001	0.0107
$VTD_{light\ truck}$	b	0.0018	0.0071
$VTD_{heavy\ truck}$	c	0.0006	0.0000
VTD_{bus}	d	0.0001	0.3493
Road length	e	0.0039	0.0043
Project duration	f	1.0297	1.0151

The statistical analyses were performed for all kinds together of work packages illustrated in Table 3.6. For the complete closure (work package #2 in Table 3.6), the F-statistic = 1.078 < $F_{0.05}$ = 1.093; therefore H_0 ($\sigma_1 = \sigma_2$) is accepted. The t-test assuming equal variances has a p-value = 0.70, so H_0 ($\mu_1 = \mu_2$) is accepted. So, the regression function for complete closure is validated. For the partial closure (work package #5 in Table 3.6), the F-statistic = 1.095 > $F_{0.05}$ = 1.093; therefore H_0 ($\sigma_1 = \sigma_2$) is rejected. The t-test assuming unequal variances has a p-value = 0.88, so H_0 ($\mu_1 = \mu_2$) is accepted. So, the regression function for partial closure is also validated. Note that the results can be slightly different according to the kind of work packages illustrated in Table 3.6.

5.3.10.3 Methodology for machine AP

$AP_{machine}$ costs are based upon the fuel consumption (FC) and are estimated solely for GHG and PM_{10}. The fuel consumption for all work packages is described in Appendix F. Table 5.27 is an example of fuel consumption for road minor rehabilitation.

Table 5.27: Fuel consumption for road minor rehabilitation

Type of machines	Nb.	hr	gal/h
Truck Ford 450	3	2	2.6
Hauling truck	10	2	2.6
Motor scraper	1	2	4.5
Mechanical broom	1	2	2.6
Truck for glue	1	2	2.6
Asphalt Compactor	2	5	4.8
Asphalt Paver	2	5	5.3
Backhoe	1	9	1.9
TOTAL		**97.4 gal**	

5.3.10.4 Regression functions for machine AP

Once the Air pollution (AP) costs from machinery were predicted through models, the regression function is built in a way to find the relationship between predicted $AP_{machine}$ costs (in $), Road length (in meter) and Type of work (1=if performed and 0=if not).

Equation 13
$$\mathrm{AP_{machine}} = (\mathrm{a.WT\ CIPP} + \mathrm{b.WT\ Open\ cut} + \mathrm{c.SW\ CIPP} + \mathrm{d.SW\ Open\ cut} + \mathrm{e.RD\ Minor\ rehab} + \mathrm{f.RD\ Major\ rehab} + \mathrm{g.RD\ Open\ cut}).\mathrm{Road\ Length}$$

Values of coefficients are presented in Table 5.28. The regression was performed by minimising the sum of the squares of the errors, i.e. differences between modeled and measured values.

Table 5.28: Regression coefficients for AP from machinery use

Variables	Coefficients	
WT CIPP (0/1)	a	1.8775
WT Open-cut reconstruction (0/1)	b	1.7934
SW CIPP (0/1)	c	3.4523
SW Open-cut reconstruction (0/1)	d	1.6293
RD Minor rehabilitation (0/1)	e	0.7949
RD Major rehabilitation (0/1)	f	1.7777
RD Open-cut reconstruction (0/1)	g	3.5378

For instance, if water main CIPP is performed then WT CIPP = 1.

The statistical analyses were performed for all kinds together of work packages illustrated in Table 3.6. The F-statistic = 1.0 < $F_{0.05}$ = 1.02; therefore H_0 ($\sigma_1 = \sigma_2$) is accepted. The t-test assuming equal variances has a p-value = 0.95, so H_0 ($\mu_1 = \mu_2$) is accepted. The regression function is validated. Figure 5.14 illustrates the AP costs for a complete reconstruction of all assets.

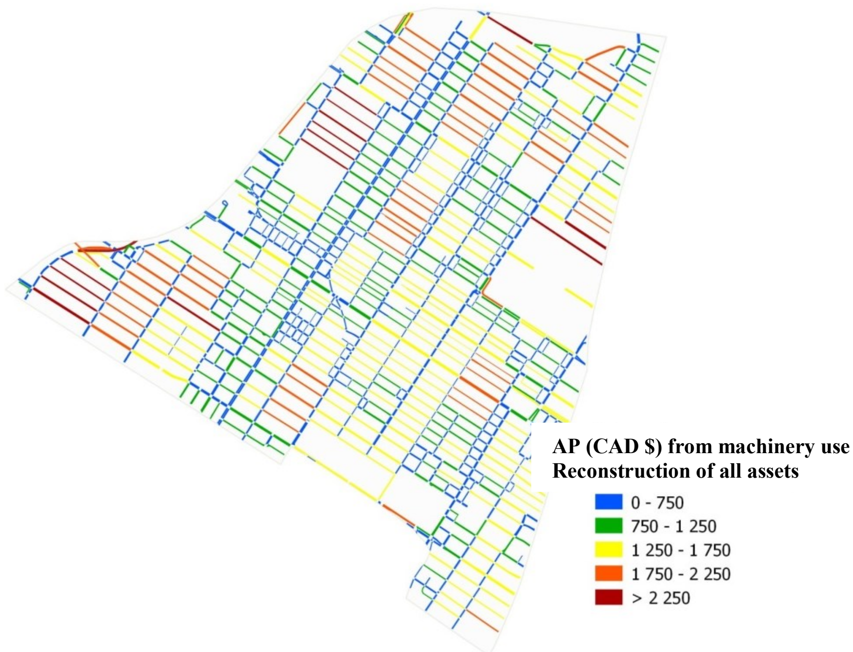

Figure 5.14 : AP cost visualization

The resulting regression curves are innovative ways to compute social costs at a large scale for macro studies on coordination decisions or practices. This research identifies ten key indicators that municipal planners can use to achieve the optimal coordination strategy producing the best outcome for the society. In a nutshell, the observed and modeled cost indicators were performed in Excel and are very data intensive. For further steps, probability distributions can be assigned to some variables of regression functions to perform risk analysis, using available statistical tools such as @Risk. Table 5.29 summarizes the regression analysis for all indicators.

Table 5.29: Regression analysis summary

I – ROAD TRAFFIC AND SAFETY		
Traffic control measures	TCM	No regression. Normally included in the contract bid.
Vehicle accident damage	VAD	No regression. Uncertain event that may or not happen. Average value of claim can be applied to every road corridor.
Vehicle delays	VED	**Regression analysis performed with 3 variables: AADT, project duration and road length**
Pedestrian delays	PED	**Regression analysis performed with 3 variables: number of pedestrian per day, road width and project duration**
Vehicle maintenance and operations	VMO	**Regression analysis performed with 3 variables: AADT, project duration and road length**
Obstruction to emergency vehicle	OEV	No regression. Road closures do not necessarily have an impact on response time for emergency vehicles
II – LOCAL ECONOMY		
Parking revenue loss	PRL	**Regression analysis performed with 2 variables: number of on street paid-parking spaces and project duration**
Tax revenue loss	TRL	**Regression performed with 2 variables: property values and project duration**
Net business income loss	NBIL	No regression. It strongly depends on local regulations and policies to help business owners in various ways.
Property sale-and-rent loss	PSRL	**Regression performed for solely for property rent loss with 2 variables: number of apartment for rent beside the road corridor and project duration**
Productivity reduction	PR	**Regression analysis performed with 2 variables: total number of employees working beside the road corridor and duration of noise**
III – LIFE QUALITY		
Human life loss	HLL	No regression. Uncertain event that may or not happen.
Accidental injuries	AI	No regression. An average value based on records can be applied to every road corridor.
Service interruption	SI	**Regression analysis performed with 2 variables: number of households and duration of interruption. Bypass installation costs are normally included in the contract bid**
Resident noise discomfort	RND	No regression analysis. Works are usually performed during the day. Some people can function with a certain level of noise and others not.

IV – URBAN LANDSCAPE		
Property structural damage	PSD	No regression. An average value based on records can be applied to every road corridor.
Dirt and dust cleaning	DDC	**Regression analysis performed with 4 variables: number of business properties, number of non-business properties, total width of building facades to clean, project duration**
V – ADJACENT UTILITY		
Buried utility damage	BUD	No regression. An average value based on records can be applied to every road corridor. Uncertain event that may or not happen
Accelerated asset deterioration	AAD	No regression. Many competing factors involved.
VI – ECOLOGICAL ENVIRONMENT		
Air pollution	AP	**Regression analysis performed for vehicular emission costs with 3 variables: AADT, road length and project duration; and for machinery emission costs with 1 variable: road length**
Soil/Groundwater pollution	SGP	No regression. Case-by-case assessment.
Green amenity suppression	GAS	No regression. Willingness to accept compensation should be estimated.
Ecosystem restoration	ER	No regression. Case-by-case assessment.
VII – CLAIM MANAGEMENT		
Administrative burden	AB	No regression. Montreal Public Transport Agency estimates a cost of an average delay of 5 min per road work for each bus
Citizen claims	CC	No regression. An average value based on records can be applied to every road corridor.
VIII – CONSTRUCTION WORK		
Unforeseen work activities	UWA	No regression. Usually included in the contract bid for construction projects in Montreal
Urban landscape reinstatement	ULR	No regression. Usually included in the contract bid for construction projects in Montreal

5.4. SIMULATION OF COORDINATION SCENARIOS

This section deals with the simulation conducted to study different strategies of coordination of works among three types of assets: water, sewer and road segments. The decision support system InfraModex was used to simulate coordination strategies. The data came from the database of water, sewer and road networks that is prepared for producing the Intervention plan of the City of Montreal. As a first step, the simulation will generate individual work programs per asset types. Then these programs will be integrated in order to produce a coordinated work program for each strategy of coordination. The least cost strategy in terms of social and construction costs is selected.

5.4.1. Introduction

Simulations were conducted to study scenarios of coordination of works among buried pipes and road segments. Three scenarios of coordination were implemented in such a way that open-cut works (reconstruction) can only be performed when both pipe and road segments are due for a treatment. That is to say, open-cut reconstruction should not be performed individually for each type of assets. Therefore, the first scenario is to do road open-cut works when pipes are due for replacement, the second is to do pipe open-cut works when roads are due for reconstruction and the third one is a mixed of the first two scenarios (see Section 3.5). The goal is to select the strategy that will bring the best outcomes to the society in terms of total costs and levels of service.

5.4.2. Data

One particular district of the City of Montreal was used to run simulations. The selected district totalizes nearly 650 road segments (140 km), 3000 sewer segments from manhole to manhole (170 km) and 645 water segments from one road intersection to the other (100 km).

These segments came from the database used to produce the Intervention plan of water/sewer/road segments of the City of Montreal (see Appendix O). The database, which was built by a dedicated team of municipal engineers, had been formatted to be integrated in InfraModex for the production of the Intervention plan. In this research, the social cost module was added in InfraModex to run different coordination strategies.

5.4.3. Approach

The three coordination strategies that are analysed in this study are explained in the section 3.5. The overall approach of the simulation is described in section 2.5.2. The goal is to study the coordination scenario that will minimize the total (social plus construction) costs and maximize the levels of service. As a first step, a Monte-Carlo simulation is conducted by generating random values of probabilistic variables such as costs, treatment lifespan, etc., in order to produce individual work programs per asset types over a 150-year horizon planning. Then, the coordination rules will be applied to produce an integrated work program.

5.4.4. Results

The scenario analyses were performed by comparing the total costs and the impacts on the level of service (LOS). The total costs are divided into three: the renewal costs for CIPP or reconstruction, the repair costs for pipe and road deficiencies (breaks, defects, potholes, cracks, etc.), and the social costs for works. Note that social costs related to repair costs are not included, assuming a preventive maintenance leading to low impacts. The LOS for water mains is measured by the break rate (i.e. number of break per 100 km per year) and the LOS for sewer mains is measured by the structural condition grade (SCG, from Camera inspections). The LOS for roads is measured by the performance condition index (PCI from ASTM-D 6344 protocol). The evolution of LOS throughout the planning horizon stems from deterioration curves built by

Montreal engineers. Table 5.30 illustrates the total costs of all scenarios that are described in section 3.5, using the InfraModex decision support system.

Table 5.30: Present value of total costs over a 150-year planning horizon

Types of costs	**Scenario 1** *Roads await*	**Scenario 2** *Pipes await*	**Scenario 3** *Mixed*
Renewal costs	366 M$	330 M$	343 M$
Repair costs	9 M$	15 M$	13 M$
Sub-total	375 M$	345 M$	356 M$
Social costs	232 M$	195 M$	205 M$
Total costs	607 M$	540 M$	561 M$

The following observations can be outlined:

- Scenario 2 is the cheapest in terms of total costs whereas scenario 1 is the highest. Scenario 1 has the highest renewal costs because frequent resurfacing of roads until buried pipes are due for replacement becomes expensive at a long run, knowing that the pipe lifespan is more than four times higher than road's one. However, scenario 2 has the lowest social costs. Therefore, if the goal of the municipality is to reduce total costs, scenario 2 is the best. Scenario 2 is the highest in terms of repair costs because pipe repairs increase while waiting for the road reconstruction.
- Scenario 1 is the highest in terms of total costs. The road reconstruction is always synchronized with pipe replacement, therefore there is a lesser number of road reconstruction in comparison to scenario 2. Even though social costs of road reconstruction are much higher than social costs of road resurfacing, social costs in scenario 1 increase at long run because of a greater number of road resurfacing that is done before pipe replacement.

- Scenario 3 is slightly higher than scenario 2 and cheaper than scenario 1 because both strategies are mixed (see Section 3.5). Sometimes the road reconstruction waits for the pipe replacement and other times the pipe replacement waits for road reconstruction (in case of sewer replacement alone).

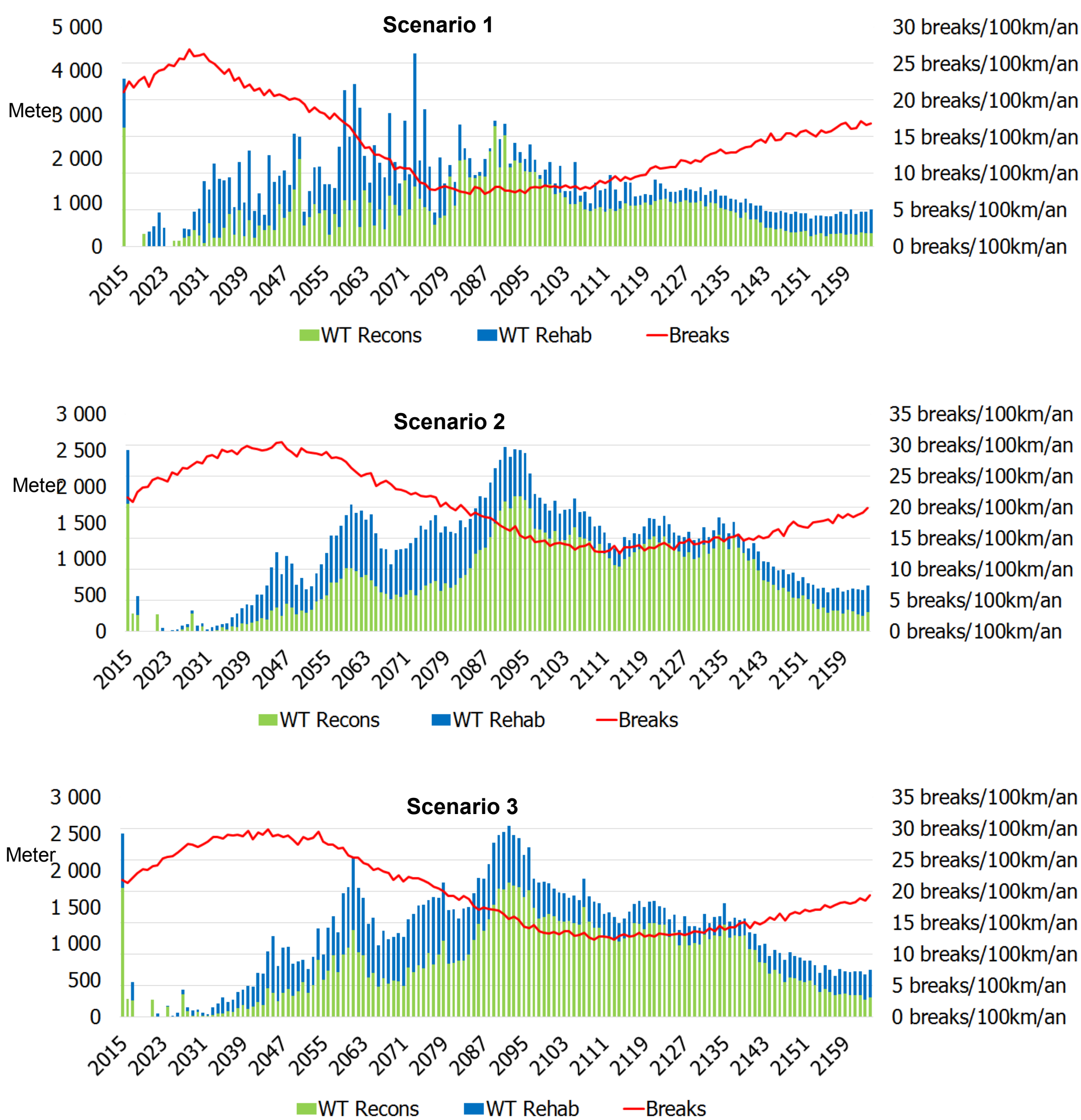

Figure 5.15 : Evolution of water main breaks over 150 years

In a nutshell, a mixed strategy is better in terms of total costs. Nevertheless, it is also important to analyze the scenarios in terms of levels of service (LOS). Figures 5.15, 5.16 and 5.17 show the evolution of LOS respectively for water, sewer and road. The left scale represents the meters of asset renewed (histogram bars) and the right scale the LOS (curves). Figure 5.15 illustrates that scenarios 2 and 3 offer the same LOS at short / long run. The break rate starts at 21 break/100 km/yr, then increases to almost 30 in 2050 before going down to a lowest rate of nearly 14. Scenario 1 offers the best LOS because more water mains are renewed at the beginning (4 km instead of 2.5 km for scenarios 2 and 3). The break rate starts at 21 break/100km/yr, and then increases to 25 in 2031 before going down to a lowest rate of 10. In a nutshell, scenario 1 offers better LOS than scenarios 2 and 3 because more treatments on water mains are done in scenario 1. Scenarios 2 and 3 postpone pipe treatments for coordination sake; thus, increasing risks of failure (increase of breaks). Scenario 1 is the best in terms of LOS for water pipes but the highest in terms of total costs whereas scenario 3 has lower total costs at the expense of diminishing LOS.

Figure 5.16 illustrates the evolution of the mean structural condition grade (SCG). SCG of 1 stands for an excellent condition whereas SCG of 5 for a very poor condition. The mean SCG is the average of the SCG of all sewer pipes. Scenarios 2 and 3 offer the same LOS at short and long run. The mean SCG starts at nearly 1.5, and then increases to almost 2 in 2050 before stabilizing at a rate of 1.5. For scenario 1, a few more sewers are renewed at the beginning (9 km instead of 8 km for scenarios 2 and 3) because more treatments on sewer mains are done in scenario 1. The mean SCG starts also at 1.5, and then increases to nearly 2 in 2050 before stabilizing at rate slightly under 1.5. Scenario 1 offers similar LOS for sewer pipes as scenarios 2 and 3 even though the latter scenarios postpone pipe treatments for coordination sake; thus, increasing risks of sewer defects.

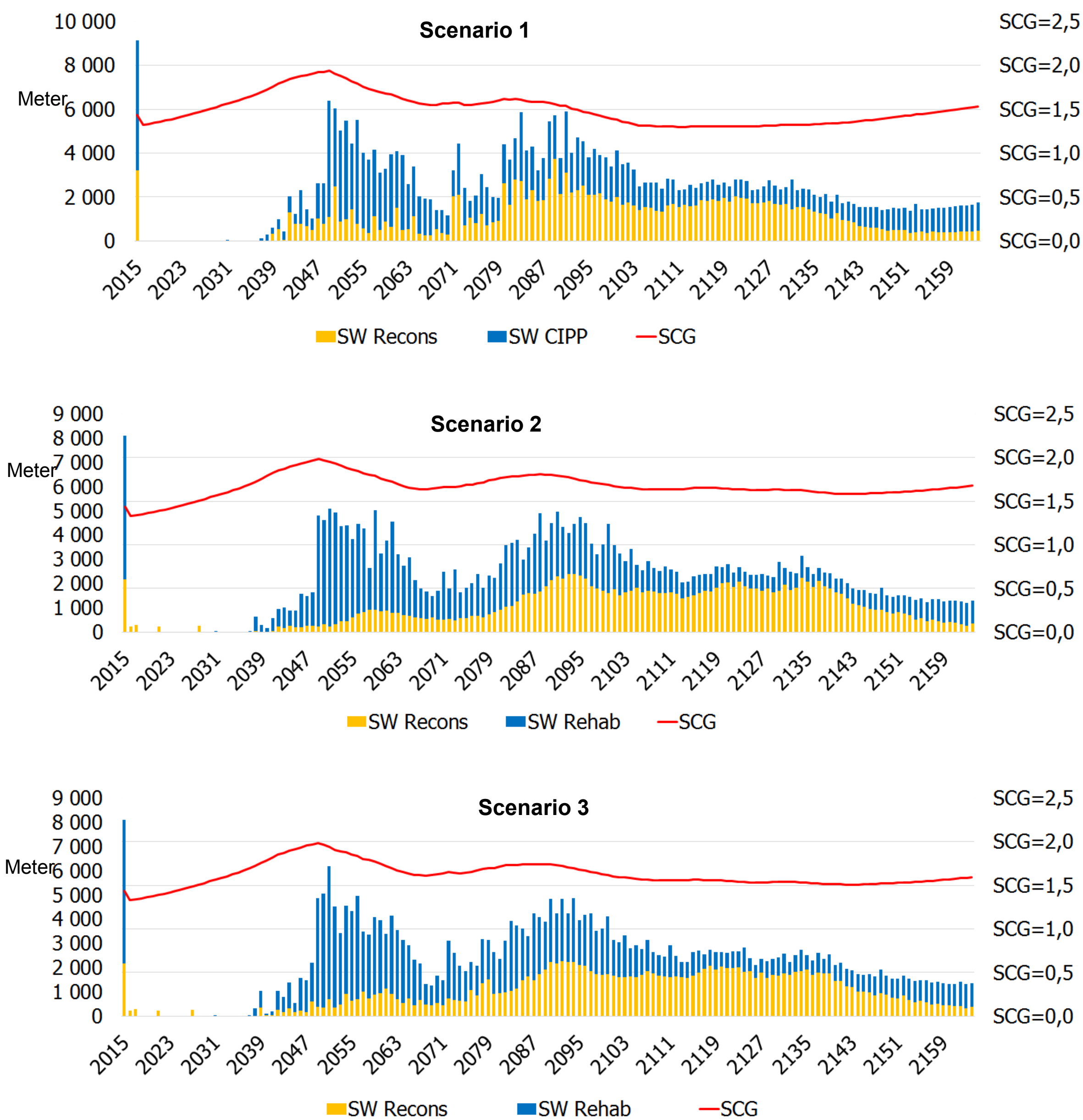

Figure 5.16 : Evolution of structural condition grade over 150 years

Figure 5.17 illustrates the evolution of the mean pavement condition index (PCI). The mean PCI is the average of all roads PCI where a PCI of 100 stands for an excellent condition and a PCI of 20 and less for a very poor road condition. The same amount of treatments is done at the beginning for all scenarios (80 km).

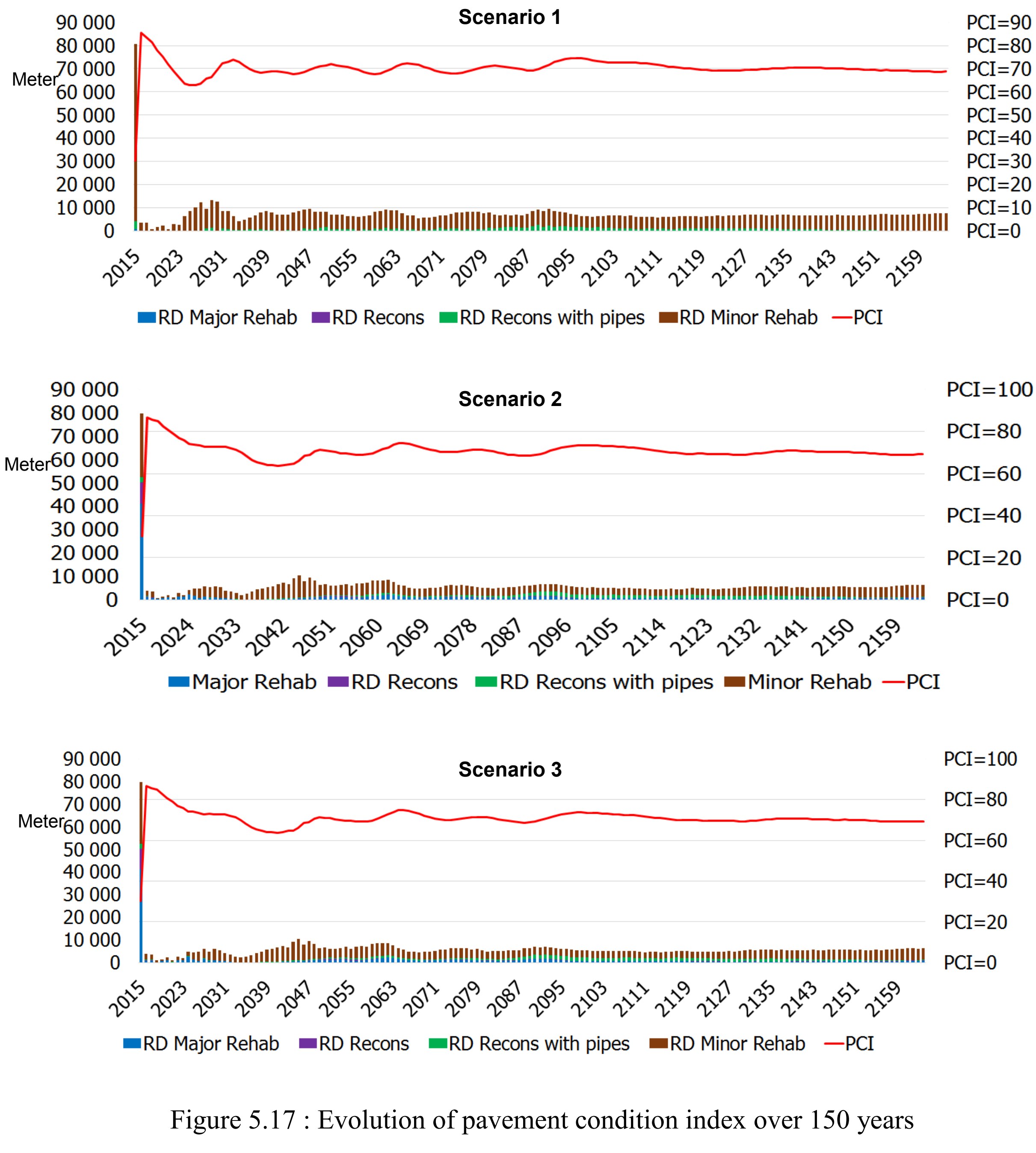

Figure 5.17 : Evolution of pavement condition index over 150 years

Road reconstruction synchronized with pipe replacement and road minor rehabilitation are the only types of treatments for scenario 1. Scenarios 2 and 3 add on road major rehabilitation and road reconstruction not synchronized with pipe replacement. So the average PCI is almost the same for all scenarios, even though the LOS for scenario 1 tends to decrease rapidly at the beginning as opposed to the other scenarios. The reason is minor rehabilitation / resurfacing has a very low lifespan. Also, more kilometers of treatments are done in scenario 1 because of a greater number of road resurfacing while waiting for pipe replacement. Scenarios 1 and 3 show more road reconstruction synchronized with pipe replacement. Therefore, the LOS for road condition is quite similar for all scenarios because resurfacing the roads while waiting for pipe replacement (in scenario 1) helps to keep an acceptable road condition. The differences in the LOS between scenarios are more tangible for water pipe assets. Table 5.31 shows a summary of advantages and disadvantages for all scenarios.

Table 5.31: Comparison of the three coordination scenarios

Scenario 1	Scenarios 2/3
Advantages	
• Decrease in repair costs	• Decrease in renewal costs • Decrease in social costs
Disadvantages	
• Increase in renewal costs • Increase in social costs	• Increase in repair costs

In conclusion, the integration of social costs in infrastructure renewal policies or decisions allows choosing policies that suit municipal goals. The policies are trade-offs between maximising the LOS, minimizing the total costs and the social costs. One type of scenario is not the best in overall: for instance, scenario 2 is the cheapest in total costs with lower LOS whereas scenario 1 is the highest in total costs with better LOS. The decision is up to the municipal planners to choose the scenario that brings the best outcome for the residents.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

6.1. CONCLUSIONS

This thesis developed regression curves to assess social costs related to municipal infrastructure works. This was achieved in three (3) first steps: specification of social cost indicators, prediction of social cost indicators through complex models and development of social cost regression curves. The last step consisted in integrating social costs in a decision support system (DSS) to optimize coordination of works. The four steps were successfully achieved during this study. Works are performed on solely three types of infrastructure assets: water, sewer and road lines. Social costs have been assessed for eighteen types of work packages and integrated in a DSS. The least-cost coordination scenario consists of mixing different strategies of renewals.

Work-related impacts are initially classified in twenty-seven indicators. The indicators already included in the contract bid are not assessed in this study: Traffic Control Measures (TCM), Unforeseen Work Activities (UWA) and Urban Reinstatement Landscape (URL). The indicators with unpredictable features during works are assessed but no regression curve was developed: Administrative Burden (AB), Accelerated Asset Deterioration (AAD), Resident Noise Disruption (RND), Net Business Income Loss (NBIL) and Obstruction to Emergency vehicle (OEV). For some indicators, an average cost value is provided for all types of works: Accidental Injuries (AI), Property Structural Damage (PSD), Citizen Claims (CC), Vehicle Accident Damage (VAD) and Buried Utility Damage (BUD), based on the analysis of municipal records. In fact, these events are random and don’t always occur during works. Finally, some indicators can only be assessed after works: Soil and Groundwater Pollution (SGP), Human Life Loss (HLL), Green Amenity Suppression (GAS) and Ecosystem Restoration (ER).

Therefore, only ten significant indicators are retained for regression analyses: Vehicle Delays (VED), Pedestrian Delays (PED), Vehicle Maintenance and Operations (VMO), Parking Revenue Losses (PRL), Tax Revenue Losses (TRL), Property Sale-and-Rent Losses (PSRL), Productivity reduction (PR), Service Interruption (SI), Dirt and Dust Cleaning (DDC) and Air Pollution (AP). It should be noted at this stage that TRL can be used as a proxy for NBIL. These ten indicators are prevalent in work-related impacts.

The collection of data was fastidious given the large volume of information processed to feed regression models. Three kinds of data are necessary: hard data that are straightforwardly collected from different data repositories, soft data that are computed on basis of different assumptions, and finally data that are obtained through literature, interviews and reports. Therefore, a data dictionary and a data model were proposed to collect and save the information for assessment purposes. The data integration in the road corridors was made possible through spatial requests on GIS-data layers from different sources. Therefore, a common key identifier, which is the road identification number, was linked to all data layers.

This research demonstrates that social cost indicators related to infrastructure works can be modeled by regression curves, thus enabling to assess social costs at a large scale with a few parameters. This research cuts the large number of needed variables to fourteen key variables that municipal planners should collect in order to predict social costs: AADT (annual average daily traffic), project duration, road length, sidewalk width, number of business properties, number of non-business properties, property values, number of households, number of employees, number of on-street paid parking spaces, number of pedestrian, number of apartments for rent, total building facade width and noise duration. Note that the vehicle traffic density for each type of vehicle can be estimated by the AADT. The following conclusions can be stated from this research:

- Generally, the project duration follows an exponential law, the length of the road follows a power law and the vehicle traffic density follows a linear law with respect to social costs.
- VED costs depend on three main variables: the vehicle traffic density, the road length and the project duration. VED costs increase along with the vehicle traffic density. They are lesser for partial than complete road closure. The presence of heavy trucks can significantly increase VED costs.
- PED costs depend on three main variables: the number of pedestrian per day, the sidewalk width and the project duration. PED costs are lesser for partial than complete sidewalk closure.
- VMO costs depend on three main variables: the vehicle traffic density, the road length and the project duration. VMO costs are lesser for partial than complete road closure. The presence of buses and heavy trucks can significantly increase VMO costs.
- PRL depend on two main variables: the number of on-street paid parking spaces and the project duration. The higher the tariff zones, the higher the PRL. The number of on-street paid parking spaces follows a linear law with respect to PRL costs.
- TRL depend on two main variables: the property value per class of buildings and the project duration. TRL can be used as willingness-to-pay for business losses. The

commercial streets bear higher losses than residential or institutional streets. The property value follows a power law with respect to PRL costs.

- PSRL depend on two main variables: the number of apartments and the project duration. The number of apartment follows a linear law with respect to PSRL costs.
- PR costs depend on two main variables: the number of employees and the project duration. The number of employees follows a linear law with respect to PR costs. Commercial and institutional streets bear higher PR costs than residential ones.
- SI costs depend on two main variables: the number of employee and the project duration. The SI costs of bypass installation are already included in the contract bid. It remains the costs borne by residents for water service interruption. The number of households follows a linear law and the duration of interruption follows a power law with respect to SI costs.
- DDC costs depend on four main variables: the number of commercial buildings, the number of non-commercial buildings, the total facade width to be cleaned and the project duration. DDC costs are higher for commercial buildings. The number of buildings follows a linear law and the surface of the building facade follows an exponential law with respect to DDC costs.
- AP costs depend on two main variables: the type of works and the road length. Open-cut works are generally bundled together and thus bear higher AP costs.
- The optimization of the coordination of works consists in trade-off analyses between minimizing total costs and maximizing the levels of services (LOS). The reason is that the least total cost scenario has the lowest LOS. Therefore, municipal planners should clearly set their objectives whether maximizing LOS with cost constraints or minimizing costs with LOS constraints.

6.2. RESEARCH CONTRIBUTIONS

This project achieved the following:

- The time of the day and the day of the week play a major role in social cost assessment. These variables are considered in the developed regression models. For instance, impacts at nighttime and evening are lesser than during peak hours.
- Social costs were studied at macro scale for an entire road network and for eighteen different work packages, which include different treatments (of open-cut reconstruction or trenchless rehabilitation) on various asset types. Moreover, road status during works whether partially or completely closed is a key parameter for some indicators.
- Data dictionary and model are proposed for collecting and processing information on different variables. This information is useful to build the regression curves for a sample of streets. Once the regression curves are developed, solely fourteen significant variables should be collected to assess social costs at macro level.
- Attention is given to compensations and tax rebates. From a municipal point of view, compensations are internal costs that neutralize or reduce impacts; whereas from a society point of view, they are transfer costs that should not be considered in the analysis because a transfer was made from one party (cost for municipality) to another (gain for businesses) within the society.
- This research should enable municipal planners to estimate the true cost of projects, which is the renewal cost plus the social cost. Moreover, the incorporation the social costs in a decision support system was tested and revealed the trade-offs between optimizing total and social costs and levels of service (LOS):

- Avoiding open-cut road reconstruction until a buried pipe is scheduled for replacement is a coordination scenario that leads to the highest total costs and the best LOS.
- Avoiding pipe replacement until the road is scheduled for reconstruction is a coordination scenario that leads to the lowest total costs and the lowest LOS. This is because of the increase of pipe failures.
- A scenario of coordination mixing both of the aforementioned strategies leads to an in-between solution with lower total costs and acceptable LOS.

6.3. RESEARCH LIMITATIONS

The developed regression curves can be applied to all road networks. However, the estimation of regression parameters should be calibrated per the studied networks. The regression parameters in this research are adapted to the City of Montreal road networks.

- The assessment of vehicle and pedestrian delays use a predetermined value of time lost in traffic (VOT) set at a fixed rate per the type of vehicle (business and non-business), the time of the day and the day of week. The change in VOTs implies rebuilding the regression curves.
- Regression curves are based on fixed conditions (for example, parking meter cost, productivity reduction factor, volumetric emission costs, street levels of service, vehicle operating costs, etc.) and thus are invalid whenever these conditions change.
- The coordination of works through the DSS within a road corridor can be scheduled for a specific timing. However, in practice, many elements can change the proposed timing, such as municipal events (marathon, street sales, etc.), uses of the corridor as a detour route because of works in a neighbouring site, major projects in the vicinity of the corridor

(demolishing a bridge, etc.), and city development projects, etc. All these elements lead to postpone or delay works and can barely be taken into consideration in a DSS for now.

- Solely three types of assets are considered: water, sewer and road lines, even though road works can also involve other assets such as buried gas and electrical lines.
- The intangible costs are economic costs, which represent the value that people place on what they lost.

6.4. RECOMMENDATIONS FOR FUTURE WORKS

The ability to assess social costs opens the door to further in-depth investigation on work-related impacts at the academic level for research enhancements, as well as at the governmental level for research extensions.

6.4.1. Research enhancements

- The regression curves for productivity reduction (PR) can be developed per the kind of streets: commercial, industrial, institutional and mixed. In this study, PR regression curves are built for all streets; but the productivity reduction factor depends on the type of buildings (low for industry, mean for institution and high for commerce). For future, it will be more accurate to develop PR curves per kind of streets whether industrial, institutional or commercial. Nonetheless the PR curve built in this study can be used for mixed streets.
- Uncertain input variables can be assigned with probability distributions, thus allowing taking into consideration risks of estimation. Knowing the regression curves, a probability distribution can be assigned to regression variables such as Vehicle traffic density (VTD), Number of employees, etc., to build probability distributions of social costs; thus, allowing knowing the probability of occurrence of a social cost value.

- The value of time lost in traffic (VOT) is a very controversial value. Therefore, different regression curves can be modeled for different VOT to perform sensitivity analysis on the matter. VOT was set in this study per the time of the day and the day of the week, at a fixed rate for both business and non-business vehicles. Given that VOT is a critical value for vehicle delay costs, for further investigations, different regression curves for different VOT values should be built to pick the best curve adapted to the road corridor.
- The integration of social costs was tested in this study to optimize scenarios of coordination of works among various infrastructure assets within the same corridor. For further developments, the coordination decision tree can be tested to include the possibility of advancing works (see Appendix P). For instance, instead of doing palliative works or repairs on asset A while waiting for the replacement of asset B, a premature replacement of asset B can be done by searching for the optimal period of time (in years) where works can be advanced.
- Trade-off analyses between maximizing the levels of service (LOS) and minimizing both social and total costs of municipal projects should be studied in-depth. Different optimization scenarios with constraints can be compared such minimizing total costs with LOS constraints or maximizing LOS with budget constraints.

6.4.2. Research extensions

- Federal, provincial and municipal can carry out studies on a new classification of roadways with the consideration of social costs. Now, the road classification is based upon their function (arterial, collector, local, etc.) or their character (commercial, industrial, institutional, etc.) but levels of social cost impacts in the road hierarchy can be incorporated as well.

- Public Works and Government Services Canada (PWGSC) can address studies on new methods of bid selection that integrate work-related social costs, for example, studies on penalty fees to contractors delaying works in terms of social costs per day and studies on choosing tenders that offer the lowest costs in terms of social plus construction costs.
- Municipal governments should conduct studies on the mitigation of work impacts by giving compensations, subsidies and tax rebates for business owners based on social costs; thus allowing fair amounts of money given to affected parties to alleviate their losses. Likewise, studies on road toll charges to prevent people from going through a particular construction zone can be carried on as well.

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APPENDICES

The average annual daily traffic (AADT) was obtained from the Montreal Department of Transportation for a large number of connection nodes (road intersections). The AADT represents the typical daily traffic on a road segment for all seven days of the week over one-year period and accounts for total volume of traffic for one year divided by 365 days.

The collected AADT are factored twice in order to take into account both weekly and daily variations of traffic volumes. Therefore, the estimates of typical traffic volumes for each day of the week are obtained by factoring the AADT with Day Factors illustrated in Table A1.

TABLE A1: Day Factors for all seven days of the week

Days	ID.Day	Day Factor
Sunday	1	0.7077
Monday	2	1.0130
Tuesday	3	1.0646
Wednesday	4	1.0779
Thursday	5	1.1138
Friday	6	1.1212
Saturday	7	0.9018
	Total	7.0000

The average traffic for each day of the week (ATDW) is illustrated in Figure A1. We observe that the traffic volumes tend to decrease over the weekend days and vary a little during weekdays.

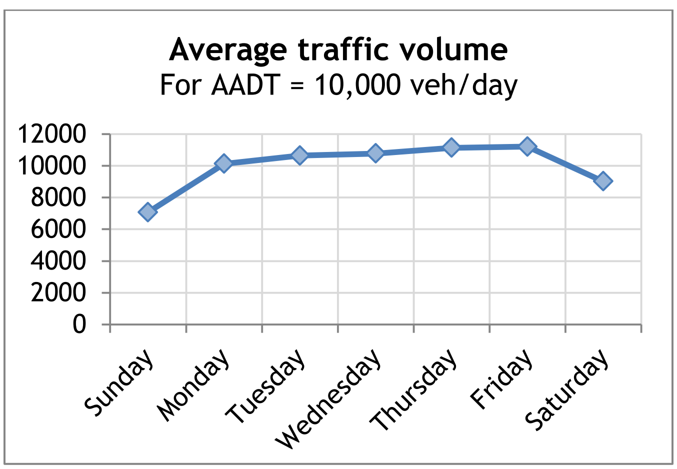


FIGURE A1: Montreal Traffic Volume Day Pattern (City of Montreal)

The estimates of typical traffic volumes for each hour of the day are assessed by factoring ATDW with the Hour Factors illustrated in Table A2.

TABLE A2: Hourly rate factors (City of Montreal)

Hours	ID.Hour	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday/ Sunday[(1)]
00:00	0	0.2952	0.3020	0.3384	0.4073	0.4224	0.3531
01:00	1	0.1478	0.1587	0.1716	0.1982	0.2367	0.1826
02:00	2	0.1081	0.1097	0.1113	0.1371	0.1805	0.1293
03:00	3	0.1052	0.1041	0.1002	0.1307	0.1568	0.1194
04:00	4	0.1185	0.1282	0.1217	0.1461	0.1621	0.1353
05:00	5	0.3406	0.3571	0.3486	0.3394	0.3575	0.3486
06:00	6	1.0911	1.1550	1.1767	1.0799	1.0064	1.1018
07:00	7	1.6848	1.7492	1.7213	1.5841	1.4764	1.6432
08:00	8	1.7246	1.7843	1.6712	1.5663	1.4923	1.6477
09:00	9	1.2947	1.3334	1.2337	1.1848	1.1618	1.2417
10:00	10	1.2233	1.1913	1.1479	1.1227	1.1330	1.1636
11:00	11	1.2564	1.2136	1.1841	1.1781	1.2050	1.2074
12:00	12	1.2526	1.1814	1.1306	1.1488	1.1868	1.1800
13:00	13	1.3609	1.2864	1.2528	1.2343	1.2845	1.2838
14:00	14	1.4295	1.3880	1.3477	1.3129	1.3976	1.3751
15:00	15	1.5360	1.5109	1.4476	1.4841	1.5381	1.5033
16:00	16	1.7058	1.6880	1.6243	1.6407	1.6279	1.6573
17:00	17	1.6903	1.6577	1.6046	1.6273	1.4834	1.6127
18:00	18	1.3228	1.3426	1.2907	1.3015	1.2330	1.2981
19:00	19	1.1091	1.1067	1.1512	1.2955	1.2825	1.1890
20:00	20	0.9027	0.9253	1.0297	1.1041	1.1048	1.0133
21:00	21	0.8400	0.8448	1.0279	1.0811	1.1001	0.9788
22:00	22	0.8237	0.8220	0.9995	0.9407	0.9405	0.9053
23:00	23	0.6363	0.6593	0.7665	0.7539	0.8300	0.7292
	Total	24.000	24.000	24.000	24.000	24.000	24.000

[(1)] It should be noted that for Saturday and Sunday, the Hourly Rate Factors were not available; therefore, we assessed them as the mean of the weekday values (Monday to Friday).

For example, the traffic volume from 8:00 a.m. to 8:59 a.m on a roadway segment with an AADT of 10,000 veh/day on Wednesday is 750 veh (= 10,000 x 1.0779 x 1.6712 / 24).

The average traffic for each hour for weekdays (Monday to Friday) is illustrated in Figure A2. This profile reveals that traffic volumes are very low during the night, then increase (morning peak hours) and decrease slightly before rising again (afternoon peak hours), and finally decrease. Therefore, we discretize the 24 hours of the day into 6 major periods as portrayed in Table A3. These periods are used in the models in order to set different values of time lost in traffic delays (VOT) due to construction works.

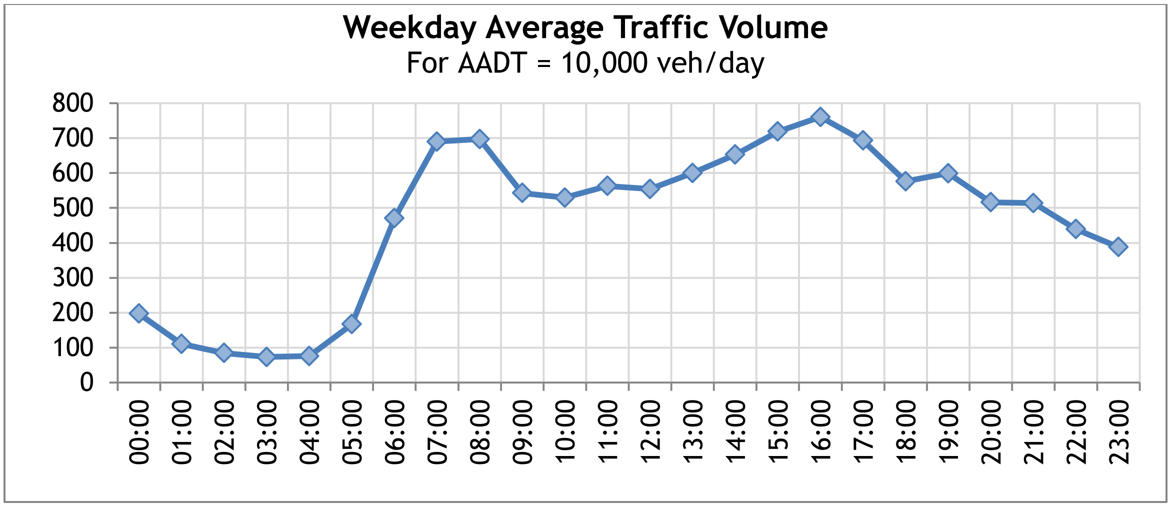


FIGURE A2: Montreal average traffic flow rate (City of Montreal)

TABLE A3: Proposed discretization of 24 hour-day period

	Night	Morning	Morning peak hours	Midday	Afternoon peak hours	Evening
From	00:00 a.m.	06:00 a.m.	07:00 a.m.	09:00 a.m.	04:00 p.m.	06:00 p.m.
To	05:59 a.m.	06:59 a.m	08:59 a.m.	03:59 p.m.	05:59 p.m.	11:59 p.m.
Total	6 hours	1 hour	2 hours	7 hours	2 hours	6 hours

From each period, we can estimate the Hourly Rate Factor for a Period as the product of the Day Factor and the sum of all Hour Factors of the period, divided by 24. For example, the Hourly rate Factor for the Night on Monday is set at the value of 0.0470 (=0.0130*(0.2952+0.1478+0.1081+0.1052+0.1185+0.3406) / 24). Finally, the Hourly rate Factors for a period on weekdays are estimated as the mean value of the five days (from Monday to Friday). Therefore, we deducted Traffic Volume Factors that will be used in the models to compute traffic volumes per periods of day and of week as illustrated in Table A4.

TABLE A3: Traffic Volume Factors used in models

	Weekday	Saturday	Sunday
Night	0.0572	0.0477	0.0374
Morning	0.0495	0.0414	0.0325
Morning peak hours	0.1476	0.1237	0.0970
Midday	0.4019	0.3365	0.2641
Afternoon peak hours	0.1468	0.1229	0.0964
Evening	0.2752	0.2297	0.1803

For example, the traffic volumes during morning peak hours on both weekdays and Saturday are expressed respectively as 0.1476 x AADT and 0.1237 x AADT.

Table A4 shows the Month Factors used to estimate monthly traffic volume from AADT. They were not used in this research because we cannot at this stage anticipate months when works are going to be performed.

TABLE A4: Month Factors for one year period (City of Montreal)

Month	ID.Month	Month Factor
January	1	0.91217
February	2	0.91866
March	3	0.99733
April	4	0.99184
May	5	1.03250
June	6	1.05136
July	7	0.91927
August	8	1.00272
September	9	1.03752
October	10	1.05268
November	11	1.05665
December	12	1.02730
	Total	12.0000

Appendix B – Modal Share of Vehicles in circulation

The typology of vehicles in circulation can be grouped into four classes: automobiles, light trucks, heavy trucks and buses (MTQ, 2013). The SAAQ (Société de l'Assurance Automobile du Québec) produces every year a report on vehicle volumes authorized to circulate on Montreal Island jurisdiction as illustrated in Table B1 for 2013.

TABLE B1: Montreal Island Vehicles in circulation (adapted from SAAQ)

Vehicle Types	Numbers in 2013	Adjusted typology
Non-business	**750,437**	
Automobile	523,987	Automobile
Light truck	205,981	Light truck
Automobile et light truck [(1)]	92	Automobile
Others	20,377	-
Business	**143,824**	
Automobile	39,611	Automobile
Light truck	63,129	Light truck
Automobile et light truck [(1)]	53	Automobile
Taxi	3,260	Automobile
Regular bus	2,378	Bus
School bus	1,028	Bus
Heavy truck	24,319	Heavy truck
Others	10,046	-
Restricted	**946**	-
Off network	**21,458**	-
Total	916,665	863,838

[(1)] Undistinguished, but considered as automobile by default in this study

The Modal Shares resulting from Table B1 are illustrated in Table B2. They were expressed as the percent of the total volume for each vehicle type existing in the adjusted typology.

TABLE B2: Modal Shares of vehicle volumes in circulation

	Non-business	Business
Automobile	60.67 %	4.97 %
Light truck	23.84 %	7.31 %
Heavy truck		2.82 %
Bus		0.39 %

For example, let us consider a 700 m road segment of class IV with AADT of 10,000 veh/h undergoing a 3-week reconstruction, with a partial closure allowing vehicles to go through the work zone

a) Traffic volume per period

TVPP = Traffic volume factor (in Table A3) x AADT

	Weekday	Saturday	Sunday
Night	572	477	374
Morning	495	414	325
Morning peak hours	147.6	123.7	970
Midday	401.9	336.5	264.1
Afternoon peak hours	146.8	122.9	964
Evening	275.2	229.7	180.3

b) Traffic volume per period per type of vehicle

TVPPPTOV = TVPP x Modal shares (in Table B2)

Weekday[1]	Total	Auto		Light truck		Heavy truck	Bus
		Non-bus.	Bus.	Non-bus.	Bus.		
Night	572	347	28	136	42	16	2
Morning	495	300	25	118	36	14	2
Morning peak hours	1476	895	73	352	108	42	6
Midday	4019	2438	200	958	294	113	16
Afternoon peak hours	1468	891	73	350	107	41	6
Evening	2752	1670	137	656	201	78	11

[1] This should be done for Saturday and Sunday as well.

Appendix C – Traffic delays due to construction works

Traffic delays are assessed for two work zone configuration: partial and complete closure of road segment. Partial closure allows vehicles to go through the work zone contrarily to complete closure.

1. Partial closure

The traffic delay resulting from construction works represents the average additional travel time needed to travel from one point to another. This does not include existing delays. The estimation of delays can be performed with the help of traffic simulation tools. Without simulation models, macroscopic analytical approaches are still used to determine traffic delays as the difference between travel time on a road segment without works and the actual longer travel time in work zones (Weng & Meng, 2013). These approaches are mostly deterministic and does not take into account : 1) speed-reduction delays caused by the deceleration and acceleration maneuvers and 2) queuing or congestion delays due to queue formation at upstream of the work zone when traffic flow exceeds work zone capacity.

In general, before entering the work zone area, vehicles decelerate, which result in decelaration delays. Then vehicles travel through the work zone at the reduced speed, which result in speed-reduction delays. Very often, congestion is formed at work zone area whether the traffic flow is lower than the work zone capacity or not, which result in delays due to queue formation. Finally, vehicles accelerate to their original speed after exiting the work zone, which result in acceleration delays.

Jiang (2001) proposed mathematical models to assess total traffic delays per vehicle at freeway work zones in hour i as follows:

- Under uncongested traffic conditions

$$\Delta T = F_{ai}.(\Delta T_d + \Delta T_{sr} + \Delta T_w + \Delta T_a) \qquad [1]$$

- Under congested traffic conditions, which occurs when the traffic flow exceeds the work zone capacity

$$\Delta T = F_{ai}.(\Delta T_d + \Delta T_{sr} + \Delta T_a) + \Delta T_{qi} \qquad [2]$$

Where

F_{ai}: Flow rate of arrival vehicles at hour i (veh)

ΔT_d: Delay due to deceleration (h)

ΔT_{sr}: Delay due to speed reduction (h)

ΔT_w: Delay due to queue formation in uncongested traffic conditions (h)

ΔT_a: Delay due to acceleration (h)

ΔT_{qi}: Delay due to queue formation in congested traffic conditions (h)

The following models expressed abovementioned delays per vehicle.

$$\Delta T_d = \frac{2.L}{V_n + V_w} - \frac{L}{V_n} \qquad [3]$$

$$\Delta T_{sr} = L.\left(\frac{1}{V_w} - \frac{1}{V_n}\right) \qquad [4]$$

$$\Delta T_w = \frac{F_a}{F_c.(F_c - F_a)} \qquad [5]$$

$$\Delta T_{qi} = \frac{Q_{i-1}^2}{2.(F_d - F_{ai})} \qquad [6]$$

$$\Delta T_a = \frac{(V_n - V_w)^2}{2.A.V_n} \qquad [7]$$

Where

L: Road segment length (km)

V_n : Vehicle average speed under normal condition (km/h)

V_w : Vehicle average speed under work condition (km/h)

F_a : Flow rate of arrival vehicles

F_c : Flow rate in the work zone

Q_{i-1} : Vehicle queue at the end of hour i-1

F_d : Vehicle queue-discharge rate (i.e. flow rate of exiting vehicles)

A : Average acceleration (km/h^2)

Very often, construction works are carried out on a road segment from one signalized intersection to another. In this research, we neglect both delays due to queue formation and acceleration. Therefore, travel delays are expressed as follows:

$$\Delta T = \Delta T_d + \Delta T_{sr} = \frac{2.L}{V_n + V_w} - \frac{L}{V_n} + L.\left(\frac{1}{V_w} - \frac{1}{V_n}\right) \qquad [8]$$

Furthermore, traffic demand (in vehicle per hour, vph) varies according to time of the day such as rush hours, off-peak hours, etc. A systematic method is proposed to assess vehicle speeds using levels of service (LOS) for urban streets as displayed in Table C1.

For instance, a road segment in the district of Le Plateau-Mont Royal is classified IV when the vehicle free-flow average speed ranges from 40 to 55 km. For each time of the day (see Table A3), we determine V_n by using the appropriate LOS as well as V_w, as set in Table C2. Vehicle speeds matching with LOS are available in Table C1.

TABLE C2 : Systematic preselection of LOS

Flow conditions	Normal	Work zone	
Road closure status		Partial	Complete
Time of the day	V_n	V_w	V_d
Night	A	A	B
Morning	C	E	D
A.M. peak hours	D	F	E
Midday	B	D	C
P.M. peak hours	D	F	E
Evening	B	D	C

A reasonable assumption for the speed through the work zone is to drop from at least one level the LOS in normal conditions, except for night. In the previous exemple, in case of a partial closure of the road segment, the average vehicle speed during a.m. peak hours at the work zone is 16 km/h (ranging from 14 to 18 km/h) instead of 27.5 km/h (ranging from 23 to 32 km/h) in normal conditions.

TABLE C1: LOS for urban streets (HCM, 2000)

Urban street class	I	II	III	IV
Free-flow speed range (FFS)	70 - 90 km/h	55 - 70 km/h	50 - 55 km/h	40 - 55 km/h
Typical FFS	80 km/h	65 km/h	55 km/h	45 km/h
LOS	Average travel speed (km/h)			
A	> 72	> 59	> 50	> 41
B	> 56-72	> 46-59	> 39-50	> 32-41
C	> 40-56	> 33-46	> 28-39	> 23-32
D	> 32-40	> 26-33	> 22-28	> 18-23
E	> 26-32	> 21-26	> 17-22	> 14-18
F	≤ 26	≤ 21	≤ 17	≤ 14

** Note 1: In case of partial closure, some vehicles normally going through the work zone can take detours. In this research, we choose to assess delays as if all vehicles are passing through work zone.

2. Complete closure

When traffic is detoured to an alternative route, delays caused by travel route lengthening can occur. They are assessed as the difference between travel times on normal and detour routes.

$$\Delta T_{detour} = \frac{L_d}{V_d} - \frac{L}{V_n} \qquad [9]$$

Where

L_d : Detour road segment length (km)

V_d : Vehicle average speed on alternate or detour road (km/h)

Moreover, the additional demand that is placed on the alternative route can result in exceeding the available capacity and thus in delays due to queue formation. Equations [5] and [6] can be used to assess these delays respectively under uncongested and congested traffic conditions. However, in this research, we neglect them, as well as delays due to acceleration (Equation [7]). We solely consider detour delays in case of complete closure of the road segment.

** Note 2: V_d is preselected for complete closure (see Table C2). In general rule, roads whether arterial or local are detoured on alternate roads of the same kind in order to provide the same LOS. However, we choose to set V_d at one lower level than V_n, except for night, to take into account potential speed reduction due to the higher capacity.

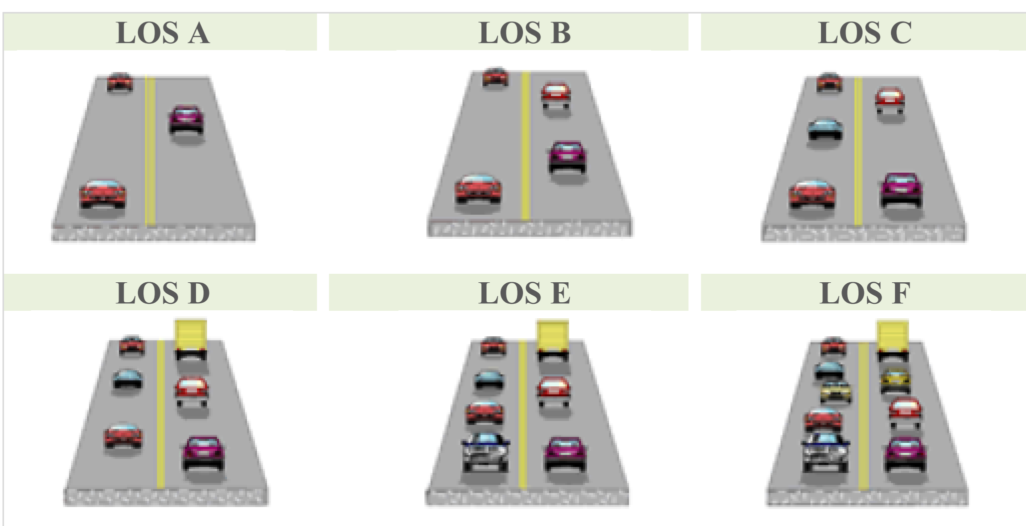


FIGURE C1: LOS for road segments (Courtesy of Polytechnic School of Montreal)

For example, let us consider a 700 m road segment of class IV with AADT of 10,000 veh/h undergoing a 3-week reconstruction, with a partial closure allowing vehicles to go through the work zone

a) Vehicle speed before and during works

Average V_n (see Table C1) ➔ corresponding LOS (see Table C2, average values)

	Normal conditions		Work conditions	
	LOS	Average V_n	LOS	Average V_w
Night	A	48	A	48
Morning	C	28	E	16
Morning peak hours	D	21	F	7
Midday	B	37	D	21
Afternoon peak hours	D	21	F	7
Evening	B	37	D	16

b) Traffic delays per vehicle

$\Delta T = \Delta T_d + \Delta T_{sr}$ (see Equation 8)

	Average ΔT	
	Hour	Min
Night	0.000	0.0
Morning	0.026	1.5
Morning peak hours	0.083	5.0
Midday	0.020	1.2
Afternoon peak hours	0.083	5.0
Evening	0.032	1.9

Appendix D – Value of time

The value of time lost in traffic (VOT) is a critical factor in evaluating delay costs. It must be assessed as the driver's Willingness-to-pay (WTP) to reduce travel time. In fact, time saved from travel can be dedicated to work, leisure or other activities for which individuals are willing to pay, and can prevent from unpleasant trips involving irritation, fatigue and discomfort. More often, stated preference methods are employed to assess travelers' willingness to pay to save time, even though they are subject to unrealistical answers from respondents. Different factors have been studied in estimating VOT:

- *Trip purpose*: commuting (home-school, home-work), leisure, personal and business trips, etc. However, if the traveler is willing to pay to spend more time traveling, VOT could be actually negative.
- *Personal characteristics*: drivers vs. passengers, parents vs. children. Without the knowledge of both the travel composition and motive, it must be assumed that all travelers' VOT are independent and additive (Belensky, 2011).
- *Hourly income*: median vs. mean value, household income vs. wage for all occupations. Differentiating VOT on the basis of travelers' incomes is difficult.
- *Transport mode*: automobile vs. buses.

In this reseach, two groups of trip purpose (non-business and business trips) and four types of transport mode (automobile, light truck, heavy truck, bus) are studied.

1. Business trips

For all business vehicles (see Table B.2) except for buses, we use VOT for business trips which is commonly agreed to be equal the gross hourly cost of employment (with a range of 80 to 120 % to reflect uncertainty). No distinction is made for freight trucks often greatly affected by changes in travel time. In reality, their VOT should be a function of: labor costs of vehicle operators, operating costs of vehicles, types of products (whether they spoil over time such as food) and production processes at the destination (whether they depend upon timely delivery).

2. Non-business trips

For all non-business vehicles, we use VOT for non-business trips which is equal to the price of a cup of coffee as a WTP for waiting time. In fact, travelers that are uncertain about their travel time typically include a "buffer" in their schedules, thus leaving early and sacrificing a known amount of time at the origin to insure against a more costly delay in arriving at the destination (Belensky, 2001). We assume that travelers in non-business vehicles (see Table B.2) including for buses are involved in non-business trips.

TABLE D.1: VOT used for automobiles

VOT	Non-business trips			Business trips		
	Weekday	Saturday	Sunday	Weekday	Saturday	Sunday
Night	0	0	0	0	0	0
Morning	1.5	1.5	1.5	17.6	17.6	17.6
Morning peak hours	1.5	1.5	1.5	17.6	17.6	17.6
Midday	1.5	1.5	1.5	17.6	17.6	17.6
Afternoon peak hours	1.5	1.5	1.5	17.6	17.6	17.6
Evening	1.5	1.5	1.5	17.6	17.6	17.6

TABLE D.2: VOT used for light trucks

VOT	Non-business trips			Business trips		
	Weekday	Saturday	Sunday	Weekday	Saturday	Sunday
Night	0	0	0	0	0	0
Morning	1.5	1.5	1.5	17.6	17.6	17.6
Morning peak hours	1.5	1.5	1.5	17.6	17.6	17.6
Midday	1.5	1.5	1.5	17.6	17.6	17.6
Afternoon peak hours	1.5	1.5	1.5	17.6	17.6	17.6
Evening	1.5	1.5	1.5	17.6	17.6	17.6

TABLE D.3: VOT used for heavy trucks

VOT	Business trips		
	Weekday	Saturday	Sunday
Night	0	0	0
Morning	17.6	17.6	17.6
Morning peak hours	17.6	17.6	17.6
Midday	17.6	17.6	17.6
Afternoon peak hours	17.6	17.6	17.6
Evening	17.6	17.6	17.6

TABLE D.4: VOT used for buses

VOT	Non-business trips		
	Weekday	Saturday	Sunday
Night	0	0	0
Morning	1.5	1.5	1.5
Morning peak hours	1.5	1.5	1.5
Midday	1.5	1.5	1.5
Afternoon peak hours	1.5	1.5	1.5
Evening	1.5	1.5	1.5

For example, let us consider a 700 m road segment of class IV with AADT of 10,000 veh/h undergoing a 3-week reconstruction, with a partial closure allowing vehicles to go through the work zone

a) Traffic delay costs

$$TDC_{weekday} = 15\ days \times (\Sigma_{period}\ \Delta T \times (\Sigma_{type\ of\ vehicle}\ Average\ passenger\ occupancy \times (\Sigma_{type\ of\ trip}\ TVPPPTOV \times VOT)))$$

3-weeks of works ➔ 15 weekdays, 3 Saturdays and 3 Sundays

Weekday[(1)]	**ΔT**	TVPPPTOV					
		Auto		Light truck		Heavy truck	Bus
		Non-bus.	Bus.	Non-bus.	Bus.		
Night	0.000	347	28	136	42	16	2
Morning	0.026	300	25	118	36	14	2
Morning peak hours	0.083	895	73	352	108	42	6
Midday	0.020	2438	200	958	294	113	16
Afternoon peak hours	0.083	891	73	350	107	41	6
Evening	0.032	1670	137	656	201	78	11

(1) This should be done for Saturday and Sunday as well.

Using VOT values of Tables D1, D2, D3 and D4 ➔ $TDC_{weekday}$ = 33,344 $

= 15 x [

0.000 x (1.3x(347x1.5 + 28x17.6) + 1.3x(136x1.5 + 42x17.6) + 1.3x(16x17.6) + 20x(2x1.5))

+0.026 x (1.3x(300x1.5 + 25x17.6) + 1.3x(118x1.5 + 36x17.6) + 1.3x(14x17.6) + 20x(2x1.5))

+0.083 x (1.3x(895x1.5 + 73x17.6) + 1.3x(352x1.5 + 108x17.6) + 1.3x(42x17.6) + 20x(6x1.5))

+0.020 x (1.3x(2438x1.5 + 200x17.6) + 1.3x(958x1.5 + 294x17.6) + 1.3x(113x17.6) + 20x(16x1.5))

+0.083 x (1.3x(891x1.5 + 73x17.6) + 1.3x(350x1.5 + 107x17.6) + 1.3x(41x17.6) + 20x(6x1.5))

+0.032 x (1.3x(1670x1.5 + 137x17.6) + 1.3x(656x1.5 + 201x17.6) + 1.3x(78x17.6) + 20x(11x1.5))

]

** Note 1: in application, vehicle-hours are to be converted to person-hours by multiplying by average passenger occupancy of vehicles, for example 1.3 for automobiles and trucks, and 20 for buses.

The approach to assess vehicle emission costs related to construction works does not required traffic simulation. Generalized relationships between the travel speed and traffic emissions have been developed for four types of vehicles: automobile, light truck, heavy truck and bus (MTQ, 2013). They are presented in Tables D2, D3, D4 and D5 in terms of speed-based emission factor in grams per kilometer for seven types of pollutant: GES, CO, HC, NO_x, SO_x, $PM_{2,5}$ and PM_{10}.

In general, construction works will cause either additional travel time ΔT per vehicle going through the work zone or additional travel distance ΔL per vehicle detouring the work zone. If congestion reduces the average vehicle speed below 30 km/h, GES emissions will increase (see Figure D1).

- Complete closure

Based on the average vehicle speed on the alternate road V_d, we determine the volume of pollutant emitted (km/g) using Tables E2, E3, E4 and E5, then multiply it the extra distance ΔL (km) to assess pollution costs for each pollutant.

- For partial closure

Based on the average vehicle speeds before and during works, V_n and V_w, we assessed the difference of the pollution costs obtained from respective speeds.

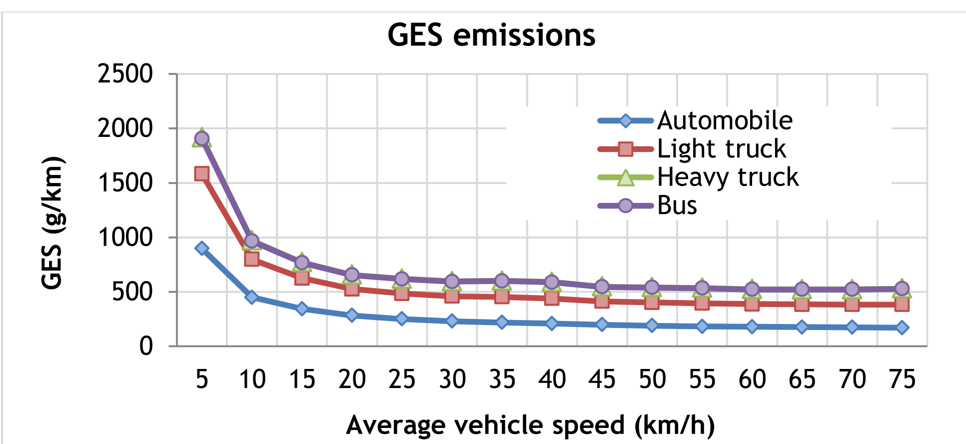


FIGURE D1: GES emissions-speed curve (MTQ, 2013)

Table D1 illustrates vehicle emission costs used in the study (MTQ, 2013).

TABLE E1: Vehicle emission costs (VEC) (MTQ, 2013)

	GES (g/km)	CO (g/km)	HC (g/km)	NO_x (g/km)	SO_x (g/km)	$PM_{2,5}$ (g/km)	PM10 (g/km)
$ CAN 2011 per metric ton	81	1 742	6 339	8 086	6 747	30 822	8 655

TABLE E2: Volumetric pollutant emissions per km (VPEK) for autos (MTQ, 2013)

V (km/h)	GES (g/km)	CO (g/km)	HC (g/km)	NO_x (g/km)	SO_x (g/km)	$PM_{2,5}$ (g/km)	PM10 (g/km)	Fuel (l/km)
5	898	17,406	0,765	0,689	0,004	0,008	0,016	0,369
10	450	9,699	0,452	0,552	0,004	0,008	0,016	0,185
15	344	6,945	0,316	0,446	0,004	0,008	0,016	0,142
20	284	5,681	0,24	0,376	0,004	0,008	0,016	0,117
25	251	5,008	0,196	0,338	0,004	0,008	0,016	0,103
30	231	4,797	0,179	0,343	0,004	0,008	0,016	0,095
35	219	4,646	0,168	0,346	0,004	0,008	0,016	0,09
40	208	4,532	0,159	0,349	0,004	0,008	0,016	0,085
45	199	4,441	0,152	0,351	0,004	0,008	0,016	0,082
50	190	4,392	0,145	0,353	0,004	0,008	0,016	0,078
55	182	4,393	0,137	0,353	0,004	0,008	0,016	0,075
60	180	4,512	0,132	0,356	0,004	0,008	0,016	0,074
65	177	4,66	0,129	0,36	0,004	0,008	0,016	0,073
70	175	4,822	0,126	0,366	0,004	0,008	0,016	0,072
75	171	4,982	0,124	0,372	0,004	0,008	0,016	0,07

TABLE E3: Volumetric pollutant emissions per km (VPEK) for light trucks (MTQ, 2013)

V (km/h)	GES (g/km)	CO (g/km)	HC (g/km)	NO_x (g/km)	SO_x (g/km)	$PM_{2,5}$ (g/km)	PM10 (g/km)	Fuel (l/km)
5	1583,36	11,42	0,993	2,335	0,006	0,043	0,056	0,632
10	798,332	7,728	0,701	2,089	0,006	0,043	0,056	0,319
15	625,324	5,9	0,553	1,919	0,006	0,043	0,056	0,25
20	526,215	4,719	0,453	1,776	0,006	0,043	0,056	0,211
25	485,281	3,944	0,385	1,675	0,006	0,043	0,056	0,194
30	459,264	3,398	0,332	1,601	0,006	0,043	0,056	0,184
35	453,372	3	0,291	1,549	0,006	0,043	0,056	0,182
40	439,727	2,695	0,259	1,51	0,006	0,043	0,056	0,177
45	412,314	2,469	0,233	1,492	0,006	0,043	0,056	0,166
50	402,949	2,3	0,212	1,483	0,006	0,043	0,056	0,162
55	394,855	2,18	0,194	1,488	0,006	0,043	0,056	0,159
60	387,568	2,12	0,18	1,51	0,006	0,043	0,056	0,156
65	385,025	2,086	0,169	1,538	0,006	0,043	0,056	0,155
70	383,753	2,088	0,16	1,588	0,006	0,043	0,056	0,154
75	384,218	2,112	0,153	1,653	0,006	0,043	0,056	0,155

TABLE E4: Volumetric pollutant emissions per km (VPEK) for heavy trucks (MTQ, 2013)

V (km/h)	GES (g/km)	CO (g/km)	HC (g/km)	NO_x (g/km)	SO_x (g/km)	$PM_{2,5}$ (g/km)	PM10 (g/km)	Fuel (l/km)
5	1917,029	7,29	0,766	6,261	0,007	0,089	0,108	0,806
10	970,522	5,557	0,629	5,612	0,007	0,089	0,108	0,408
15	771,455	4,457	0,538	5,175	0,007	0,089	0,108	0,324
20	656,848	3,582	0,457	4,79	0,007	0,089	0,108	0,276
25	620,513	2,963	0,398	4,509	0,007	0,089	0,108	0,261
30	596,308	2,469	0,346	4,273	0,007	0,089	0,108	0,251
35	602,174	2,106	0,305	4,101	0,007	0,089	0,108	0,253
40	590,063	1,825	0,272	3,969	0,007	0,089	0,108	0,248
45	547,975	1,616	0,244	3,891	0,007	0,089	0,108	0,23
50	541,881	1,456	0,222	3,845	0,007	0,089	0,108	0,228
55	535,806	1,337	0,203	3,835	0,007	0,089	0,108	0,225
60	523,79	1,254	0,188	3,871	0,007	0,089	0,108	0,22
65	523,752	1,194	0,175	3,928	0,007	0,089	0,108	0,22
70	523,733	1,166	0,165	4,046	0,007	0,089	0,108	0,22
75	529,694	1,158	0,157	4,202	0,007	0,089	0,108	0,233

TABLE E5: Volumetric pollutant emissions per km (VPEK) for buses (MTQ, 2013)

V (km/h)	GES (g/km)	CO (g/km)	HC (g/km)	NO_x (g/km)	SO_x (g/km)	$PM_{2,5}$ (g/km)	PM10 (g/km)	Fuel (l/km)
5	1906,621	6,243	0,646	7,092	0,007	0,069	0,084	0,805
10	965,302	4,774	0,537	6,191	0,007	0,069	0,084	0,407
15	767,445	3,837	0,463	5,584	0,007	0,069	0,084	0,324
20	653,528	3,088	0,397	5,048	0,007	0,069	0,084	0,276
25	617,554	2,558	0,348	4,656	0,007	0,069	0,084	0,261
30	593,571	2,133	0,304	4,324	0,007	0,069	0,084	0,25
35	599,567	1,82	0,27	4,082	0,007	0,069	0,084	0,253
40	587,575	1,577	0,241	3,896	0,007	0,069	0,084	0,248
45	545,605	1,395	0,217	3,782	0,007	0,069	0,084	0,23
50	539,61	1,257	0,198	3,714	0,007	0,069	0,084	0,228
55	533,614	1,152	0,182	3,696	0,007	0,069	0,084	0,225
60	521,623	1,08	0,169	3,742	0,007	0,069	0,084	0,22
65	521,623	1,027	0,158	3,816	0,007	0,069	0,084	0,22
70	521,623	1	0,149	3,973	0,007	0,069	0,084	0,22
75	527,619	0,991	0,142	4,185	0,007	0,069	0,084	0,223

For example, let us consider a 700 m road segment of class IV with AADT of 10,000 veh/h undergoing a 3-week reconstruction, with a partial closure allowing vehicles to go through the work zone

a) Vehicle emission costs

$$VEC_{weekdays} = 15\ days\ x\ 0.7\ km\ x\ \Sigma_{pollutant}\ VEC\ x\ \Sigma_{period}\ \Sigma_{type\ of\ vehicle}\ TVPPPTOV\ x\ (VPEK_w - VPEK_n)$$

GES[(1)]	Normal conditions					
	LOS	V_w (km/h)	VPEK (g/km)			
			Auto	Light truck	Heavy truck	Bus
Night	A	48	194	407	544	542
Morning	C	28	239	470	606	603
Morning peak hours	D	21	277	518	650	646
Midday	B	37	215	448	597	595
Afternoon peak hours	D	21	277	518	650	646
Evening	B	37	215	448	597	595

(1) This should be done for each other pollutant (CO, HC, NO_x, SO_x, $PM_{2,5}$, PM_{10}).

GES[(1)]	Work conditions					
	LOS	V_w (km/h)	VPEK (g/km)			
			Auto	Light truck	Heavy truck	Bus
Night	A	48	194	407	544	542
Morning	E	16	332	606	749	745
Morning peak hours	F	7	719	1269	1538	1530
Midday	D	21	277	518	650	646
Afternoon peak hours	F	7	719	1269	1538	1530
Evening	D	16	332	606	749	745

(1) This should be done for each other pollutant (CO, HC, NO_x, SO_x, $PM_{2,5}$, PM_{10}).

Knowing that 1 metric ton ≈ 1.1023 tons = 1.1023 x 10^6 grams ➔ PC for GES = 1,912 $

= 15 x 0.7 x (81/1.023x10^6) x [

((347+28)x(194–194) + (136+42)x(407-407) + (16)x(544-544) + (2)x(542-542))

+((300+25)x(332-239) + (118+36)x(606-470) + (14)x(749-606) + (2)x(745-603))

+((895+73)x(719-277) + (352+108)x(1269-518) + (42)x(1538-650) + (6)x(1530-646))

+((2438+200)x(277-215) + (958+294)x(518-448) + (113)x(650-597) + (16)x(646-595))

+((891+73)x(719-277) + (350+107)x(1269-518) + (41)x(1538-650) + (6)x(1530-646))

+((1670x+137)x(332-215) + (656+201)x(606-448) + (78)x(749-597) + (11)x(745-595))

]

Machinery emissions are based upon fuel consumption (gal/h), which are converted into kg of CO_2 using 10.1 kg of CO_2 for each gallon of diesel fuel used (Rehan and Knight, 2007). Machines used for each scenario are displayed from Table F.1 to Table F.35.

TABLE F.1: Road minor rehabilitation tools

Type of machines	Nb.	hr	gal/h
Truck Ford 450	3	2	2,6
Hauling truck	10	2	2,6
Motor scraper	1	2	4,5
Mechanical broom	1	2	2,6
Truck for glue	1	2	2,6
Asphalt Compactor	2	5	4,8
Asphalt Paver	2	5	5,3
Backhoe	1	9	1,9

TABLE F.2: Road major rehabilitation tools

Type of machines	Nb.	hr	gal/h
Truck Ford 450	3	2	2,6
Hauling truck	15	2	2,6
Motor scraper	1	2	4,5
Mechanical broom	1	2	2,6
Excavator	3	10	4,7
Backhoe	3	10	1,4
Soil Compactor	2	5	2,4
Truck glue	1	2	2,6
Asphalt Paver	2	5	5,3
Asphalt Compactor	2	5	4,8

For example, let us consider a 700 m road segment undergoing reconstruction

Table F.3 illustrates the number of machine used, the operating hour per machine and fuel consumption per machine during the whole process of reconstruction. Therefore, the volume of pollutant emitted is assessed as follows:

TABLE F.3: Road reconstruction tools

Type of machines	Nb.	hr	gal/h
Truck Ford 450	3	2	2,6
Hauling truck	25	2	2,6
Driller	1	5	28,9
Motor scraper	1	2	4,5
Mechanical broom	1	2	2,6
Excavator	3	18	4,7
Backhoe	3	18	1,4
Soil Compactor	2	5	2,4
Truck for glue	1	2	2,6
Asphalt Paver	2	5	5,3
Asphalt Compactor	2	5	4,8
Concrete auger	1	18	2,6
Concrete Mixer Truck	1	18	2,6

TABLE F.4: Water main CIPP tools

Type of machines	Nb.	hr	gal/h
Truck Ford 450	3	2	2,6
Hauling truck	8	2	2,6
Air compressor	1	10	6,6
Pump	1	10	1,7
Driller	1	3	28,9
Excavator	2	5	4,7
Backhoe	2	5	1,9
Soil Compactor	1	5	2,4
Hand compactor	2	5	0,4
Truck for glue	1	2	2,6
Asphalt paver	1	5	5,3
Asphalt compactor	1	5	4,8
Generator	1	18	8,1

VPE for CO_2 = (10.1 kg) x (3x2x2,6 + 25x2x2,6 + 1x5x28,9 + 1x2x4,5 + 1x2x2,6 + 3x18x4,7 + 3x18x1,4 + 2x5x2,4 + 1x2x2,6 + 2x5x5,3 + 2x5x4,8 + 1x18x2,6 + 1x18x2,6) = 8,661 kg

TABLE F.5: Water main reconstruction tools

Type of machines	Nb.	hr	gal/h
Truck Ford 450	3	2	2,6
Hauling truck	10	2	2,6
Driller	1	4	28,9
Excavator	2	9	4,7
Backhoe	2	9	1,9
Crane	2	5	2,1
Soil Compactor	1	5	2,4
Hand compactor	2	5	0,4
Truck for glue	1	2	2,6
Asphalt paver	1	5	5,3
Asphalt compactor	1	5	4,8
Generator	1	18	8,1

TABLE F.7: Sewer main reconstruction tools

Type of machines	Nb.	hr	gal/h
Truck Ford 450	3	2	2,6
Hauling truck	15	2	2,6
Driller	1	5	28,9
Excavator	2	18	4,7
Backhoe	2	18	1,9
Crane	2	9	2,1
Soil Compactor	1	9	2,4
Hand compactor	2	5	0,4
Truck for glue	1	2	2,6
Asphalt paver	1	5	5,3
Asphalt compactor	1	5	4,8
Generator	1	18	8,1

TABLE F.6: Sewer main CIPP tools

Type of machines	Nb.	hr	gal/h
Truck Ford 450	3	2	2,6
Hauling truck	13	2	2,6
Refrigerator Truck	1	18	11,8
Steam Boiler	1	18	1,1
Steamer truck	1	10	2,6
Air compressor	1	18	6,6
Pump	1	10	1,7
Shooter truck	1	10	2,6
Crane	1	9	2,1
Driller	1	5	28,9
Backhoe	2	9	1,9
Soil Compactor	1	2	2,4
Hand compactor	1	6	0,4
Asphalt paver	1	2	5,3
Asphalt compactor	1	2	4,8
Generator	1	18	8,1

TABLE F.8: Water main CIPP and road minor rehabilitation tools

Type of machines	Nb.	hr	gal/h
Truck Ford 450	6	2	2,6
Hauling truck	18	2	2,6
Motor scraper	1	2	4,5
Mechanical broom	1	2	2,6
Truck for glue	1	2	2,6
Asphalt Compactor	2	5	4,8
Asphalt Paver	2	5	5,3
Excavator	2	5	4,7
Backhoe	2	5	1,9
Soil Compactor	1	5	2,4
Hand compactor	2	5	0,4
Air compressor	1	10	6,6
Pump	1	10	1,7
Generator	1	18	8,1

TABLE F.9: Water main CIPP and road major rehabilitation tools

Type of machines	Nb.	hr	gal/h
Truck Ford 450	3	2	2,6
Hauling truck	15	2	2,6
Motor scraper	1	2	4,5
Mechanical broom	1	2	2,6
Excavator	3	11	4,7
Backhoe	3	11	1,4
Soil Compactor	2	5	2,4
Truck Colle	1	2	2,6
Asphalt Paver	2	5	5,3
Asphalt Compactor	2	5	4,8
Crane	2	9	2,1
Generator	2	9	28,7
Refrigerator Truck	2	9	11,8
Air compressor	1	18	6,6
Steam Boiler	2	9	1,1
Pump	1	10	1,7

TABLE F.10: Water main CIPP and road reconstruction tools

Type of machines	Nb.	hr	gal/h
Truck Ford 450	6	2	2,64
Hauling truck	30	2	2,64
Driller	1	5	28,93
Motor scraper	1	2	4,49
Mechanical broom	1	2	2,64
Excavator	3	19	4,73
Backhoe	3	18	1,39
Soil Compactor	2	6	2,40
Truck Colle	1	2	2,64
Asphalt Paver	2	5	5,28
Asphalt Compactor	2	5	4,76
Toupie Béton	1	18	2,64
Generator	1	18	8,11
Air compressor	1	10	6,55
Pump	1	10	1,74

TABLE F.11: Sewer main CIPP and road minor rehabilitation tools

Type of machines	Nb.	hr	gal/h
Truck Ford 450 + Steamer truck + Shooter truck	7	2	2,6
Hauling truck	23	2	2,6
Refrigerator Truck	1	18	2,6
Steam Boiler	1	18	1,1
Motor scraper	1	2	4,5
Air compressor	1	18	6,6
Pump	1	10	1,7
Generator	1	18	8,1
Balai mécanique	1	2	2,6
Crane	1	9	2,1
Driller	1	5	28,9
Backhoe	2	9	1,9
Soil Compactor	1	3	2,4
Hand compactor	1	6	0,4
Asphalt paver	1	9	5,3
Asphalt compactor	1	9	4,8

TABLE F.12: Sewer main CIPP and road major rehabilitation tools

Type of machines	Nb.	hr	gal/h
Truck Ford 450 + Steamer truck + Shooter truck	8	2	2,6
Hauling truck	25	2	2,6
Motor scraper	1	2	4,5
Mechanical broom	1	2	2,6
Excavator	3	11	4,7
Backhoe	3	11	1,4
Soil Compactor	2	5	2,4
Truck Colle	1	2	2,6
Asphalt Paver	2	5	5,3
Asphalt Compactor	2	5	4,8
Refrigerator Truck	1	18	2,6
Steam Boiler	1	18	1,1
Air compressor	1	18	6,6
Pump	1	10	1,7
Generator	1	18	8,1
Crane	1	10	2,1

TABLE F.13: Sewer main CIPP and road reconstruction tools

Type of machines	Nb.	hr	gal/h
Driller	1	5	28,93
Hauling truck + Truck Ford 450 + Steamer truck + Shooter truck	46	2	2,64
Motor scraper	1	2	4,49
Mechanical broom	1	2	2,64
Excavator	3	20	4,73
Backhoe	3	20	1,39
Soil Compactor	2	6	2,40
Truck for glue	1	2	2,64
Asphalt Paver	2	5	5,28
Asphalt Compactor	2	5	4,76
Refrigerator Truck	1	18	2,64
Steam Boiler	1	18	1,14
Air compressor	1	18	6,55
Pump	1	10	1,74
Generator	1	18	8,11
Crane	1	10	2,11

TABLE F.14: Water main reconstruction and road minor rehabilitation tools

Type of machines	Nb.	hr	gal/h
Truck Ford 450	6	2	2,6
Hauling truck	18	2	2,6
Driller	1	4	28,9
Excavator	2	9	4,7
Backhoe	2	9	1,9
Crane	2	5	2,1
Soil Compactor	1	5	2,4
Hand compactor	2	5	0,4
Truck for glue	1	2	2,6
Asphalt paver	1	6	5,3
Asphalt compactor	1	6	4,8
Generator	1	18	8,1
Mechanical broom	1	2	2,6

TABLE F.15: Water main reconstruction and road major rehabilitation tools

Type of machines	Nb.	hr	gal/h
Truck Ford 450	6	2	2,6
Hauling truck	22	2	2,6
Driller	1	4	28,9
Excavator	3	18	4,7
Backhoe	3	18	1,9
Crane	2	9	2,1
Soil Compactor	1	5	2,4
Hand compactor	2	5	0,4
Truck for glue	1	2	2,6
Asphalt paver	2	9	5,3
Asphalt compactor	2	9	4,8
Generator	1	18	8,1

TABLE F.16: Water main reconstruction and road reconstruction tools

Type of machines	Nb.	hr	gal/h
Truck Ford 450	6	2	2,6
Hauling truck	23	2	2,6
Driller	1	5	28,9
Motor scraper	1	2	4,5
Mechanical broom	1	2	2,6
Excavator	3	20	4,7
Backhoe	3	20	1,4
Soil Compactor	2	6	2,4
Truck for glue	1	2	2,6
Asphalt Paver	2	9	5,3
Asphalt Compactor	2	9	4,8
Concrete auger	1	18	2,6
Crane	2	5	2,1
Hand compactor	2	5	0,4

TABLE F.17: Sewer main reconstruction and road minor rehabilitation tools

Type of machines	Nb.	hr	gal/h
Truck Ford 450	6	2	2,6
Hauling truck	25	2	2,6
Driller	1	5	28,9
Excavator	2	18	4,7
Backhoe	2	18	1,9
Crane	2	9	2,1
Soil Compactor	1	9	2,4
Hand compactor	2	5	0,4
Truck for glue	1	2	2,6
Asphalt paver	2	6	5,3
Asphalt compactor	2	6	4,8
Generator	1	18	8,1
Mechanical broom	1	2	2,6
Motor scraper	1	2	4,5

TABLE F.18: Sewer main reconstruction and road major rehabilitation tools

Type of machines	Nb.	hr	gal/h
Truck Ford 450	6	2	2,6
Hauling truck	28	2	2,6
Motor scraper	1	2	4,5
Balai mécanique	1	2	2,6
Excavator	3	19	4,7
Backhoe	3	19	1,4
Soil Compactor	2	5	2,4
Truck for glue	1	2	2,6
Asphalt Paver	2	9	5,3
Asphalt Compactor	2	9	4,8
Driller	1	4	28,9
Crane	2	9	2,1

TABLE F.19: Sewer main reconstruction and road reconstruction tools

Type of machines	Nb.	hr	gal/h
Truck Ford 450	6	2	2,6
Hauling truck	38	2	2,6
Driller	1	5	28,9
Motor scraper	1	2	4,5
Mechanical broom	1	2	2,6
Excavator	3	20	4,7
Backhoe	3	20	1,4
Soil Compactor	2	5	2,4
Truck for glue	1	2	2,6
Asphalt Paver	2	9	5,3
Asphalt Compactor	2	9	4,8
Toupie Béton	1	18	2,6
Crane	2	5	2,1
Hand compactor	2	5	0,4
Generator	1	18	8,1

TABLE F.20: Water and sewer main CIPP and road minor rehabilitation tools

Type of machines	Nb.	hr	gal/h
Truck Ford 450 + Hauling truck	38	3	2,6
Motor scraper	1	2	4,5
Mechanical broom + Truck for glue	2	2	2,6
Asphalt Compactor	2	9	4,8
Asphalt Paver	2	9	5,3
Excavator	2	8	4,7
Backhoe	2	8	1,9
Soil Compactor	1	5	2,4
Hand compactor	2	5	0,4
Air compressor	1	18	6,6
Pump system + Shooter truck	2	10	1,7
Generator	1	36	8,1
Crane	1	10	2,1
Steam boiler	1	18	1,1
Pump	2	10	1,7
Steamer truck	1	10	2,6

TABLE F.21: Water and sewer main CIPP and road major rehabilitation tools

Type of machines	Nb.	hr	gal/h
Truck Ford 450 + Hauling truck	43	2	2,6
Motor scraper	1	2	4,5
Mechanical broom + Truck for glue	2	2	2,6
Asphalt Compactor	2	9	4,8
Asphalt Paver	2	9	5,3
Excavator	3	20	4,7
Backhoe	3	20	1,9
Soil Compactor	1	5	2,4
Hand compactor	2	5	0,4
Air compressor	1	18	6,6
Pump system + shooter	2	10	1,7
Generator	1	36	8,1
Crane	1	10	2,1
Steam boiler	1	18	1,1
Pump	2	10	1,7
Steamer truck	1	10	2,6

TABLE F.22: Water and sewer main CIPP and road reconstruction tools

Type of machines	Nb.	hr	gal/h
Truck Ford 450 + Hauling truck	60	2	2,6
Motor scraper	1	2	4,5
Mechanical broom + Truck for glue	2	2	2,6
Asphalt Compactor	2	9	4,8
Asphalt Paver	2	9	5,3
Excavator	3	36	4,7
Backhoe	3	36	1,9
Soil Compactor	1	8	2,4
Hand compactor	2	5	0,4
Air compressor	1	18	6,6
Pump system + Shooter	2	10	1,7
Generator	1	36	8,1
Crane	1	10	2,1
Steam boiler	1	18	1,1
Pump	2	10	1,7
Steamer truck	1	10	2,6

TABLE F.23: Water main reconstruction, sewer main CIPP and road minor rehabilitation tools

Type of machines	Nb.	hr	gal/h
Truck Ford 450	9	2	2,6
Hauling truck	25	2	2,6
Refrigerator Truck	1	18	11,8
Steam Boiler	1	18	1,1
Camion vapeur	1	10	2,6
Air compressor	1	18	6,6
Pump	1	10	1,7
Shooter truck	1	10	2,6
Crane	2	9	2,1
Driller	1	5	28,9
Backhoe	4	9	1,9
Soil Compactor	1	9	2,4
Hand compactor	1	9	0,4
Asphalt paver	1	9	5,3
Asphalt compactor	1	9	4,8
Generator	1	36	8,1

TABLE F.24: Water main reconstruction, sewer main CIPP and road major rehabilitation tools

Type of machines	Nb.	hr	gal/h
Truck Ford 450 + Shooter + Steamer truck + Camion for glue	11	2	2,6
Hauling truck	40	2	2,6
Refrigerator Truck	1	18	11,8
Steam Boiler	1	18	1,1
Motor scraper	1	2	2,6
Air compressor	1	18	6,6
Pump	1	10	1,7
Mechanical broom	1	2	2,6
Crane	2	9	2,1
Driller	1	5	28,9
Backhoe	4	9	1,9
Soil Compactor	1	9	2,4
Hand compactor	1	9	0,4
Asphalt paver	1	9	5,3
Asphalt compactor	1	9	4,8
Generator	1	36	8,1

TABLE F.25: Water main reconstruction, sewer main CIPP and road reconstruction tools

Type of machines	Nb.	hr	gal/h
Truck Ford 450 + Shooter + Steamer truck + Camion for glue	13	2	2,6
Hauling truck	60	2	2,6
Refrigerator Truck	1	18	11,8
Steam Boiler	1	18	1,1
Motor scraper	1	2	2,6
Air compressor	1	18	6,6
Pump	1	10	1,7
Mechanical broom	1	2	2,6
Crane	2	9	2,1
Driller	1	5	28,9
Backhoe	4	9	1,9
Soil Compactor	1	9	2,4
Hand compactor	1	9	0,4
Asphalt paver	1	9	5,3
Asphalt compactor	1	9	4,8
Generator	1	36	8,1

TABLE F.26: Water and sewer main reconstruction and road minor rehabilitation tools

Type of machines	Nb.	hr	gal/h
Truck Ford 450	9	2	2,6
Hauling truck	30	2	2,6
Driller	1	5	28,9
Motor scraper	1	2	4,5
Mechanical broom	1	2	2,6
Excavator	2	18	4,7
Backhoe	2	18	1,4
Soil Compactor	2	9	2,4
Truck for glue	1	2	2,6
Asphalt Paver	2	9	5,3
Asphalt Compactor	2	9	4,8
Concrete auger	1	18	2,6
Generator	1	36	8,1
Crane	2	36	2,1

TABLE F.27: Water and sewer main reconstruction and road major rehabilitation tools

Type of machines	Nb.	hr	gal/h
Truck Ford 450	9	2	2,6
Hauling truck	45	2	2,6
Driller	1	5	28,9
Motor scraper	1	2	4,5
Mechanical broom	1	2	2,6
Excavator	3	18	4,7
Backhoe	3	18	1,4
Soil Compactor	2	9	2,4
Truck for glue	1	2	2,6
Asphalt Paver	2	9	5,3
Asphalt Compactor	2	9	4,8
Concrete auger	1	18	2,6
Generator	1	36	8,1
Crane	2	36	2,1

TABLE F.28: Water and sewer main reconstruction and road reconstruction tools

Type of machines	Nb.	hr	gal/h
Truck Ford 450	10	2	2,6
Hauling truck	65	2	2,6
Driller	2	5	28,9
Motor scraper	1	2	4,5
Mechanical broom	1	2	2,6
Excavator	3	36	4,7
Backhoe	3	36	1,4
Soil Compactor	3	9	2,4
Truck for glue	1	2	2,6
Asphalt Paver	2	9	5,3
Asphalt Compactor	2	9	4,8
Concrete auger	1	18	2,6
Generator	1	36	8,1
Crane	2	36	2,1

TABLE F.29: Water main CIPP, sewer main reconstruction and road minor rehabilitation tools

Type of machines	Nb.	hr	gal/h
Truck Ford 450	9	2	2,6
Hauling truck	28	3	2,6
Driller	1	5	28,9
Motor scraper	1	2	4,5
Mechanical broom	1	2	2,6
Excavator	2	9	4,7
Backhoe	2	9	1,4
Soil Compactor	2	2	2,4
Truck for glue	1	2	2,6
Asphalt Paver	2	8	5,3
Asphalt Compactor	2	5	4,8
Concrete auger	1	18	2,6
Generator	1	135	8,1
Crane	2	36	2,1

TABLE F.30: Water main CIPP, sewer main reconstruction and road major rehabilitation tools

Type of machines	Nb.	hr	gal/h
Truck Ford 450	9	2	2,6
Hauling truck	28	3	2,6
Driller	1	5	28,9
Motor scraper	1	2	4,5
Mechanical broom	1	2	2,6
Excavator	2	9	4,7
Backhoe	2	9	1,4
Soil Compactor	2	2	2,4
Truck for glue	1	2	2,6
Asphalt Paver	2	8	5,3
Asphalt Compactor	2	5	4,8
Concrete auger	1	18	2,6
Generator	1	36	8,1
Crane	2	36	2,1
Air compressor	1	18	6,6
Pump	2	10	1,7

TABLE F.31: Water main CIPP, sewer main reconstruction and road reconstruction tools

Type of machines	Nb.	hr	gal/h
Truck Ford 450	9	2	2,6
Hauling truck	40	3	2,6
Driller	1	5	28,9
Motor scraper	1	2	4,5
Mechanical broom	1	2	2,6
Excavator	2	9	4,7
Backhoe	2	9	1,4
Soil Compactor	2	2	2,4
Truck Colle	1	2	2,6
Asphalt Paver	2	9	5,3
Asphalt Compactor	2	9	4,8
Concrete auger	1	18	2,6
Generator	1	36	8,1
Crane	2	36	2,1
Air compressor	1	18	6,6
Pump	2	10	1,7

TABLE F.32: Water and sewer main CIPP tools

Type of machines	Nb.	hr	gal/h
Truck Ford 450	3	2	2,6
Hauling truck	25	2	2,6
Refrigerator Truck	1	18	11,8
Steam Boiler	1	18	1,1
Camion vapeur	1	10	2,6
Air compressor	1	36	6,6
Pump	1	36	1,7
Shooter truck	2	10	2,6
Crane	2	9	2,1
Driller	1	5	28,9
Backhoe	2	9	1,9
Soil Compactor	1	2	2,4
Excavator	2	9	4,7
Asphalt paver	1	5	5,3
Asphalt compactor	1	5	4,8
Generator	1	36	8,1

TABLE F.33: Water main rehabilitation and sewer main reconstruction tools

Type of machines	Nb.	hr	gal/h
Truck Ford 450	3	2	2,6
Hauling truck	20	2	2,6
Air compressor	1	36	6,6
Pump	2	36	1,7
Driller	1	3	28,9
Excavator	2	9	4,7
Backhoe	3	9	1,9
Soil Compactor	1	5	2,4
Hand compactor	2	5	0,4
Truck Colle	1	2	2,6
Asphalt paver	1	5	5,3
Asphalt compactor	1	5	4,8
Generator	2	36	8,1
Crane	2	18	2,1

TABLE F.34: Water main reconstruction and sewer main rehabilitation tools

Type of machines	Nb.	hr	gal/h
Truck Ford 450	3	2	2,6
Hauling truck	23	2	2,6
Refrigerator Truck	1	18	11,8
Steam Boiler	1	18	1,1
Steamer truck	1	10	2,6
Air compressor	2	18	6,6
Pump	2	18	1,7
Shooter truck	2	18	2,6
Crane	2	18	2,1
Driller	1	5	28,9
Backhoe	2	18	1,9
Soil Compactor	1	5	2,4
Hand compactor	1	5	0,4
Asphalt paver	1	5	5,3
Asphalt compactor	1	5	4,8
Generator	1	36	8,1

TABLE F.35: Water and sewer main reconstruction tools

Type of machines	Nb.	hr	gal/h
Truck Ford 450	3	2	2,6
Hauling truck	25	2	2,6
Driller	1	5	28,9
Excavator	2	18	4,7
Backhoe	2	18	1,9
Crane	2	18	2,1
Soil Compactor	1	9	2,4
Hand compactor	2	5	0,4
Truck Colle	1	2	2,6
Asphalt paver	1	9	5,3
Asphalt compactor	1	9	4,8
Generator	1	18	8,1

We denote that some traffic-related indicators are expressed in terms of ΔT such as vehicle delays (VED) and others of ΔL such as increased vehicle maintenance and operations (VMO). ΔT refers to the difference between travel times in work and in normal conditions, whereas ΔL is the difference between travel distances in work and in normal conditions in case of complete road closure. The following sections explain the assessment of traffic-related ΔT and ΔL due to the presence of works in case of partial or complete closure.

1. Partial closure

The additional travel time is computed as follows (see Appendix C):

$$\Delta T = \Delta T_d + \Delta T_{sr} = \left(\frac{2.L}{V_n + V_w} - \frac{L}{V_n}\right) + \left(\frac{L}{V_w} - \frac{L}{V_n}\right) \qquad [8]$$

Even though there is no additional distance, ΔT can be converted into a ΔL equivalent (taking into account both speed reduction and deceleration delays) based upon the normal speed V_n.

$$\Delta L_{eq} = V_n.\Delta T \qquad [10]$$

2. Complete closure

The additional travel time is computed as follows (see Appendix C):

$$\Delta T_{detour} = \frac{L_d}{V_d} - \frac{L}{V_n} = \left(\frac{L_d}{V_d} - \frac{L_d}{V_n}\right) + \left(\frac{L_d}{V_n} - \frac{L}{V_n}\right) = \left(\frac{L_d}{V_d} - \frac{L_d}{V_n}\right) + \left(\frac{L_d - L}{V_n}\right) \qquad [9]$$

If $V_d = V_n$ then $\Delta L = L_d - L$. However, if congestion occurs ($V_d < V_n$) due to increased vehicle density on the alternate route, ΔT due to congestion can be converted into a ΔL equivalent (taking into account congestion on the alternate road) based upon the normal speed.

$$\Delta L_{total} = (L_d - L) + \Delta L_{eq} = (L_d - L) + \left(\frac{L_d}{V_d} - \frac{L_d}{V_n}\right).V_n \qquad [11]$$

All vehicles that are detoured will bear an increment of ΔL_{total} whereas vehicles normally in circulation in the alternate road will only bear an increment of ΔL_{eq}. We assume that V_n is the normal speed on the alternate road to keep at least the same LOS.

Buried pipe and road interventions within the same road corridor can be bundled in one single project. The following sections describe the types of interventions for buried pipe and road segments, and coordination scenarios.

1. Buried pipe interventions

Buried pipes interventions can be divided into open-cut reconstruction (OCR) and trenchless technologies (TT). OCR referred as conventional trenching, involves digging from pavement surface to pipe level in urban areas using heavy machineries such as backhoes and shovels that should be manoeuvred cautiously in order to avoid damages of landscape and buried utilities surrounding the pipe. TT referred as “no-dig” or “low-dig” techniques because some of them are not completely excavation-free (e.g., low-dig), can be separated into trenchless replacement (TRP) and rehabilitation (TRH) (Halfawy and Baker, 2008). Figure I.1 shows TRP methods that are divided into in-line methods (which consist in installing a new pipe in the same line as the old one, e.g. pipe bursting) and off-line methods (which consist in installing a new pipe in a new line, e.g. micro-tunneling, horizontal directional drilling, pipe jacking); and TRH methods which can be fully/semi/non-structural and involve installation of a new coating or liner in the existing pipe (i.e. Cured-in-place pipe/CIPP, slip-lining, epoxy/mortar lining, etc.).

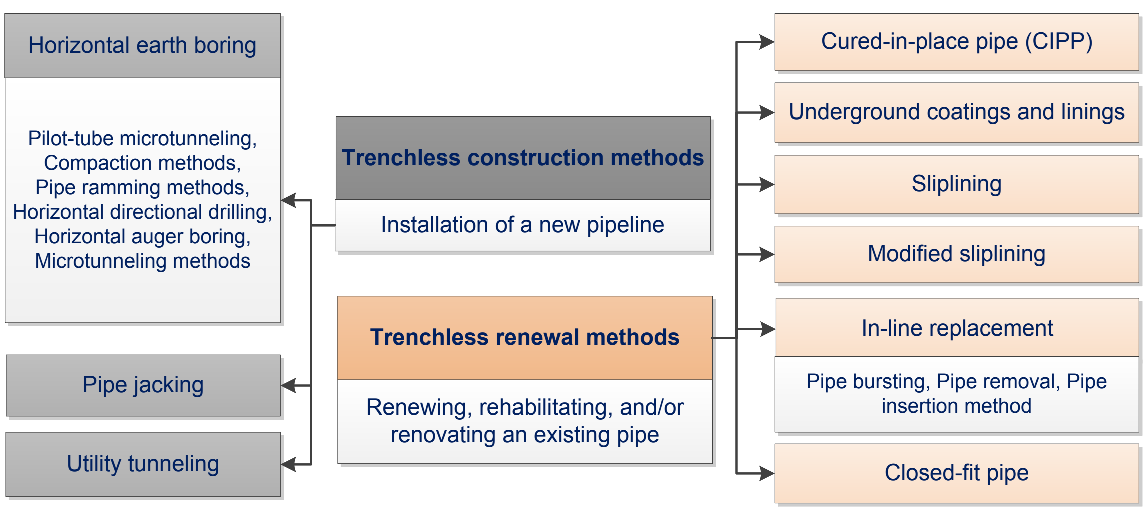


FIGURE I.1: Trenchless pipe renewal methods

In the city of Montreal, CIPP and OCR are commonly used for buried pipe renewals. The use of CIPP is widely accepted because its duration of implementation is typically shorter than OCR and it significantly reduces social costs, which can account for up to 3% of project costs for CIPP as opposed to 78 % for OCR (Rahman, et al., in 2005).

2. Road interventions

Road interventions can be divided into three groups: reconstruction OCR, pulverization-stabilization OCP and surface treatment TST. Figure I.2 shows road pavement sections composed of sub-grade (i.e. existing soil), sub-base (usually treated sand, gravel, crushed stones), base and surface (which are layers of asphalt for flexible pavement and of concrete for rigid one). Road reconstruction is an adequate solution when major sub-grade correction is required and involves complete removal of the sub-base structure.

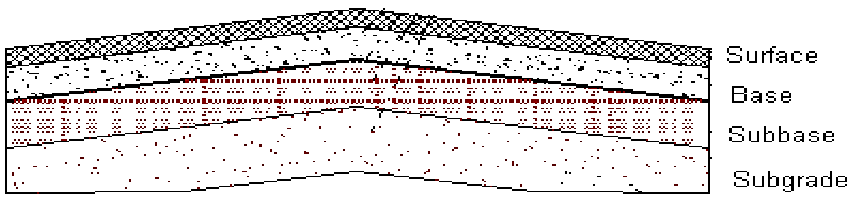


FIGURE I.2: Road pavement sections

Road pulverization-stabilization (e.g. full depth reclamation, cold-in-place or hot-in-place recycling) is an adequate solution when the sub-grade is in a fairly good condition and involves at most removal of the upper layer of the sub-grade structure. A predetermined portion of base/sub-base/sub-grade is uniformly pulverized (with addition of a binder) and mixed to form a new homogeneous material. If the new material does not provide a sufficient base/sub-base for the new pavement surface, then stabilizing additives are blended to sub-grade prior to installing base/sub-base.

Surface treatment is an adequate solution when sub-grade and sub-base/base structure are in a good condition and are divided into surface sealing and surface overlay. Surface sealing is a non-structural treatment generally composed of emulsified asphalt spread on the pavement in order to fix deficiencies such as non-load associated cracks and to increase surface friction. Surface overlay on the other hand is a structural treatment which consists of placing a new surface (hot-mix bituminous or concrete) on an existing pavement structure that helps increase the structural capacity of the pavement as well as correct road deficiencies including skid resistance, surface roughness and distress.

3. Coordination scenarios

Table I.1 enumerates 35 renewal projects that can be implemented on a road corridor and which result from a silo-approach simulation of implementation timing among three types of municipal linear assets (i.e. water, sewer and road) comprised in a road corridor. The project duration (PD) is estimated for each scenario (see Appendix M).

TABLE I.1: Renewal alternatives

	Road	Water	Sewer	PD		Road	Water	Sewer	PD
1	TST				20		CIPP	CIPP	
2	OCP				21		CIPP	OCR	
3	OCR				22		OCR	CIPP	
4		CIPP			23		OCR	OCR	
5		OCR			24	TST	CIPP	CIPP	
6			CIPP		25	OCP	CIPP	CIPP	
7			OCR		26	OCR	CIPP	CIPP	
8	TST	CIPP			27	TST	CIPP	OCR	
9	OCP	CIPP			28	OCP	CIPP	OCR	
10	OCR	CIPP			29	OCR	CIPP	OCR	
11	TST		CIPP		30	TST	OCR	CIPP	
12	OCP		CIPP		31	OCP	OCR	CIPP	
13	OCR		CIPP		32	OCR	OCR	CIPP	
14	TST	OCR			33	TST	OCR	OCR	
15	OCP	OCR			34	OCP	OCR	OCR	
16	OCR	OCR			35	OCR	OCR	OCR	
17	TST		OCR						
18	OCP		OCR						
19	OCR		OCR						

Pedestrian delays are assessed for two work zone configuration: partial and complete closure of sidewalks. Contrarily to complete closure, partial closure allows pedestrian to go through with very little space some time.

FIGURE J.1: Examples of sidewalk partial closure during works

1. Sidewalk partial closure

In the partial closure, either both of the sidewalks are partially closed, or one sidewalk is closed and the other on the opposite side is open. This induces a loss of pedestrian traffic, because people will tend to either take detours based on their safety and comfort desire to get to their final destination. Experiences reveal that the sidewalk effective width during works is sometimes restricted to one pedestrian width, almost an average of 0.584 mm.

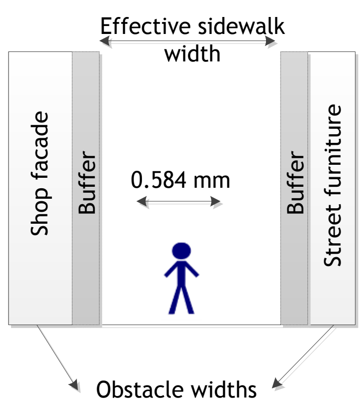
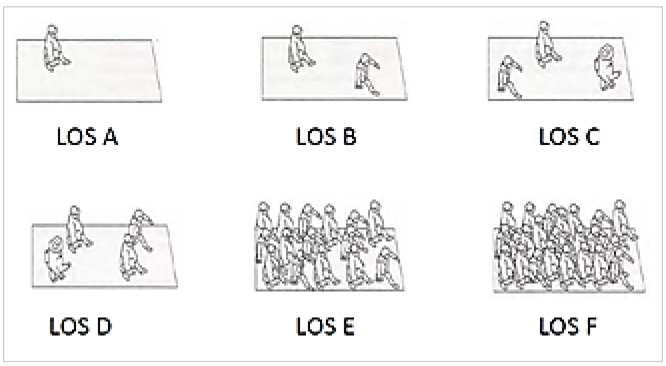


FIGURE J.2: Effective width on a sidewalk (Finch, 2010)

Levels of service of pedestrians (LOS) are expressed in terms of pedestrian flow rate (PFR) and associated pedestrian walking speed (PWS). PFR is the number of pedestrians crossing the effective sidewalk width each minute (ppmm). A neperian logarithmic relationship between PFR (p/ms) and PWS (m/s) were demonstrated respectively for normal (≤4.0 m) and large sidewalks (Rastogi, et al., 2013).

$$\mathrm{PFR} = -\alpha.\mathrm{PWS}.\ln\left(\frac{\mathrm{PWS}}{\beta}\right) \qquad [12]$$

Figure J.3 illustrates the LOS for pedestrians in normal conditions. However, two things happen in work conditions: first, the effective sidewalk width is reduced and second, the pedestrian traffic flow drops.



LOS	PFR (p/min/m-width)	PWS (m/s)	PS (m^2/p)
A	≤ 16	>1.33	>5.6
B	> 16-23	>1.17-1.33	>3.7-5.6
C	> 23-33	>1.00-1.17	>2.2-3.7
D	> 33-49	>0.83-1.00	>1.4-2.2
E	> 49-75	>0.58-0.83	>0.75-1.4

FIGURE J.3: LOS for pedestrian walking speed (HCM, 2000)

Pedestrian delay costs (PDC) will be assessed as the difference between PDC in work and normal conditions.

Two different situations are studied:

a) Pedestrians going through the sidewalk

The delay time is computed as follows:

$$\Delta T = \frac{L}{PWS_{work}} - \frac{L}{PWS_{normal}}$$

Where L is the length of the road or sidewalk

b) Pedestrians crossing to the opposite sidewalk

The delay is computed as follows:

$$\Delta T = \frac{L}{PWS_{opposite}} - \frac{L}{PWS_{normal}}$$

Where $PWS_{opposite}$ is the pedestrian walking speed on opposite sidewalk

We neglect the crossing time and consider solely incremental effect on the pedestrian flow rate of the opposite side.

2. Sidewalk complete closure

The delay is computed as follows:

$$\Delta T = \frac{L_d}{PWS_d} - \frac{L}{PWS_{normal}}$$

Where

L_d: length of detour road

PWS_d: pedestrian walking speed on detour road

We can neglect the crossing time and consider solely incremental effect of pedestrian flow rate (PFR).

The number of pedestrians is also estimated per period of time of the day (see Table A3). Moreover, pedestrian delays incurred by bus passengers due to temporal removals of bus stops are insignificant according to Montreal Public Transport Agency planners, because what matters is the final destination which can be lengthened or shortened from case to case.

For example, let us consider a 200 m road segment with 2 sidewalks of 3 meter of effective width each, and a LOS of B throughout the day except for night

The PFR is about 20 ppmm and the PWS_{normal} 1.5 m/s. Therefore, the average number of pedestrians per day is 21,600 people.

NP = 20 ppmm x 18 x 60 min = 21,600

The travel time to go through the entire sidewalk in normal condition is 3 minutes per pedestrian.

TT = 200 m / (1.25 m/s) = 3 min

Assuming a detour length of 400 m, the travel time to go around is 6 minutes per pedestrian due to work conditions.

TT = 400 m / (1.25 m/s) = 6 min

Assuming one sidewalk is closed thus leading to incrementation of pedestrian traffic on the opposite sidewalk with originally the same LOS:

- If all pedestrians move to the opposite sidewalk, then there is a loss in PWS and an increase in PFR. The $PWS_{opposite}$ is about 0.9 m/s. The total number of affected pedestrians is 43,200.

$$\frac{N_{ped}}{(W_e\!=\!3\text{ m}).T_{min}} = 20 \text{ ppmm} \leftrightarrow 60 \text{ pedestrians are crossing per minute}$$

$$\frac{N_{ped}^{opposite} = 60 + 60}{(W_e = 3\text{ m}).T_{min}} = 40 \text{ ppmm } \leftrightarrow 120 \text{ pedestrians are crossing per minute}$$

- If ½ of pedestrians move to the opposite sidewalk with the same LOS, then there is a loss in PWS and an increase of PFR. The $PWS_{opposite}$ is 1.2 m/s. The total number of affected pedestrians is 32,400.

$$\frac{N_{ped}^{opposite} = 60 + 30}{(W_e = 3\text{ m}).T_{min}} = 30 \text{ ppmm } \leftrightarrow 90 \text{ pedestrians are crossing per minute}$$

Assuming a reduction of effective width to 1 meter due to works:

- If the LOS remains B (20 ppmm), then there is a loss of pedestrian traffic. Only 1/3 remains.

$$\frac{N_{ped}}{(W_e = 3\text{ m}).T_{min}} = 20 \text{ ppmm } \leftrightarrow 60 \text{ pedestrians are crossing per minute}$$

$$\frac{N_{ped}^{new}}{(W_e = 1\ m).T_{min}} = 20\ \text{ppmm} \leftrightarrow \text{ 20 pedestrians are crossing per minute}$$

- If the LOS drops to C (30 ppmm), then there is a loss of pedestrian traffic. Only 1/2 remains.

$$\frac{N_{ped}^{new}}{(W_e = 1\ m).T_{min}} = 30\ \text{ppmm} \leftrightarrow \text{30 pedestrians are crossing per minute}$$

- If all pedestrians remains, obviously they will have very little personal space, speed and restricted movement. The LOS drops to E (60 ppmm).

$$\frac{N_{ped}^{new} = 60}{(W_e = 1\ m).T_{min}} = 60\ \text{ppmm} \leftrightarrow \text{30 pedestrians are crossing per minute}$$

In a nutshell, a sidewalk partially closed will naturally induce a loss of traffic pedestrian without necessarily a change in LOS. The increase of pedestrians on the opposite side will lead to a decrease in LOS. In practice, complete closure of sidewalks is exceptional because people need access to their buildings. However, if the sidewalk is almost closed, the increment of pedestrian traffic on detour walkways should be considered as well.

Tax revenue loss is assessed as the Willingness-to-accept compensation (a proxy of business revenue loss) equivalent to the amount of general property tax. It is based on categories of non-residential or commercial immovable.

TABLE L.1: Assessment of tax rate per $ 100 of taxation value

Classes	% of tax rate(1)	General property tax						
1	0.5 %	= 0.5 %	x	NRTR	+	(100 % – 0.5 %)	x	BR
2	3 %	= 3 %	x	NRTR	+	(100 % – 3 %)	x	BR
3	6 %	= 6 %	x	NRTR	+	(100 % – 6 %)	x	BR
4	12 %	= 12 %	x	NRTR	+	(100 % – 12 %)	x	BR
5	22 %	= 22 %	x	NRTR	+	(100 % – 22 %)	x	BR
6	40 %	= 40 %	x	NRTR	+	(100 % – 40 %)	x	BR
7	60 %	= 60 %	x	NRTR	+	(100 % – 60 %)	x	BR
8	85 %	= 85 %	x	NRTR	+	(100 % – 85 %)	x	BR
9	100 %	= 100 %	x	NRTR				
10	100 %	= 100 %	x	NRTR				
11	100 %	= 100 %	x	NRTR				
12	20 %	= 100 %	x	NRTR				

[1] Almost equivalent to % of non-residential value /total value

TABLE L.2: Tax rate (City of Montreal)

Type of immovable	Abbr.	Tax rate(1)
Basic rate	BR	3.272
Non-residential immovable and 5 or less dwelling units	NRTR	0.6812
Non-residential immovable and 6 and more dwelling units	NRTR	0.7143

In $ per $ 100 $ of assessed valuation

For example, let us consider a property of class 5 having 5 or less dwellings with a taxable value of $ 1,000,000

Class 5:
- 22 % = property's non-residential percentage
- $ 3.272 = general property tax for non-residential property
- 78 % = property's residential percentage
- $ 0.6812 = general property tax for residual property (5 or less dwellings)

General property tax = [(22 % x $ 3.272) + (78 % x $ 0.6812)] x $ 1,000,000 / 100

= $ 1.2512 x 1,000,000 = $ 12,512

A Gantt Diagram was built for each type of work packages to evaluate the effective duration of noise as illustrated in Figure K.1.

Type of work	Work steps	Type of machine	# of machines	Duration (hour)	Machine Decibel
Road minor rehab	Mobilization	Truck	2	4	85
		Truck Ford 450	3	2	55
		Truck	8	2	85
	Resurface	Motor scraper	1	2	85
	Crack sealing	Mechanic broom	1	2	85
	Bitumen binder	Truck Colle	1	2	85
		Asphalt Compactor	2	5	80
		Asphalt Paver	2	5	85
	Evacuation des débris	Backhoe	1	9	80

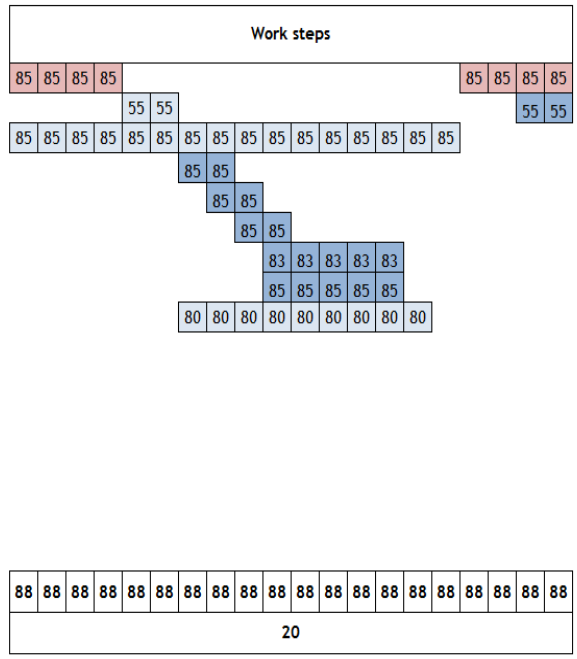


Figure K.1: Noise Diagram for road minor rehabilitation

First, for each work step, the decibel produced by each type of machine is reported a number of times corresponding to the length of time used. Then, for each hour of use, if two or more machines are operating, the resulting decibel equals the highest decibel plus 3 dBA. For example, 20 hours of use is computed for road minor rehabilitation. Figure K.1 can be simplified in Table K.2 by considering 20 hours of noise disturbance at 88 dBA. Table K.2 illustrates the noise duration with regard to the level of dBA for each type of works (a total of 18 work packages in Table 3.6). At last, we can associate the productivity reduction factor (PRF) to the level of dBA according to the type of building (institution, industry and retailer), in order to compute the production reduction cost.

For example, let us consider a 100 % industrial street under road minor rehabilitation work (Road_TST), with a total number of 150 employees

Productivity reduction cost = 20 h x 50 p x 0.18 x 17 $/h-p

= $ 540

Table K.2: Noise Diagram for road minor rehabilitation

Duration Noise (hour)	Total dBA	Productivity reduction factor (PRF)		
		Institution	Industry	Retailer
#1 Water_OCR, Sewer_OCR, Road_OCR				
58	88	0,3	0,18	0,45
#2 Water_OCR, Sewer_CIPP, Road_OCR				
7	83	0,2	0,1	0,3
66	88	0,3	0,3	0,45
18	110	1	1	1
#3 Water_CIPP, Sewer_CIPP, Road_OCR				
2	58	0,01	0	0,03
2	83	0,2	0,2	0,3
9	85	0,3	0,3	0,45
71	88	0,3	0,3	0,45
18	110	1	1	1
#4 Water_CIPP, Sewer_CIPP, Road_OCP				
2	83	0,2	0,1	0,3
9	85	0,3	0,3	0,45
64	88	0,3	0,3	0,45
18	110	1	1	1
#5 Water_CIPP, Sewer_CIPP, Road_TST				
2	83	0,2	0,1	0,3
9	85	0,3	0,3	0,45
58	88	0,3	0,3	0,45
18	110	1	1	1
#6 Water_CIPP, Sewer_CIPP				
2	83	0,2	0,1	0,3
9	85	0,3	0,3	0,45
38	88	0,3	0,3	0,45
18	110	1	1	1
#7 Sewer_CIPP, Road_OCR				
2	58	0,01	0	0,03
2	83	0,2	0,2	0,3
48	88	0,3	0,3	0,45
18	110	1	1	1
#8 Sewer_CIPP, Road_OCP				
2	83	0,2	0,1	0,3
41	88	0,3	0,3	0,45
18	110	1	1	1

#9 Sewer_CIPP, Road_TST				
2	83	0,2	0,1	0,3
35	88	0,3	0,3	0,45
18	110	1	1	1
#10 Sewer_CIPP				
2	83	0,2	0,1	0,3
15	88	0,3	0,3	0,45
18	110	1	1	1
#11 Water_OCR, Road_OCR				
5	83	0,2	0,1	0,3
51	88	0,3	0,3	0,45
#12 Water_CIPP, Road_OCR				
9	85	0,3	0,18	0,45
58	88	0,3	0,3	0,45
#13 Water_CIPP, Road_OCP				
9	85	0,3	0,18	0,45
49	88	0,3	0,3	0,45
#14 Water_CIPP, Road_TST				
9	85	0,3	0,18	0,45
43	88	0,3	0,3	0,45
#15 Water_CIPP				
9	85	0,3	0,18	0,45
23	88	0,3	0,3	0,45
#16 Road_OCR				
2	58	0,01	0	0,03
33	88	0,3	0,3	0,45
#17 Road_OCP				
26	88	0,3	0,18	0,45
#18 Road_TST				
20	88	0,3	0,18	0,45

Appendix M – Project duration

Contractual delays for water, sewer and road projects had been proposed for the City of Montreal (Desparois, 2014). They were evaluated for the following single activities: road minor rehabilitation, road major rehabilitation, road reconstruction, water pipe lining (CIPP), water pipe reconstruction, sewer pipe lining (CIPP) and sewer reconstruction. However, coordination of works induces mitigation of particular costs such as mobilization / demobilization, pavement reconstruction, etc. therefore, the previous works had been used as a basis and was adjusted in order to reflect both coordination practices and economies of scale.

The automated assessment of project duration was performed for 35 scenarios of works, even though solely 18 of them are in practice carried out on the ground (see section 3.4.2). The valuation of contractual delays is based on a number of activities which generate an output in hour. These outputs had been established on previous project analyses, on the basis of 10 h of work per day. Factors influencing the delays are to name a few: soil characterizations (presence of rocks, water table level, and frost), buried infrastructure networks (density, depth, etc.), location of works (local/arterial, trees, existing mails, etc.), traffic control (working period, road closure, accessibility to commercial and institutional buildings), special events, etc.

The following methodology was used. First, the delays were assessed for each single work on one type of assets (water, sewer or road), according to the listed activities. Then, a combination of activities were performed when works involved more than 2 asset types, in order to produce the list of activities and associated output values. In practice, CIPP works are performed individually, thus resulting in simply addition of activities and outputs. Reconstruction works on more than 2 asset types induce a revaluation of global activities and pavement refection costs, to avoid respectively overstatement and double counting. Global activities refer to general actions linked to the work construction site, to name a few: mobilization, demobilization, signaling, cleaning, unforeseen problems, etc. They cannot be duplicated but rather reevaluate downwards to some extents, unless works are performed sequentially because of any reason such as Christmas time. At last, the proposed delays should be adjusted according to the particularities and the complexity of a project. For instance, some activities can be performed at the same time.

TABLE M.1: Road minor rehabilitation steps

Activities	Unit	Output
Mobilization, cleaning, etc.	Global	5
Resurface	m.sq.	7000
Crack sealing (type 1 and 2)	m.sq.	200
New sump w/o connection	unit	10
New sump w/ connection	unit	5
Lid change	unit	5
Bitumen binder - base layer	m.sq.	7000
Bitumen binder - surf layer	m.sq.	7000

TABLE M.2: Road major rehabilitation steps

Activities	Unit	Output
Mobilization, cleaning, etc.	Global	5
Lid preparation and removal	unit	15
Pulverization	m.sq.	500
New sump w/o connection	unit	10
New sump w/ connection	unit	5
Stabilization	m.sq.	800
Lid installation and change	unit	15
Bitumen binder - base layer	m.sq.	7000
Bitumen binder - surf layer	m.sq.	7000

TABLE M.3: Road reconstruction steps

Activities	Unit	Output
Mobilization, cleaning, etc.	Global	4,5
Bedding preparation	m.sq.	500
Rock excavation	m.cu.	20
New sump w/o connection	unit	10
New sump w/ connection	unit	5
Granular sub-base (500mm)	m.sq.	1500
Granular base (MG-20,200 mm)	m.sq.	2000
Lid change	unit	5
Bitumen binder - base layer	m.sq.	7000
Bitumen binder - midlayer	m.sq.	7000
Bitumen binder - surf layer	m.sq.	7000

TABLE M.4: Water main CIPP steps

Activities	Unit	Output
Mobilization, bypass, etc.	Global	8,75
Trenchless work	m	80
Valve chamber	unit	1
Fire hydrant	unit	1
Connection ≤ 50 mm	unit	5
Connection > 50 mm	unit	3

TABLE M.5: Water main reconstruction steps

Activities	Unit	Output
Mobilization, bypass, etc.	Global	5,3
Transmission main	m	35
Distribution main	m	30
Valve chamber	unit	1
Fire hydrant	unit	1
Connections	unit	5
Granular sub-base (500 mm)	m.sq.	1500
Granular base (MG20, 200mm)	m.sq.	2000
Bitumen binder - base layer	m.sq.	7000
Bitumen binder - midlayer	m.sq.	7000
Bitumen binder - surf layer	m.sq.	7000

TABLE M.6: Sewer main CIPP

Activities	Unit	Output
Mobilization, cleaning, etc.	Global	3,25
Trenchless work	m	100
Sump cleaning/inspection	unit	10
Coating of sump connection	unit	4
Connecting sump	unit	3
Inspection after 20 months	m	200

TABLE M.7: Sewer main reconstruction steps

Activities	Unit	Output
Mobilization, bypass, etc.	Global	5
Installation 0-5 m w/ rock	m	20
Installation 0-5 m w/o rock	m	10
Installation > 5 m w/o rock	m	10
Installation > 5 m w/ rock	m	5
Sump installation - other side	unit	5
Connection install. – other side	unit	5
Manhole on-site	unit	0,067
Manhole precast	unit	1
Granular sub-base (500 mm)	m.sq.	1500
Granular base (MG20, 200mm)	m.sq.	2000
Bitumen binder - base layer	m.sq.	7000
Bitumen binder - midlayer	m.sq.	7000
Bitumen binder - surf layer	m.sq.	7000

TABLE M.8: Water main CIPP and road minor rehabilitation steps

Activities	Unit	Output
Mobilization, bypass, etc.	Global	8,75
Trenchless work	m	80
Valve chamber	unit	1
Fire hydrant	unit	1
Connection ≤ 50 mm	unit	5
Connection > 50 mm	unit	3
Mobilization, cleaning, etc.	Global	5
Resurface	m.sq.	7000
Crack sealing (type 1 and 2)	m.sq.	200
New sump w/o connection	unit	10
New sump w/ connection	unit	5
Lid change	unit	5
Bitumen binder – base layer	m.sq.	7000
Bitumen binder - surf layer	m.sq.	7000

TABLE M.9: Water main CIPP and road major rehabilitation steps

Activities	Unit	Output
Mobilization, bypass, etc.	Global	8,75
Trenchless work	m	80
Valve chamber	unit	1
Fire hydrant	unit	1
Connection ≤ 50 mm	unit	5
Connection > 50 mm	unit	3
Mobilization, cleaning, etc.	Global	5
Lid preparation and removal	unit	15
Pulverization	m.sq.	500
New sump w/o connection	unit	10
New sump w/ connection	unit	5
Stabilization	m.sq.	800
Lid installation and change	unit	15
Bitumen binder - base layer	m.sq.	7000
Bitumen binder - surf layer	m.sq.	7000

TABLE M.10: Water main CIPP and road reconstruction steps

Activities	Unit	Output
Mobilization, bypass, etc.	Global	8,75
Trenchless work	m	80
Valve chamber	unit	1
Fire hydrant	unit	1
Connection ≤ 50 mm	unit	5
Connection > 50 mm	unit	3
Mobilization, cleaning, etc.	Global	4,5
Bedding preparation	m.sq.	500
Rock excavation	m.cu.	20
New sump w/o connection	unit	10
New sump w/ connection	unit	5
Granular sub-base (500 mm)	m.sq.	1500
Granular base (MG20, 200mm)	m.sq.	2000
Lid change	unit	5
Bitumen binder - base layer	m.sq.	7000
Bitumen binder - midlayer	m.sq.	7000
Bitumen binder - surf layer	m.sq.	7000

TABLE M.11: Sewer main CIPP and road minor rehabilitation steps

Activities	Unit	Output
Mobilization, cleaning, etc.	Global	3,25
Trenchless work	m	100
Sump cleaning/inspection	unit	10
Coating of sump connection	unit	4
Connecting sump	unit	3
Inspection after 20 months	m	200
Mobilization, cleaning, etc.	Global	5
Resurface	m.sq.	7000
Crack sealing (type 1 and 2)	m.sq.	200
New sump w/o connection	unit	10
New sump w/ connection	unit	5
Lid change	unit	5
Bitumen binder - base layer	m.sq.	7000
Bitumen binder - surf layer	m.sq.	7000

TABLE M.12: Sewer main CIPP and road major rehabilitation steps

Activities	Unit	Output
Mobilization, cleaning, etc.	Global	3,25
Trenchless work	m	100
Sump cleaning/inspection	unit	10
Coating of sump connection	unit	4
Connecting sump	unit	3
Inspection after 20 months	m	200
Mobilization, cleaning, etc.	Global	5
Lid preparation and removal	unit	15
Pulverization	m.sq.	500
New sump w/o connection	unit	10
New sump w/ connection	unit	5
Stabilization	m.sq.	800
Lid installation and change	unit	15
Bitumen binder - base layer	m.sq.	7000
Bitumen binder - surf layer	m.sq.	7000

TABLE M.13: Sewer main CIPP and road reconstruction steps

Activities	Unit	Output
Mobilization, cleaning, etc.	Global	3,25
Trenchless work	m	100
Sump cleaning/inspection	unit	10
Coating of sump connection	unit	4
Connecting sump	unit	3
Inspection after 20 months	m	200
Mobilization, cleaning, etc.	Global	4,5
Bedding preparation	m.sq.	500
Rock excavation	m.cu.	20
New sump w/o connection	unit	10
New sump w/ connection	unit	5
Granular sub-base (500 mm)	m.sq.	1500
Granular base (MG20, 200mm)	m.sq.	2000
Lid change	unit	5
Bitumen binder - base layer	m.sq.	7000
Bitumen binder - midlayer	m.sq.	7000
Bitumen binder - surf layer	m.sq.	7000

TABLE M.14: Water main reconstruction and road minor rehabilitation steps

Activities	Unit	Output
Mobilization, bypass, etc.	Global	5,3
Transmission main	m	35
Distribution main	m	30
Valve chamber	unit	1
Fire hydrant	unit	1
Connections	unit	5
Granular sub-base (500 mm)	m.sq.	1500
Granular base (MG20, 200mm)	m.sq.	2000
Bitumen binder - base layer	m.sq.	7000
Bitumen binder - midlayer	m.sq.	7000
Bitumen binder - surf layer	m.sq.	7000
Special measures, etc.	Global	3
Resurface	m.sq.	7000
Crack sealing (type 1 and 2)	m.sq.	200
New sump w/o connection	unit	10
New sump w/ connection	unit	5
Lid change	unit	5
Bitumen binder - base layer	m.sq.	7000*
Bitumen binder - surf layer	m.sq.	7000*

* On the remaining surface

TABLE M.15: Water main reconstruction and road major rehabilitation steps

Activities	Unit	Output
Mobilization, bypass, etc.	Global	5,3
Transmission main	m	35
Distribution main	m	30
Valve chamber	unit	1
Fire hydrant	unit	1
Connections	unit	5
Granular sub-base (500 mm)	m.sq.	1500
Granular base (MG20, 200mm)	m.sq.	2000
Bitumen binder - base layer	m.sq.	7000
Bitumen binder - midlayer	m.sq.	7000
Bitumen binder - surf layer	m.sq.	7000
Special measures, etc.	Global	3
Lid preparation and removal	unit	15
Pulverization	m.sq.	500
New sump w/o connection	unit	10
New sump w/ connection	unit	5
Stabilization	m.sq.	800
Lid installation and change	unit	15
Bitumen binder - base layer	m.sq.	7000*
Bitumen binder - surf layer	m.sq.	7000*

*on the remaining surface

TABLE M.16: Water main reconstruction and road reconstruction steps

Activities	Unit	Output
Mobilization, bypass, etc.	Global	5,3
Transmission main	m	35
Distribution main	m	30
Valve chamber	unit	1
Fire hydrant	unit	1
Connections	unit	5
Special measures, etc.	Global	3
Bedding preparation	m.sq.	500
Rock excavation	m.cu.	20
New sump w/o connection	unit	10
New sump w/ connection	unit	5
Granular sub-base (500 mm)	m.sq.	1500
Granular base (MG20, 200mm)	m.sq.	2000
Lid change	unit	5
Bitumen binder - base layer	m.sq.	7000
Bitumen binder - midlayer	m.sq.	7000
Bitumen binder - surf layer	m.sq.	7000

TABLE M.17: Sewer main reconstruction and road minor rehabilitation steps

Activities	Unit	Output
Mobilization, derivation, etc.	Global	5
Installation 0-5 m w/ rock	m	20
Installation 0-5 m w/o rock	m	10
Installation > 5 m w/o rock	m	10
Installation > 5 m w/ rock	m	5
Sump installation - other side	unit	5
Connection install. -other side	unit	5
Manhole on-site	unit	0,067
Manhole precast	unit	1
Granular sub-base (500 mm)	m.sq.	1500
Granular base (MG20, 200mm)	m.sq.	2000
Bitumen binder - base layer	m.sq.	7000
Bitumen binder - midlayer	m.sq.	7000
Bitumen binder - surf layer	m.sq.	7000
Special measures, etc.	Global	3
Resurface	m.sq.	7000
Crack sealing (type 1 and 2)	m.sq.	200
New sump w/o connection	unit	10
New sump w/ connection	unit	5
Lid change	unit	5
Bitumen binder - base layer	m.sq.	7000*
Bitumen binder - surf layer	m.sq.	7000*

* On the remaining surface

TABLE M.18: Sewer main reconstruction and road major rehabilitation steps

Activities	Unit	Output
Mobilization, derivation, etc.	Global	5
Installation 0-5 m w/ rock	m	20
Installation 0-5 m w/o rock	m	10
Installation > 5 m w/o rock	m	10
Installation > 5 m w/ rock	m	5
Sump installation - other side	unit	5
Connection install. -other side	unit	5
Manhole on-site	unit	0,067
Manhole precast	unit	1
Granular sub-base (500 mm)	m.sq.	1500
Granular base (MG20, 200mm)	m.sq.	2000
Bitumen binder - base layer	m.sq.	7000
Bitumen binder - midlayer	m.sq.	7000
Bitumen binder - surf layer	m.sq.	7000
Special measures, etc.	Global	3
Lid preparation and removal	unit	15
Pulverization	m.sq.	500
New sump w/o connection	unit	10
New sump w/ connection	unit	5
Stabilization	m.sq.	800
Lid installation and change	unit	15
Bitumen binder - base layer	m.sq.	7000*
Bitumen binder - surf layer	m.sq.	7000*

TABLE M.19: Sewer main reconstruction and road reconstruction steps

Activities	Unit	Output
Mobilization, bypass, etc.	Global	5
Installation 0-5 m w/ rock	m	20
Installation 0-5 m w/o rock	m	10
Installation > 5 m w/o rock	m	10
Installation > 5 m w/ rock	m	5
Sump installation - other side	unit	5
Connection install. -other side	unit	5
Manhole on-site	unit	0,067
Manhole precast	unit	1
Special measures, etc.	Global	3
Bedding preparation	m.sq.	500
Rock excavation	m.cu.	20
New sump w/o connection	unit	10
New sump w/ connection	unit	5
Granular sub-base (500 mm)	m.sq.	1500
Granular base (MG20, 200mm)	m.sq.	2000
Lid change	unit	5
Bitumen binder - base layer	m.sq.	7000
Bitumen binder - midlayer	m.sq.	7000
Bitumen binder - surf layer	m.sq.	7000

TABLE M.20: Water and sewer main CIPP and road minor rehabilitation steps

Activities	Unit	Output
Mobilization, bypass, etc.	Global	8,75
Trenchless work	m	80
Valve chamber	unit	1
Fire hydrant	unit	1
Connection ≤ 50 mm	unit	5
Connection > 50 mm	unit	3
Mobilization, cleaning, etc.	Global	3,25
Trenchless work	m	100
Sump cleaning/inspection	unit	10
Coating of sump connection	unit	4
Connecting sump	unit	3
Inspection after 20 months	m	200
Mobilization, cleaning, etc.	Global	5
Resurface	m.sq.	7000
Crack sealing (type 1 and 2)	m.sq.	200
New sump w/o connection	unit	10
New sump w/ connection	unit	5
Lid change	unit	5
Bitumen binder - base layer	m.sq.	7000
Bitumen binder - surf layer	m.sq.	7000

TABLE M.21: Water and sewer main CIPP and road major rehabilitation steps

Activities	Unit	Output
Mobilization, bypass, etc.	Global	8,75
Trenchless work	m	80
Valve chamber	unit	1
Fire hydrant	unit	1
Connection ≤ 50 mm	unit	5
Connection > 50 mm	unit	3
Mobilization, cleaning, etc.	Global	3,25
Trenchless work	m	100
Sump cleaning/inspection	unit	10
Coating of sump connection	unit	4
Connecting sump	unit	3
Inspection after 20 months	m	200
Mobilization, cleaning, etc.	Global	5
Lid preparation & removal	unit	15
Pulverization	m.sq.	500
New sump w/o connection	unit	10
New sump w/ connection	unit	5
Stabilization	m.sq.	800
Lid installation and change	unit	15
Bitumen binder - base layer	m.sq.	7000
Bitumen binder - surf layer	m.sq.	7000

TABLE M.22: Water and sewer main CIPP and road reconstruction steps

Activities	Unit	Output
Mobilization, bypass, etc.	Global	8,75
Trenchless work	m	80
Valve chamber	unit	1
Fire hydrant	unit	1
Connection ≤ 50 mm	unit	5
Connection > 50 mm	unit	3
Mobilization, cleaning, etc.	Global	3,25
Trenchless work	m	100
Sump cleaning/inspection	unit	10
Coating of sump connection	unit	4
Connecting sump	unit	3
Inspection after 20 months	m	200
Mobilization, cleaning, etc.	Global	4,5
Bedding preparation	m.sq.	500
Rock excavation	m.cu.	20
New sump w/o connection	unit	10
New sump w/ connection	unit	5
Granular sub-base (500 mm)	m.sq.	1500
Granular base (MG20, 200mm)	m.sq.	2000
Lid change	unit	5
Bitumen binder - base layer	m.sq.	7000
Bitumen binder - midlayer	m.sq.	7000
Bitumen binder - surf layer	m.sq.	7000

TABLE M.23: Water main reconstruction, sewer main CIPP and road minor rehabilitation steps

Activities	Unit	Output
Mobilization, bypass, etc.	Global	5,3
Transmission main	m	35
Distribution main	m	30
Valve chamber	unit	1
Fire hydrant	unit	1
Connections	unit	5
Granular sub-base (500 mm)	m.sq.	1500
Granular base (MG20, 200mm)	m.sq.	2000
Bitumen binder - base layer	m.sq.	7000
Bitumen binder - midlayer	m.sq.	7000
Bitumen binder - surf layer	m.sq.	7000
Mobilization, cleaning, etc.	Global	3,25
Trenchless work	m	100
Sump cleaning/inspection	unit	10
Coating of sump connection	unit	4
Connecting sump	unit	3
Inspection after 20 months	m	200
Special measures, etc.	Global	3
Resurface	m.sq.	7000
Crack sealing (type 1 and 2)	m.sq.	200
New sump w/o connection	unit	10
New sump w/ connection	unit	5
Lid change	unit	5
Bitumen binder - base layer	m.sq.	7000*
Bitumen binder - surf layer	m.sq.	7000*

* On the remaining surface

TABLE M.24: Water main reconstruction, sewer main CIPP and road major rehabilitation steps

Activities	Unit	Output
Mobilization, bypass, etc.	Global	5,3
Transmission main	m	35
Distribution main	m	30
Valve chamber	unit	1
Fire hydrant	unit	1
Connections	unit	5
Granular sub-base (500 mm)	m.sq.	1500
Granular base (MG20, 200mm)	m.sq.	2000
Bitumen binder - base layer	m.sq.	7000
Bitumen binder - midlayer	m.sq.	7000
Bitumen binder - surf layer	m.sq.	7000
Mobilization, cleaning, etc.	Global	3,25
Trenchless work	m	100
Sump cleaning/inspection	unit	10
Coating of sump connection	unit	4
Connecting sump	unit	3
Inspection after 20 months	m	200
Special measures, etc.	Global	3
Lid preparation and removal	unit	15
Pulverization	m.sq.	500
New sump w/o connection	unit	10
New sump w/ connection	unit	5
Stabilization	m.sq.	800
Lid installation and change	unit	15
Bitumen binder - base layer	m.sq.	7000*
Bitumen binder - surf layer	m.sq.	7000*

TABLE M.25: Water main reconstruction, sewer main CIPP and road reconstruction steps

Activities	Unit	Output
Mobilization, bypass, etc.	Global	5,3
Transmission main	m	35
Distribution main	m	30
Valve chamber	unit	1
Fire hydrant	unit	1
Connections	unit	5
Mobilization, cleaning, etc.	Global	3,25
Trenchless work	m	100
Sump cleaning/inspection	unit	10
Coating of sump connection	unit	4
Connecting sump	unit	3
Inspection after 20 months	m	200
Special measures, etc.	Global	3
Bedding preparation	m.sq.	500
Rock excavation	m.cu.	20
New sump w/o connection	unit	10
New sump w/ connection	unit	5
Granular sub-base (500 mm)	m.sq.	1500
Granular base (MG20, 200mm)	m.sq.	2000
Lid change	unit	5
Bitumen binder - base layer	m.sq.	7000
Bitumen binder - midlayer	m.sq.	7000
Bitumen binder - surf layer	m.sq.	7000

TABLE M.26: Water and sewer main reconstruction and road minor rehabilitation steps

Activities	Unit	Output
Mobilization, bypass, etc.	Global	5,3
Transmission main	m	35
Distribution main	m	30
Valve chamber	unit	1
Fire hydrant	unit	1
Connections	unit	5
Installation 0-5 m w/ rock	m	20
Installation 0-5 m w/o rock	m	10
Installation > 5 m w/o rock	m	10
Installation > 5 m w/ rock	m	5
Sump installation - other side	unit	5
Connection install. - other side	unit	5
Manhole on-site	unit	0,067
Manhole precast	unit	1
Granular sub-base (500 mm)	m.sq.	1500
Granular base (MG20, 200mm)	m.sq.	2000
Bitumen binder - base layer	m.sq.	7000
Bitumen binder - midlayer	m.sq.	7000
Bitumen binder - surf layer	m.sq.	7000
Special measures, etc.	Global	5
Resurface	m.sq.	7000
Crack sealing (type 1 and 2)	m.sq.	200
New sump w/o connection	unit	10
New sump w/ connection	unit	5
Lid change	unit	5
Bitumen binder - base layer	m.sq.	7000*
Bitumen binder - surf layer	m.sq.	7000*

* On the remaining surface

TABLE M.27: Water and sewer main reconstruction and road major rehabilitation steps

Activities	Unit	Output
Mobilization, bypass, etc.	Global	5,3
Transmission main	m	35
Distribution main	m	30
Valve chamber	unit	1
Fire hydrant	unit	1
Connections	unit	5
Installation 0-5 m w/ rock	m	20
Installation 0-5 m w/o rock	m	10
Installation > 5 m w/o rock	m	10
Installation > 5 m w/ rock	m	5
Sump installation - other side	unit	5
Connection install. - other side	unit	5
Manhole on-site	unit	0,067
Manhole precast	unit	1
Granular sub-base (500 mm)	m.sq.	1500
Granular base (MG20, 200mm)	m.sq.	2000
Bitumen binder - base layer	m.sq.	7000
Bitumen binder - midlayer	m.sq.	7000
Bitumen binder - surf layer	m.sq.	7000
Special measures, etc.	Global	3
Lid preparation and removal	unit	15
Pulverization	m.sq.	500
New sump w/o connection	unit	10
New sump w/ connection	unit	5
Stabilization	m.sq.	800
Lid installation and change	unit	15
Bitumen binder - base layer	m.sq.	7000*
Bitumen binder - surf layer	m.sq.	7000*

TABLE M.28: Water and sewer main reconstruction and road reconstruction steps

Activities	Unit	Output
Mobilization, bypass, etc.	Global	5,3
Transmission main	m	35
Distribution main	m	30
Valve chamber	unit	1
Fire hydrant	unit	1
Connections	unit	5
Installation 0-5 m w/ rock	m	20
Installation 0-5 m w/o rock	m	10
Installation > 5 m w/o rock	m	10
Installation > 5 m w/ rock	m	5
Sump installation - other side	unit	5
Connection install. - other side	unit	5
Manhole on-site	unit	0,067
Manhole precast	unit	1
Special measures, etc.	Global	5
Bedding preparation	m.sq.	500
Rock excavation	m.cu.	20
New sump w/o connection	unit	10
New sump w/ connection	unit	5
Granular sub-base (500 mm)	m.sq.	1500
Granular base (MG20, 200mm)	m.sq.	2000
Lid change	unit	5
Bitumen binder - base layer	m.sq.	7000
Bitumen binder - midlayer	m.sq.	7000
Bitumen binder - surf layer	m.sq.	7000

* On the remaining surface

TABLE M.29: Water main CIPP, sewer main reconstruction and road minor rehabilitation steps

Activities	Unit	Output
Mobilization, bypass, etc.	Global	8,75
Trenchless work	m	80
Valve chamber	unit	1
Fire hydrant	unit	1
Connection ≤ 50 mm	unit	5
Connection > 50 mm	unit	3
Mobilization, bypass, etc.	Global	5
Installation 0-5 m w/ rock	m	20
Installation 0-5 m w/o rock	m	10
Installation > 5 m w/o rock	m	10
Installation > 5 m w/ rock	m	5
Sump installation - other side	unit	5
Connection install. - other side	unit	5
Manhole on-site	unit	0,067
Manhole precast	unit	1
Granular sub-base (500 mm)	m.sq.	1500
Granular base (MG20, 200mm)	m.sq.	2000
Bitumen binder - base layer	m.sq.	7000
Bitumen binder - midlayer	m.sq.	7000
Bitumen binder - surf layer	m.sq.	7000
Special measures, etc.	Global	3
Resurface	m.sq.	7000
Crack sealing (type 1 and 2)	m.sq.	200
New sump w/o connection	unit	10
New sump w/ connection	unit	5
Lid change	unit	5
Bitumen binder - base layer	m.sq.	7000*
Bitumen binder - surf layer	m.sq.	7000*

* On the remaining surface

TABLE M.30: Water main CIPP, sewer main reconstruction and road major rehabilitation steps

Activities	Unit	Output
Mobilization, bypass, etc.	Global	8,75
Trenchless work	m	80
Valve chamber	unit	1
Fire hydrant	unit	1
Connection ≤ 50 mm	unit	5
Connection > 50 mm	unit	3
Mobilization, bypass, etc.	Global	5
Installation 0-5 m w/ rock	m	20
Installation 0-5 m w/o rock	m	10
Installation > 5 m w/o rock	m	10
Installation > 5 m w/ rock	m	5
Sump installation - other side	unit	5
Connection install. - other side	unit	5
Manhole on-site	unit	0,067
Manhole precast	unit	1
Granular sub-base (500 mm)	m.sq.	1500
Granular base (MG20, 200mm)	m.sq.	2000
Bitumen binder - base layer	m.sq.	7000
Bitumen binder - midlayer	m.sq.	7000
Bitumen binder - surf layer	m.sq.	7000
Special measures, etc.	Global	3
Lid preparation and removal	unit	15
Pulverization	m.sq.	500
New sump w/o connection	unit	10
New sump w/ connection	unit	5
Stabilization	m.sq.	800
Lid installation and change	unit	15
Bitumen binder - base layer	m.sq.	7000*
Bitumen binder - surf layer	m.sq.	7000*

TABLE M.31: Water main CIPP, sewer main reconstruction and road reconstruction steps

Activities	Unit	Output
Mobilization, bypass, etc.	Global	8,75
Trenchless work	m	80
Valve chamber	unit	1
Fire hydrant	unit	1
Connection ≤ 50 mm	unit	5
Connection > 50 mm	unit	3
Mobilization, bypass, etc.	Global	5
Installation 0-5 m w/ rock	m	20
Installation 0-5 m w/o rock	m	10
Installation > 5 m w/o rock	m	10
Installation > 5 m w/ rock	m	5
Sump installation - other side	unit	5
Connection install. - other side	unit	5
Manhole on-site	unit	0,067
Manhole precast	unit	1
Special measures, etc.	Global	3
Bedding preparation	m.sq.	500
Rock excavation	m.cu.	20
New sump w/o connection	unit	10
New sump w/ connection	unit	5
Granular sub-base (500 mm)	m.sq.	1500
Granular base (MG20, 200mm)	m.sq.	2000
Lid change	unit	5
Bitumen binder - base layer	m.sq.	7000
Bitumen binder - midlayer	m.sq.	7000
Bitumen binder - surf layer	m.sq.	7000

TABLE M.32: Water and sewer main CIPP steps

Activities	Unit	Output
Mobilization, bypass, etc.	Global	8,75
Trenchless work	m	80
Valve chamber	unit	1
Fire hydrant	unit	1
Connection ≤ 50 mm	unit	5
Connection > 50 mm	unit	3
Mobilization, cleaning, etc.	Global	3,25
Trenchless work	m	100
Sump cleaning/inspection	unit	10
Coating of sump connection	unit	4
Connecting sump	unit	3
Inspection after 20 months	m	200

TABLE M.33: Water main CIPP and sewer main reconstruction steps

Activities	Unit	Output
Mobilization, bypass, etc.	Global	8,75
Trenchless work	m	80
Valve chamber	unit	1
Fire hydrant	unit	1
Connection ≤ 50 mm	unit	5
Connection > 50 mm	unit	3
Mobilization, derivation, etc.	Global	5
Installation 0-5 m w/ rock	m	20
Installation 0-5 m w/o rock	m	10
Installation > 5 m w/o rock	m	10
Installation > 5 m w/ rock	m	5
Sump installation - other side	unit	5
Connection install. - other side	unit	5
Manhole on-site	unit	0,067
Manhole precast	unit	1
Granular sub-base (500 mm)	m.sq.	1500
Granular base (MG20, 200mm)	m.sq.	2000
Bitumen binder - base layer	m.sq.	7000
Bitumen binder - midlayer	m.sq.	7000
Bitumen binder - surf layer	m.sq.	7000

TABLE M.34: Water main reconstruction and sewer main rehabilitation steps

Activities	Unit	Output
Mobilization, bypass, etc.	Global	5,3
Transmission main	m	35
Distribution main	m	30
Valve chamber	unit	1
Fire hydrant	unit	1
Connections	unit	5
Granular sub-base (500 mm)	m.sq.	1500
Granular base (MG20, 200mm)	m.sq.	2000
Bitumen binder - base layer	m.sq.	7000
Bitumen binder – midlayer	m.sq.	7000
Bitumen binder - surf layer	m.sq.	7000
Mobilization, cleaning, etc.	Global	3,25
Trenchless work	m	100
Sump cleaning/inspection	unit	10
Coating of sump connection	unit	4
Connecting sump	unit	3
Inspection after 20 months	m	200

TABLE M.35: Water and sewer main reconstruction steps

Activities	Unit	Output
Mobilization, bypass, etc.	Global	5,3
Transmission main	m	35
Distribution main	m	30
Valve chamber	unit	1
Fire hydrant	unit	1
Connections	unit	5
Special measures, etc.	Global	3
Installation 0-5 m w/ rock	m	20
Installation 0-5 m w/o rock	m	10
Installation > 5 m w/o rock	m	10
Installation > 5 m w/ rock	m	5
Sump installation - other side	unit	5
Connection install. - other side	unit	5
Manhole on-site	unit	0,067
Manhole precast	unit	1
Granular sub-base (500 mm)	m.sq.	1500
Granular base (MG20, 200mm)	m.sq.	2000
Bitumen binder - base layer	m.sq.	7000
Bitumen binder – midlayer	m.sq.	7000
Bitumen binder - surf layer	m.sq.	7000

TABLE M.36: Reconstruction of mails, sidewalks and curbs

Activities	Unit	Output
Mobilization, bypass, etc.	Global	5
Sidewalk demolition	m	125
Curbside demolition	m	300
Fire hydrant*	unit	1
Lid change*	unit	5
Sidewalk formwok	m	300
Sidewalk placement	m.ca	450
Curbside formwork	m	100
Curbside formwork by hand	m	300
Pedestrian island formwork	m	300
Pedestrain island placement	m.ca	450
Concrete structure refection	m	300
Water course restoration	m	300
Tree planting	m.cu	20

* Also considered in other activities

Appendix N – Decision trees for renewal

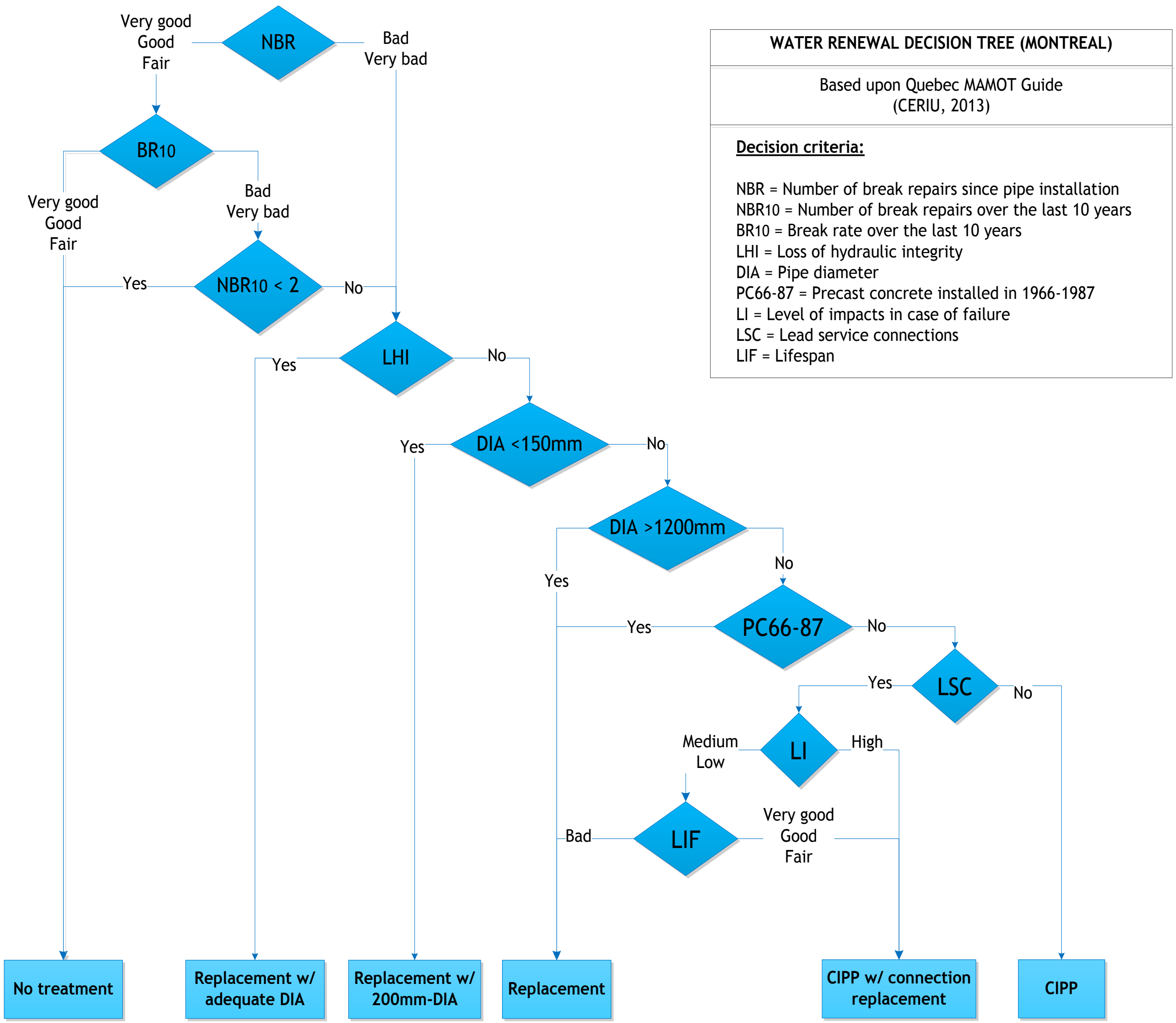


FIGURE N.1: Decision tree for water segment treatments

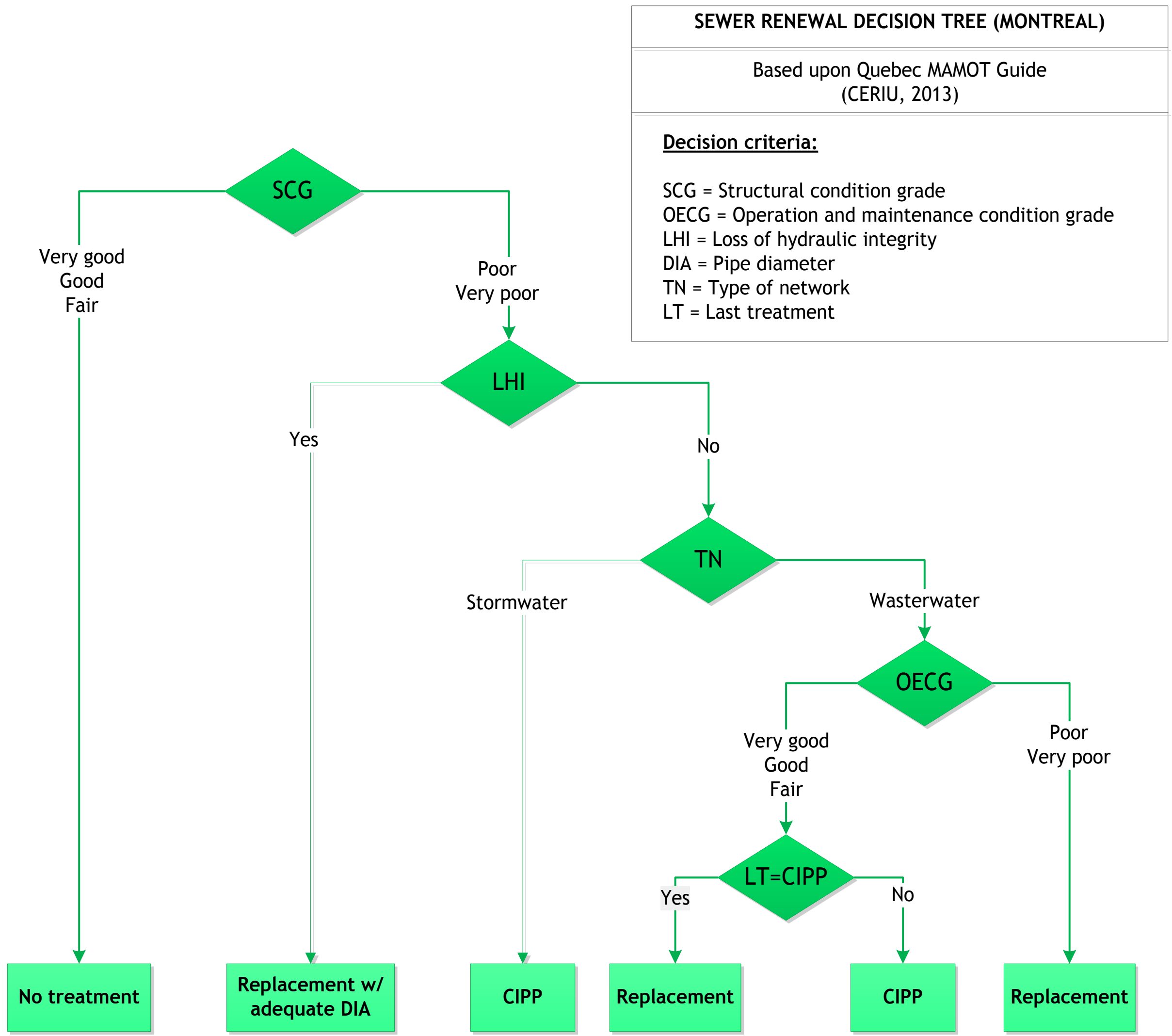


FIGURE N.2: Decision tree for sewer segment treatments

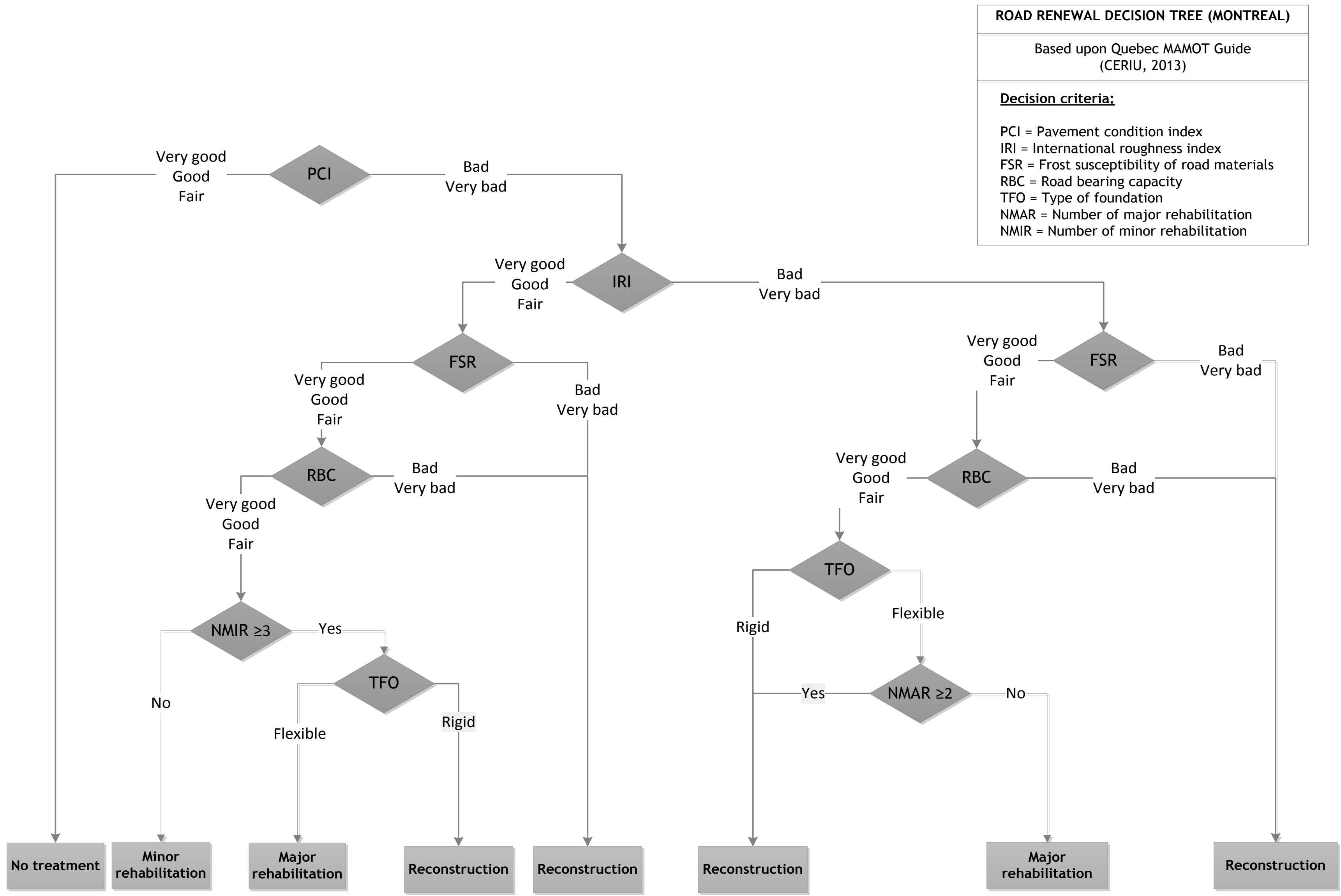


FIGURE N.3: Decision tree for road segment treatments

Appendix O – Decision support system

Table O.1: Developed analysis criteria

Water	Sewer
• Age • Years of installation, of renewal • Diameter • Cumulative number of breaks • Break rate • Length • Possibility of trenchless work (Yes/No) • Jurisdiction (secondary/primary) • Fragility of material (Yes/No) • Presence of lead service lines (Yes/No) • Elapsed lifespan • Remaining life span • Suitable diameter (Yes/No) • Recommended diameter (Yes/No) • Impact level of failure (high-to-low)Prioritization grade • Road classification • Type of material	• Age • Years of installation, of renewal, of last inspection • Diameter • Condition grades from last inspection • Current SCS • Simulated SCS • Possibility of trenchless work (Yes/No) • Remaining lifespan • Elapsed lifespan • Length • Jurisdiction (secondary/primary) • Suitable diameter (Yes/No) • Recommended diameter (Yes/No) • Prioritization grade • Road classification • Type of material • Presence of water segment in the trench • Impact level of failure (high-to-low)
Road	**Road corridor**
• Age of foundation • Year of construction, of renewal, of inspection • Road classification • Performance condition index • Roughness index • Frost susceptibility • Load bearing capacity • Prioritization grade • Treatment elapsed life span • Treatment remaining life span • Jurisdiction (arterial/local) • Length • Width • Surface • Type of foundation • Presence of central mail, sidewalk, curbs • Surface of central mail, sidewalk, curbs	• Water segment remaining lifespan • Sewer segment remaining life span • Road segment remaining life span • Road jurisdiction • Road length • Water prioritization grade • Sewer prioritization grade • Road prioritization grade • Road corridor prioritization grade • Presence of fragile water segment • Presence of fragile sewer segment

When initialisation check box is active, this means that the condition state of pipe should be reassessed after performing one detailed actions. The cost module should be upgraded in the frame of this research to incorporate social costs related to different activities (see Figure O.2).

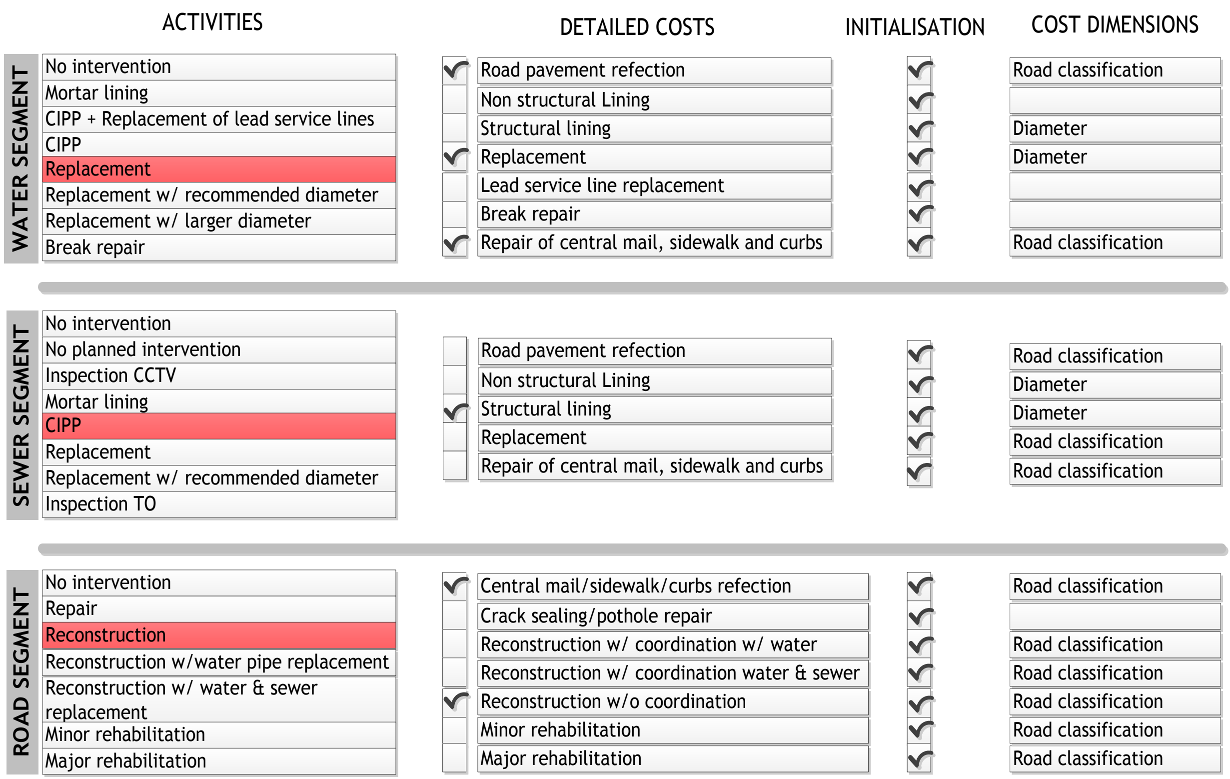


Figure O.1: Former cost module (adapted from InfraModex)

Figure O.2: New cost module (adapted from InfraModex)

The optimization of coordination decisions is achieved at two levels based on local practices. At the asset level, if a pipe segment is scheduled for OCR then all segments of the same type within the corridor will also be replaced regardless of their condition. This does not apply to CIPP for which solely the segment scheduled will be lined. At the corridor level, if a pipe is scheduled for OCR then all types of assets above will also be replaced. Therefore, it is important to verify the kind of treatment due for assets below in order to avoid repeated OCR resulting in efficient use of renewal budgets.

A proposed study in the matter of coordination could be to find the optimal *coordination tree*. This could not be achieved in this study because of extensive programming that was required in InfraModex. However, a tree search heuristic can be developed. The first step is to build the initial decision tree and estimates present value of treatment costs over the planning horizon resulting from the initial tree implementation. Initial terminal states are treatments resulting from individual programs of works.

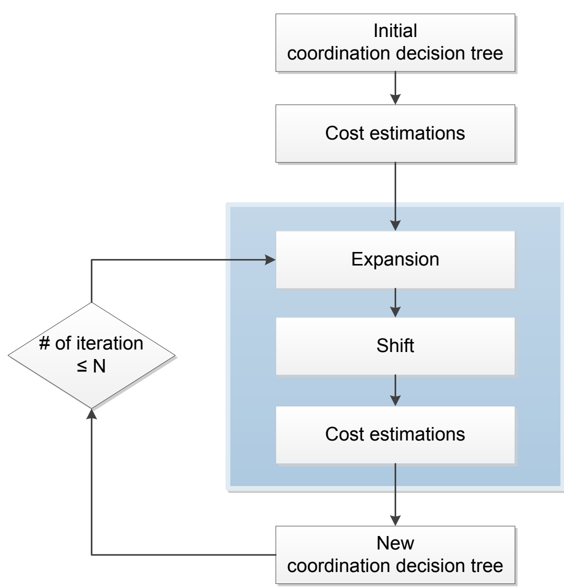


Figure P.1: Tree search heuristic for coordination

The expansion process can consist in adding one or more decision criteria to terminal nodes. Figure P.2 illustrates a node expansion where a period of T years can be generated randomly in a range from 5 to 25 years and can differ from water to sewer pipe. So if a sewer segment is due now for CIPP and another in the same corridor for OCR in less than T years, then OCR will be performed now for all sewer segments (work package #1 in Table 3.6); but if all of remaining sewer segments are due for OCR in more than T years and a water segment is due for OCR in less than T years, then OCR will be performed now for all water segments (work package #2 in Table 3.6). The complexity of buried networks resides in the fact that a corridor can have more than one pipe segments, with different treatments at different timings.

The shifting of terminal states consists in changing an initial state into another. Figure P.2 illustrates all retained potential states, for example, initial states 3 and 12 could mutate respectively to 1 and 11. Potential states for mutation are based upon policies to mitigate social disruption (such as *synchronizing* sequential OCR to avoid repeated pavement cuts over a short period, *avoiding* road OCR if pipes do not require OCR, *promoting* long-lasting road treatments to minimize treatments over the pavement life, and *performing* pipe CIPP if necessary when road OCR is due in order to reduce risks of weakening adjacent pipes because of higher break rates).

Finally, the cost estimations can be performed for the new decision tree. If the costs from the new tree are greater than the old, then new tree is retained. These processes are repeated a number of N times. Finally, the least-cost coordination tree is selected as the intervention strategy to be followed. The best timing T can also be found.

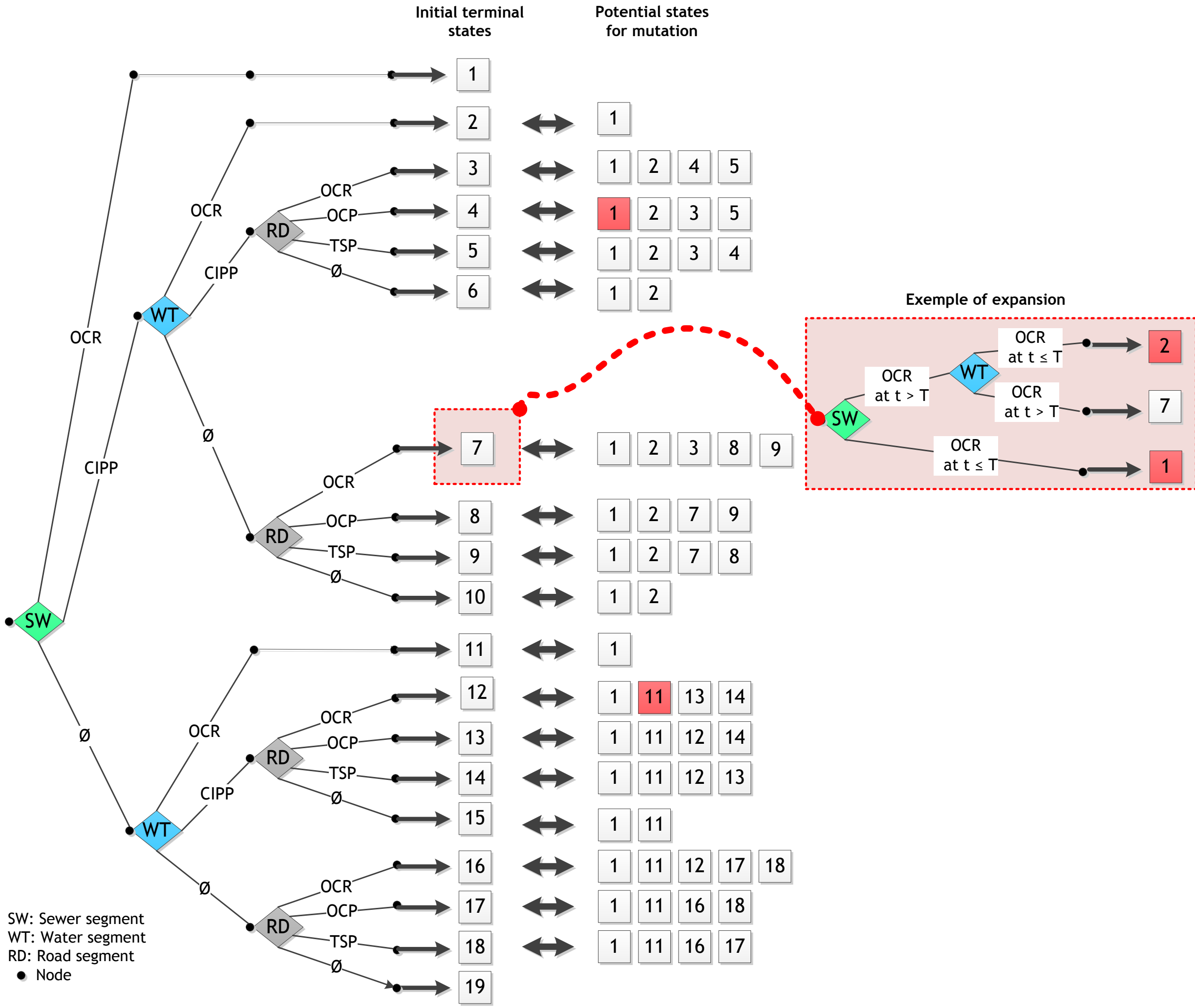


Figure P.2: Example of node expansion and mutation