Evaluating the Safety Effects of Driver Feedback Signs and Citywide Implementation Strategies

by

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Abstract

Speeding is a leading factor that contributes to about one-third of all fatal collisions. To improve drivers' compliance with speeds, various passive/active countermeasures have been adopted by municipalities around the world. A Driver Feedback Sign (DFS) is one such countermeasure as it dynamically displays the speed of the driver and warns them if they are speeding. It is relatively new, but it has the added advantage of being a low-cost intervention tool and its use is growing in urban centers worldwide. Despite documentation showing that DFSs are effective at reducing speeds, literature on its impact for reducing collisions is limited. This research serves to add to and advance the body of research into DFSs impact on traffic safety.

This research was completed in two phases. Phase I is a before-and-after study with the Empirical Bayes (EB) method to examine the effects DFSs have on reducing collisions. Safety Performance Functions (SPF) and yearly calibration factors were developed to quantify the sole effectiveness of DFSs using a large-scale spatial dataset of reference road segments. Afterwards, a detailed economic analysis was conducted to investigate the cost-effectiveness of DFSs.

As many municipalities' budgets and resources are limited, Phase II of the thesis makes use of the methods and findings from Phase I to develop a location allocation framework to aid in determining the optimal implementation strategy for DFSs for two scenarios, an all-new scenario and an expanded scenario. The all-new scenario would represent a case of moving all existing DFS to optimal locations or for a completely new DFS system. The expanded scenario takes the existing DFS system and finds optimal locations where new DFSs should be installed. This optimization framework makes use of the safety effectiveness of DFSs and its spatial coverage for vulnerable road users as factors. By assigning different weights to these factors, transportation agencies can make a preference for either one over the other. The greedy algorithm was employed to solve the combinatorial optimization problem.

The case study area is the City of Edmonton, Alberta, Canada where they have been using DFSs since 2011 and to date has installed 212 DFSs throughout the city. The City has a large and vastly varied road network with an extensive history of DFSs and other speeding countermeasures. The data set used was provided by the City and encompasses collision data, locations of school and

senior housing, traffic volumes, and road geometry over 10 years. This thesis makes use of these large data sets for both Phase I and II. The main findings of this thesis are summarized below.

Phase I results showed significant collision reductions that ranged from 32.5% to 44.9%, with the highest reductions observed for severe speed-related collisions. The economic analysis found that the benefit-cost ratios, if combining severe and Property-Damage-Only collisions, ranged from 8.2 to 20.2 indicating that the DFS can be an extremely economical countermeasure. The combined use of both DFS and mobile photo enforcement (MPE) was found to result in a slightly higher effect on safety. Before-after change models suggested that segments with higher initial collision frequencies, and generally with higher traffic volumes and longer road lengths, seem to benefit the most from the installation of DFSs. Additionally, the presence of shoulders was also found to impact the reduction in collisions for most collision types.

Phase II used the location allocation framework to develop a baseline of the City of Edmonton's existing DFS deployment for comparison to the two previously mentioned scenarios. It was found that the collision frequency reduction and coverage of vulnerable road users/facilities can be improved by up to 149.44% and 69.27%, respectively, in the all-new scenario. The expansion scenario study was done with 10 and 20 additional units to the system. It was found that collision frequency reductions can be improved by up to 30.22% and 51.61% for the additional 10 and 20 DFSs respectively, depending on the weights being used. Likewise, the coverage of vulnerable road users/facilities could be improved by up to 14.64% and 29.27% respectively.

Overall, the approaches proposed and developed in the thesis provide a new and innovative method to quantify the sole effects of DFSs on road safety. By linking risk factors that contributed to the collision reductions and increase at DFS location with various city-wide DFS implementation strategies developed herein, this research helps to provide transportation agencies in need of implementing cost-effective countermeasures with a tool they need to design a long-term strategic DFS deployment plan to ensure the safety of travelling public and thus maximize the return on their investment.

Preface

Work presented in this thesis is either accepted, published or is under-review for publication in various journals and conferences in the areas of transportation engineering.

Peer-reviewed Journal & Conference Papers (Accepted/Published)

1. **Wu, M.**, El-Basyouny, K., Kwon, T. J. (2019). Before-and-After Empirical Bayes Evaluation of Citywide Installation of Driver Feedback Signs. Accepted for presentation and recommended for publication at the *99th Annual Meeting of Transportation Research Board*, Washington, D.C., January 2020.
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3. Gu, L., **Wu, M.**, & Kwon, T. J. (2019). An Enhanced Spatial Statistical Method for Continuous Monitoring of Winter Road Surface Conditions. *Canadian Journal of Civil Engineering*. In-Press.
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Nomenclature

DFS	=	Driver feedback sign
EB	=	Empirical bayes
FLP	=	Facility location problems
$DFLP$	=	Discrete facility location problems
p	=	Number of facilities to be located
MPE	=	Mobile photo enforcement
ADT	=	Annual daily traffic volume
PDO	=	Property damage only
SPF	=	Safety performance function
μ	=	The predicted yearly average collision frequency
V	=	The traffic volume (ADT) of the road segment
L	=	The length of the road segment in meters
β_0	=	Regression parameter
β_1	=	Regression parameter
β_2	=	Regression parameter
RD	=	Residual deviance
LL	=	Loglikelihood
y_i	=	The actual number of collisions in site *i*
μ_i	=	The estimated number of collisions in site *i*
$n_{unt.}$	=	Total number of untreated sites
$Var(Y_i)$	=	Variance of collision frequency in site *i*
YCF_{cj}	=	Yearly calibration factor for collision type/severity *c* in year *j*
$N_{Expected,B}$	=	Expected number of collisions in the before period
$N_{Predicted,B}$		Predicted number of collisions in the before period
$N_{Observed,B}$	=	Observed number of collisions in the before period
w	=	Weighted adjustment factor (between 0 and 1)
k	=	Overdispersion parameter estimated from SPF
θ	=	Overall odds ratio of collision reduction

$SE(\theta)$	=	Associated standard error of θ
$N_{Expected,A}$	=	Expected number of collisions in the after period
$N_{Predicted,A}$	=	Predicted number of collisions in the after period
$N_{Observed,A}$	=	Observed number of collisions in the after period
NPV	=	Net present value
BCR	=	Benefit-cost ratio
PV	=	Present value
AV	=	Annual value
r	=	Annual interest rate
n_s	=	Number of service years
$PV_{benefits}$	=	Present value of project benefits
PV_{costs}	=	Present value of project costs
DC	=	Direct costs
HC	=	Human capital
WTP	=	Willingness-to-pay
I	=	Independent variables related to road segment characteristics
α	=	Regression parameter
β	=	Regression parameter
γ	=	Regression parameter
$\Delta(\%)$	=	Percent of change in collision frequencies, positive/negative means reduction/increase, respectively
SD	=	Scaled deviance
$Z^*(X_0)$	=	Estimated value at location X_0
$Z(X_i)$	=	Measured observations at sampling site X_i
λ_i	=	Kriging weight
$\gamma(h)$	=	Semivariance value
h	=	Lag distance
a	=	Spatial range of continuity
c	=	Sill
$C(h)$	=	Covariance value that measures the similarity of the measurements

Obj	=	Objective values of all the selected sites by integrating collision reductions and coverage of vulnerable road users/facilities
w_s	=	Weight value to adjust the importance of the two traffic safety concerns
n_{cad}	=	Total number of candidate sites
s_i	=	A binary value (0 or 1) controls the selection of the i^{th} candidate site, if s_i is equal to 1, it means the i^{th} candidate site is included, otherwise no
n_{max}	=	Maximum number of DFSs can be located in one road segment
s_i^m	=	A binary value (0 or 1) representing whether the m^{th} is located in the i^{th} candidate site
${\Delta_{EPDO}}_i^m$	=	Normalized collision reduction after putting the m^{th} DFS into the i^{th} candidate site
Cvg_i	=	Normalized coverage of vulnerable road users/facilities of segment i
B	=	Total available budget (i.e., the total number of DFSs will be located)
MSE	=	Mean Standardized Error
$RMSSE$	=	Root Mean Square Standardized Error

Chapter 1. INTRODUCTION

1.1 Background

Traffic collisions is a serious global issue causing around 1.24 million deaths and around 50 million injuries each year (World Health Organization, 2013). In Canada, there were 1,841 fatalities and 9,960 serious injuries in 2017 (Transport Canada, 2017). Traffic collisions not only cause harm to victims and their families but is also a tremendous burden to society as a whole. The estimated total social cost of motor vehicle collisions that occurred in Canadian jurisdictions in 2004 was $63 billion (Transport Canada, 2007). This number was approximately 5% of the gross domestic product (GDP) of Canada for that year. More troubling is that these statistics are very likely to be underestimated due to incomplete official police-reported data.

A number of factors contribute to the risk of collisions, the major causes include speeding, driving under the influence of alcohol and other psychoactive substances, non-use of motorcycle helmets, seat-belts and child restraints, distracted driving, unsafe road infrastructures, unsafe vehicles, inadequate post-crash care, and inadequate law enforcement of traffic laws (World Health Organization, 2018). Among all these factors, speeding greatly increases both the risk and severity of collisions as the faster the vehicle is travelling, the stopping distance required will be longer. Statistics indicate speeding is a major contributor to road injuries and fatalities (World Health Organization, 2013), an extensive survey conducted by Transport Canada showed that, on average, 40-to-50% of all drivers exceed the speed limit (Organisation for Economic Co-operation and Development, 2006) and according to collision statistics, it is conservatively estimated that about 27% of fatalities and 19% of serious injuries involve speeding (Road Safety Canada Consulting, 2011). Unfortunately, speeding continues to be a widespread problem and its dangers are underestimated (Elvik, 1997; Thomas, et al., 2008; Goldenbeld & Schagen, 2005; Li, et al., 2015).

As a result, addressing the speeding problem remains a priority for most transportation agencies. Over the past few years, the City of Edmonton has adopted various citywide safety countermeasures, placing a priority on speed management in order to achieve their Vision Zero initiative (The City of Edmonton Office of Traffic Safety), which is a multi-national road traffic safety project that aims to achieve a road system with no fatalities or serious injuries.

Consequently, the city has been systemically investing in systems, programs, and tools, including Intersection Safety Devices (ISD), Mobile Photo Enforcement (MPE) program, and Driver Feedback Signs (DFS) as means to manage speeds. It has been found that the implementation of ISD and MPE had effectively reduced collisions frequencies ranging from 12 to 25% and 14 to 20% respectively in Edmonton. (Li, et al., 2015; Contini & El-Basyouny, 2016; Contini, 2015).

Although both initiatives showed significant impacts on reducing collision frequencies, their limitations are quite evident and well documented in the literature. Many intersections are installed with ISDs that target collisions occurring within or near those intersections, however, little evidence has been found to suggest its impact on reducing collisions on midblock segments. Although MPE has proven to be an effective countermeasure for reducing speeding and related collision frequencies on mid-block locations (Li, et al., 2015; Li, et al., 2017), the deployment of MPE requires extensive resources in terms of manpower and equipment. More so, MPE is not an ideal countermeasure at locations with high traffic volumes as it is likely to present a risk to personnel during their operation (Ullman & Rose, 2005). Finally, both ISD and MPE are usually associated with negative publicity and controversy (Ullman & Rose, 2005; Kergoat, et al., 2017).

To address the above-mentioned shortcomings, the Driver Feedback Sign (DFS), as shown in **Figure 1-1**, also referred to as the Dynamic Speed Display Sign or Speed Feedback Sign, is being proposed as an effective measure to control speeds at mid-block locations and near intersections. DFSs are usually installed on roadways where speeding problems are significant or in areas frequented by pedestrians as well as areas in close proximity to school and work zones. A DFS system is composed of a digital display board paired with a speed limit sign and a radar speed detector. As a vehicle approaches a DFS, the speed automatically displays on the board. If the driver’s speed is higher than the pre-set limit, the recorded speed flashes on the board warning drivers to slow down.

Figure 1-1 A Driver Feedback Sign

Previous studies have shown that DFSs are an effective tool for reducing speeds at their implemented locations (Ullman & Rose, 2005; Garber & Patel, 1994; Gehlert, et al., 2012; McCoy, et al., 1995; Lee, et al., 1973). However, the safety effectiveness of DFSs over a long time period has not been explored in the past and thus warrants further investigation.

Due to limited financial resources the questions of how many DFSs are needed in an urban city, in order to maximize their safety benefits, is another topic that also needs to be explored. Existing literatures (Santiago-Chaparro, et al., 2012; Williamson, et al., 2016; Garber & Patel, 1994; III, et al., 2015) suggest locations with higher pedestrian flows, such as school zones and work zones, should be given priority for the installation of a DFS, with the distance interval between DFSs to be around 500 meters. However, these existing findings are not sufficient for determining detailed locations of DFSs while considering the safety effectiveness and other practical factors (e.g., vulnerable road users/facilities). As such, a new framework needs to be developed for selecting ideal DFS sites while incorporating the overall safety effectiveness and other practical factors.

1.2 Problems Statement and Motivation

Based on existing observations and previous research regarding DFSs and similar countermeasures, it has been proven that DFSs are effective in reducing vehicles' speeds in different types of areas, such as highways, work zones, and school zones. Currently, however, there exist significant gaps in knowledge and methods for quantifying the sole effectiveness of DFS and further for effective planning of DFSs over a large road network.

The first research question is ascertain whether or not the implementation of DFSs can improve traffic safety by reducing speed violations and improving speed limit compliance, on an urban road network. Previous studies only selected several specific sites to test, most of them were only conducted in school zones or work zones, which are relatively special portions of a city's road network. Arterial and collector roads carry most of the traffic volumes within cities, and the majority of collisions occur on these roadway classifications. By comparison, school zones are not typically compromised of roads that carry high daily traffic volumes, and the traffic conditions within are often impacted by pedestrian activity. Similarly, work zones might also be frequented by pedestrians, but also have the addition of workers and heavy equipment. Also, the speed limits in these two zones are usually lower compared to other roadways in the network. Thus, they are not representative of the overall effectiveness of urban roads in an entire city.

The second question is to what degree DFSs contribute to reducing collisions as the ultimate purpose of these safety devices is to minimize collisions. Hence, it is critical to quantify the magnitude of change in the number of collisions that results from the installation of a DFS. However, the majority of previous studies focused on DFS's effectiveness in reducing speeds instead of reducing collisions. The casual relationship between speed and safety has been demonstrated in previous research, meaning we can assume a reduction in speeds will result in a reduction in the occurrence of collisions; however, there is no definitive connection between speed changes promoted by DFS and reduced collisions (Elvik, 2005). The gap between DFSs and their direct impact on collisions needs to be addressed based on quantitative and objective safety measures.

The third question is whether DFSs are effective in improving traffic safety over a long-time period. Some studies (Williamson, et al., 2016; Pesti & McCoy, 2001) considered the temporary impacts of DFSs. However, these studies compared the effectiveness week by week or month by month instead of over multiple years. Typically, transportation agencies would not invest in DFSs for only a couple of months or even weeks, so the long-term effectiveness of DFS in traffic safety also needs to be established.

Finally, while deemed effective in voluntary speed reduction, DFSs can only be deployed at a limited number of locations due to restricted resources and high budgetary constraints. Considering the extensive urban road network that constantly needs to be monitored, DSFs must be located strategically so that they are collectively most informative for providing location specific speed information of the entire road network. Despite this significance, there exist a few past efforts dedicated to the DFS location problem (Ullman & Rose, 2005; Santiago-Chaparro, et al., 2012). Traffic safety authorities generally follow a laborious yet ad-hoc process when locating DFSs onto their large urban road network. Furthermore, decisions about suitable DFS locations can often become challenging, given that multiple factors that must be considered. As such, the development of a systematic location allocation framework would greatly benefit those tasked with DFS planning and placement as it will aid in evaluating the overall efficiency of their existing network and assist with any expansion plans to their network.

1.3 Research Objectives

As discussed previously, speed reduction is bound to result in a decline in the number of collisions, yet its extent remains unknown. The impact that DFS might have on reducing the severity or type of collisions has also been unexplored. Furthermore, the high installation costs of DFSs along with the need to cover Edmonton's vastly varied and large road network necessitate a strategic and scientific approach to the optimal planning of a DFS network.

The central objective of this research, therefore, is to explore and quantify the effectiveness of DFSs for reducing collision frequencies by type and severity and develop a DFS-tailored location allocation framework for determining their optimal locations over an urban road network. Since the development of the location model depends strictly upon delineating factors contributing to the collision reductions at DFS sites, two primary chronological phases can be identified as follows:

Phase I: Traffic safety assessment of DFSs. This part of the research aims to:

a) Conduct a comprehensive literature review on DFS,
b) Conduct a DFS segment-based before and after traffic safety evaluation,
c) Conduct an economic analysis of the DFS project, and
d) Compare the safety impact results for different road/collision categories and summarize the lessons learned from the existing DFS deployment.

Phase II: Development of city-wide DFS implementation strategy framework. This part of the research aims to:

a) Synthesize the current best practice and guidelines for deploying and expanding DFS network,
b) Develop a method for optimal location-allocation of DFS based on the analyses conducted, and
c) Apply the developed methodology to evaluate the goodness of existing DFS locations and create a ranked list for future DFS installation.

The results and findings from this thesis can provide transportation agencies with a tool to assess the safety impact, the economic benefit, influential factors of a countermeasure and any resulting benefits from it. Furthermore, a site selection framework, once developed, will help transportation agencies design a long-term strategic deployment plan while considering multiple factors to ensure the safety of travelling public.

1.4 Thesis Organization

The remainder of this thesis is organized into the following chapters. Chapter 2 provides a literature review in two sections related to the topics of this thesis. The first section summarizes the existing findings of DFSs based on previous studies including short-term and long-term effectiveness comparison in different areas of a city. The second section introduces the underlying theory pertaining to various location allocation models and efficient optimization algorithms.

Chapter 3 presents the Phase I of the thesis, which is the segment-based traffic safety evaluation of DFSs along with the data used, methodology proposed, and results generated therein. The results include the overall safety effects of the DFS program as well as its economic analysis. By modelling the collision frequency changes at treated sites, critical factors that tend to influence DFSs' safety effectiveness are identified.

Chapter 4 details the Phase II of the thesis by providing a new framework of the citywide implementation strategy for DFSs. The data requirement for this framework and the methodologies behind it are also included in this chapter. A geostatistical interpolation method; namely, kriging, is proposed to estimate average daily traffic volume (ADT) for the entire city road network. An efficient Greedy Algorithm (GA) is then utilized to determine the optimal location solutions based on different optimization criteria and user inputs.

Finally, Chapter 5 highlights the main findings and contributions of this thesis and includes a brief discussion of future research.

Chapter 2. LITERATURE REVIEW

This chapter provides a review of previous studies related to traffic safety countermeasures with a specific focus on driver feedback sign (DFS). Section 2.1 describes past efforts devoted to quantifying the effect of DFS on traffic safety. Section 2.2 discusses the discrete facility location problems and some of the most adopted heuristic solution algorithms. The summary of this chapter is presented in Section 2.3 with the discussion of limitations of previous studies.

2.1 Driver Feedback Sign and Traffic Safety

Previous studies have mainly focused on the effectiveness of DFSs' and similar devices' on reducing speeds, where the speed reduction was found to be as high as 33 mph (Veneziano, et al., 2010; Williamson, et al., 2016) in rural communities, school zones, and work zones (Chang, et al., 2004; III, et al., 2015). McCoy et al. (1995) selected work zones as test locations and observed changes in speed habits after DFSs were installed. Garber and Patel (1994) conducted an evaluation test after DFSs were installed on seven work zones selected from two interstate highways in Virginia. Results from their evaluation indicated that DFSs effectively reduced the number of vehicles speeding by 10 mph or more in these work zones. Another study found that DFSs could reduce the number of drivers exceeding the posted speed limit through a work zone by 20% to 40% (Fontaine & Carlson, 2001). Lee et al. (1973) showed driving speeds were reduced in both work zones and school zones during both short-term and long-term periods due to DFSs. To compare the effectiveness of DFSs' on reducing speeds, a comprehensive study (Ullman & Rose, 2005) selected seven high collision-prone sites and vulnerable facilities (e.g., school zone) over three different time periods to conduct thorough before-and-after analyses. The test results indicated that in school zones the average speeds were reduced by 9 mph while in other tested locations, speeds were reduced by 5 mph or less on average. Although there exist limited studies devoted to quantifying the safety effect of DFS, there is a general consensus that DFSs do promote reduced speeds.

The link between the reduced number of collisions and speed reductions due to DFS has been shown to be casual (Elvik, 2005). Since there is no accurate research to relate how DFS induced speed reduction is linked to the change in the number of collisions, the relationship between the

DFSs' effectiveness to collision reduction needs to be evaluated. However, the effectiveness of DFSs vary on different types of roads, furthermore, a study by Garber & Patel (1994) pointed out that the effectiveness of DFSs at reducing speeds in the same type of zones (work zone) differ from city to city. Even DFSs installed within the same city, but in different zones, had different degrees of effectiveness. Some literature (Williamson, et al., 2016; Hallmark, et al., 2015) mentioned reduced collisions, but the types of DFS, locations, and scales of study differed from the research work of this thesis and those variables would have a significant impact on the outcome of the evaluations (Ullman & Rose, 2005; Gehlert, et al., 2012). In addition, previous studies did not evaluate DFSs' effectiveness over a long-time period. Some studies such as (Ullman & Rose, 2005; Williamson, et al., 2016) only considered the effectiveness of temporary DFSs over a short time frame of a couple weeks or months, as such the long term effectiveness of DFS needs to be examined.

To address some of the issues raised in previous studies, this thesis first evaluates the safety effects of DFSs on a large-scale (including all arterials and collectors) over a 10-year time span. This study evaluates the safety effectiveness of DFS for reducing different severities and types of collisions in Edmonton using the Empirical Bayes (EB) before-and-after analysis method to account for the regression-to-the-mean bias. The EB method is the most commonly used analysis method for evaluating traffic safety and is currently considered the state-of-the-art technique for evaluating safety countermeasures as suggested by the AASHTO Highway Safety Manual(Highway Safety Manual, 2010). Since different countermeasures may exhibit a varying degree of performance, segments that combined the application of DFS and other countermeasures (e.g. MPE) should also be investigated in order to understand their collective effectiveness.

In addition to the safety evaluation, the second objective of this study is to identify factors that can lead to an evaluation of an existing DFS network and an optimal selection of future DFS sites. Current studies recommended DFS sites mostly based on local judgements or past experiences (e.g., near work zones and school zones) and do not differentiate between effective and ineffective DFS implementations (Contini & El-Basyouny, 2016). If a relationship between a reduction in collisions due to DFS installation and other external factors (e.g., roadway traffic volume, number of driving lanes, etc.) can be captured, then transportation agencies can take advantage of this new knowledgebase to make informed decisions regarding the selection of future DFS sites.

2.2 Facility Location Problems and Solution Methods

Due to limited budget, manpower, and available resources, an appropriate DFS planning and implementation strategy should be conducted before more is invested into the project. This type of problem can be classified as a Facility Location Problem (FLP), which has been well studied by operation researchers and engineers (Kwon, 2015; Hakimi, 1964; Hakimi, 1965; ReVelle, et al., 2008). The two main types of facility location problems are discrete and continuous (Owen & S.Daskin, 1998). The former one utilizes discrete sets of demands and candidate locations, while the latter one assumes facilities may be located anywhere in a service area (Daskin, 2011). In this study, the site selection of DFSs will be considered as a Discrete Facility Location Problem (DFLP), thus the following literature review will focus on DFLP and corresponding solution algorithms. Furthermore, any other relevant works that bear similarity to the City's traffic facility or implemented safety countermeasures are also reviewed.

2.2.1 Discrete Facility Location Problems (DFLP)

As mentioned above, the DFLP assumes the service demands and candidate locations are discrete and thus this kind of problem is often formulated as an integer or mixed-integer program problem (Daskin, 2011). This problem can be further classified into three broad areas as shown in **Figure 2-1**, which are covering-based models, median-based models, and other models.

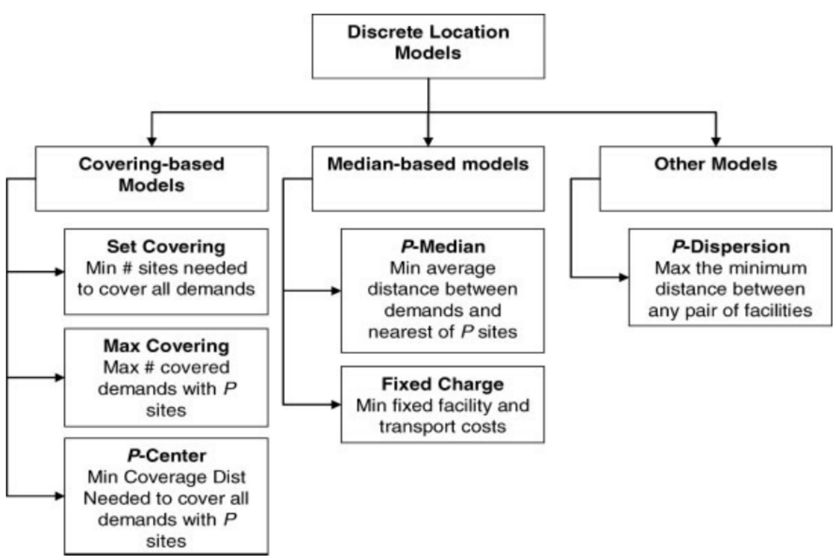


Figure 2-1 Breakdown of discrete location problems (adopted from Daskin, 2008)

The covering-based models assume there is a service distance between a facility and a demand point. A demand is said to be covered if it can be served within a specified time/distance/cost (Owen & S.Daskin, 1998). These models can further be divided into three sub-categories. Set Covering Model aims to find a minimum cost set of facilities from a finite set of candidate facilities so that all the demands are covered by at least one facility. Applications of this model ranged from airline crew scheduling to tool selection in flexible manufacturing systems (Daskin, 2011).

The Maximum Covering Model fixes the number of facilities that are to be located with the purpose of maximizing the number of covered demands. This model is widely used in facility location problems, such as gas station, and sensors (Lim & Kuby, 2010; Jin, et al., 2014).

By comparison, the p-center problem addresses the problem of minimizing the maximum distance that the demand is from its closest facility (Hakimi, 1964; Hakimi, 1965). The main concern of this problem is to keep the worst-case service level as high as possible.

Covering problems assume a demand node receives the complete benefits from a facility if it is within the coverage distance and no benefits otherwise. However, many facility location planning situations in the public and private sections are concerned with total/average travel distance between facilities and demand nodes (Daskin, 2011).

P-median problem is one of the classic models in this area which aims in finding the locations of p facilities to minimize the demand-weighted total distance between demand nodes and the corresponding assigned facilities. P-median problems assume each candidate site has the equal cost for locating one facility at it, and the capacity for serving demand has no limit. Fixed Charge Location Problem relaxes the assumptions of p-median, and in so doing its objective is to minimize total facility and transportation costs (Balinski, 1970).

The p-dispersion problem differs from the covering and median problem in two ways. First, it is only concerned with the distance between new facilities. Second, the objective is to maximize the minimum distance between any pair of facilities (Kuby, 1987). A potential application of this method includes the placement of military installations where separation distance is important for making them difficult to attack (Daskin, 2011).

2.2.2 Solution Algorithms

As mentioned in the previous sections, discrete location models are generally constructed as mixed-integer linear programs. This section is mainly to review the potential approaches to finding the optimal solution to such problems.

Facility location problems are often recognized as NP-hard problems, meaning it is impossible to obtain the optimal solution within a polynomial timeframe (Garey & Johnson, 1980). The reason is that facility location models can easily have many constraints and the number of potential placement strategies is usually very large. Standard optimization methods tend to use an unacceptable amount of computational resources and often with no guarantee of success. Since finding analytical solutions to location problems are often intractable, heuristic algorithms are applied to find optimal, or at least near optimal solutions (ReVelle, et al., 2008). In the remainder of this section, two categories of heuristic algorithms will be introduced.

Greedy Algorithm is one of the most widely used algorithms in optimization problems. This algorithm sequentially makes the optimal choice at each step by evaluating each site individually and only select the one that yields the optimal impact on the objective. Then the next facility selection will be identified by enumerating all of the remaining possible locations and again choose the site that provides the greatest improvement in the objective (Daskin, 2011). This is also referred to as the Greedy-Add Algorithm. The counterpart to the Greedy-Add Algorithm is the Greedy-Drop Algorithm whereby it starts with all the facilities located at all potential sites and then drops the facility that has the least impact on the objective. This process continues until p facilities remain. Greedy algorithms are quite successful in some problems, such as Huffman encoding which is used to compress data, and Dijkstra's algorithm which is used to find the shortest path (Cormen, et al., 2001).

Metaheuristic Algorithms are higher-level heuristic algorithms designed to find a sufficiently good solution to an optimization problem. They usually simulate the natural phenomenon to guide the search process in order to efficiently explore the search space and find optimal or near-optimal solutions. Examples of them include simulated annealing algorithm, genetic algorithm, particle swarm optimization, etc. (Laarhoven & Aarts, 1987; Goldberg, 1984; Eberhart & Kennedy, 1995).

The primary difference between these two types is the search strategy. Greedy algorithms only select the best one in each step and repeats it until p facilities are all located while metaheuristic algorithms consider all the p facilities at the same time. Typically, the latter one is able to generate relatively better results in most cases, and both of them cannot guarantee the global optimal solutions are found in the end (Daskin, 2011; Geem, et al., 2001). However, if the benefit of adding one facility is deterministic, the greedy algorithm is able to provide the global optimal solution. In our case, since the effectiveness of individual DFSs is to be modelled deterministically at every treated site, the greedy algorithm is adopted and implemented to solve the proposed DFS location problem.

2.3 Summary

The literature review has been shown that the implementation of DFSs reduced speeds on almost all road types. The public opinion of this countermeasure is generally positive, thus encouraging municipalities who have or are considering to install DFS by either relocating existing ones and/or expanding the number of DFSs in the traffic system.

Previous studies were done to analyze the site selection criteria for locating future DFSs with the emphasis on maximizing their effectiveness. However, these studies only focused on the change in speeds in select zones (i.e., schools, work zones, and rural areas), rather than urban networks as a whole. Due to the narrow focus and short time periods considered therein, they were only able to provide very limited insight into the safety effect of DFS. As such, it is of critical importance to quantify the sole effectiveness of DFS using large-scale and long-term datasets to generate more conclusive results.

Facility location modelling is a relatively mature area of study and the site selection of DFS can be categorized as a covering model. However, the conventional covering models cannot be directly applied to this case, as the service range of DFSs has yet to be studied. Therefore, this study also aims to develop an alternative facility location model, tailored specifically for solving the DFS location allocation problem, while providing insight to help mitigate risk in the future planning of DFS for an urban road network.

Chapter 3. SEGMENT-BASED SAFETY ASSESSMENT

This chapter describes Phase I of this thesis pertaining to the methods (Section 3.2) and results (Section 3.3) of assessing the segment-based safety effects of DFSs. There are three objectives of the assessment. The first objective is to examine the safety effects of DFSs implemented in urban arterial and collector roads. The second one is to compare the benefits of potential collision countermeasures to its project costs. The third objective is to identify the critical factors that would influence a DFS's safety effectiveness in different treated sites. The last section provides a summary of Phase I.

3.1 Data Description

In the City of Edmonton, the first two DFSs were installed in 2011 and this number has expanded to 212 by January of 2019. The locations for DFS sites were selected based on historical collision records, documented speeding incidents, and proximity to school or work zones. To date, there are 196 DFSs installed on arterials or collectors with 16 DFSs installed on local roads. The study area is comprised of all urban arterial and collector roads. Therefore, only collisions occurring on these roads were considered. The locations of the study sites for both DFSs and MPEs are shown in **Figure 3-1**.

To document the effects of DFS on road safety, this study uses collision statistics covering the multi-year period from January 2009 to December 2018. The study area focused primarily on arterial and collector road segments. The segmentation of arterial roads was based on end nodes that were composed of signalized intersections only, while the segmentation of collector roads was based on end nodes that were intersecting either another collector or arterial road for a total of 11260 road segments. Geometrical road properties, such as number of driving lanes, roadside parking, shoulders, and pedestrian crossings of each arterial and collector road was also collected. Annual Daily Traffic (ADT) and collision history for each year (from 2009 to 2018) in each direction were collected as well. Unfortunately, not all the segments had ADT data available, and for those that did, there were some with missing yearly ADT data. To interpolate the missing data, Edmonton's population data from 2009 to 2018 were used. In case the direction of travel information is not available, a proportioning method was used based on how many collisions had already occurred in each travel direction. To further make all the segments comparable, those with lengths between 300 m and 10 km and ADT greater than 2000 were selected, leaving 1660 segments, 105 of which had DFS installed.

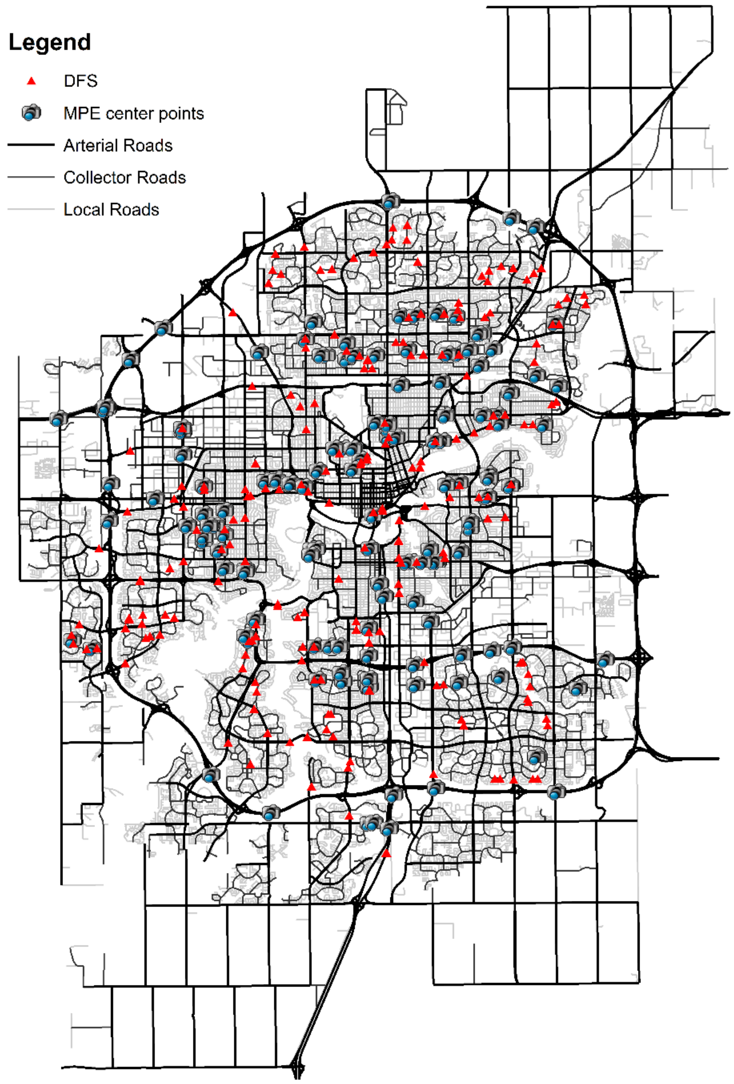


Figure 3-1 Implemented DFS and MPE locations in the City of Edmonton

To make a before-and-after comparison of collisions, it is important to have at least one whole year's worth of collision data before and after a DFS was installed on site. Therefore, of the 105 segments that had a DFS installed on it between January 2010 and January 2018, 86 segments were chosen for their collision data history that meets the aforementioned criteria. The remaining 1555 road segments that did not have a DFS installed were retained and used to construct the Safety Performance Function (SPF), which will be explained in the methodology section. The severities and types of collisions include the following:

- Total collisions;
- Collisions occurring on arterials only;
- Collisions occurring on collectors only;
- Property damage only (PDO) collisions;
- Injury collisions (sum of minor and major collisions);
- Severe collisions (sum of all injuries and fatal collisions);
- Speed-related collisions;
- Speed-related PDO collision;
- Speed-related severe collisions;
- Rear-end collisions, and;
- Improper lane-changing collisions.

Since DFS were installed on road segments, only midblock collisions were considered in this study as intersection collisions have distinct characteristics and may not be directly influenced by DFSs (Li, et al., 2015). A statistical summary of the data that was used is shown in **Table 3-1**.

Table 3-1 Descriptive Statistics

Category (from 2009 to 2018)	**Mean**	**Standard Deviation**	**Min.**	**Max.**
Average yearly ADT	9771.76	6916.55	2001.45	45792.84
Average yearly ADT in arterials	11546.30	6773.11	2007.52	45792.84
Average yearly ADT in collectors	3271.76	1115.74	2001.45	8466.86
Segment length	732.13	645.21	300.74	9200.02
Segment length of arterials	770.14	710.27	300.74	9200.02
Segment length of collectors	592.92	262.78	302.57	1654.38
Average yearly total collisions	1.82	2.65	0.00	40.82
Average yearly Arterial collisions	2.10	2.91	0.00	40.82
Average yearly Collector collisions	0.80	0.62	0.00	4.68
Average yearly PDO collisions	1.58	2.30	0.00	36.27
Average yearly injury collisions	0.23	0.38	0.00	5.36
Average yearly severe collisions	0.24	0.38	0.00	5.36
Average yearly speed-related collisions	1.09	1.77	0.00	29.45
Average yearly speed-related PDO collisions	0.94	1.49	0.00	25.27
Average yearly speed-related severe collisions	0.15	0.30	0.00	4.45
Average yearly rear-end collisions	0.71	1.27	0.00	20.64
Average yearly improper lane-changing collisions	0.38	0.76	0.00	11.00

3.2 Methodology

3.2.1 Safety Performance Function

Safety performance functions (SPF) are mathematical models that are statistically developed to relate collision frequencies to other explanatory variables such as traffic properties and road geometry (AASHO, 2010; El-Basyouny & Sayed, 2010). A common method for developing the SPFs is to adopt the generalized linear model (GLM) framework (Highway Safety Manual, 2010; El-Basyouny & Sayed, 2010). In this study, a negative binomial (NB) distribution was used since its error structure describes the overdispersion in collision data better than the Poisson distribution (Lu, et al., 2014; Team, 2015; El-Basyouny & Sayed, 2010). The model form used in this study is shown in **Equation (3-1)**.

$$\ln(\mu) = \beta_0 + \beta_1 \ln(V) + \beta_2 \ln L \tag{3-1}$$

where, μ is the predicted yearly average collision frequency; V is the traffic volume (ADT) of the road segment; L is the length of the road segment in meters; β_0, β_1, and β_2 are the regression parameters.

SPFs were developed using a set of reference road segments that do not have DFSs installed. In this study, the reference group consisted of road segments that were similar to the treated segments. The selection criteria ensured similarities in road type, traffic volume, and trends in collision frequency. In total, there were 1280 reference sites to construct SPFs. The parameters of the SPFs were estimated in R with the GLM function (Team, 2015). The residual deviance (RD) and Pearson χ^2 were used to assess the models' goodness of fit as shown in **Equations (3-2)** and **(3-3)**, respectively. Both are less than the critical Chi-square value under a certain confidence level indicating a good fitting model.

$$RD = 2 \times \left(LL(Saturated\ Model) - LL(Proposed\ Model)\right) \tag{3-2}$$

$$Pearson\ \chi^2 = \sum_{i=1}^{n_{unt.}} \frac{[y_i - \mu_i]^2}{Var(Y_i)} \tag{3-3}$$

where, LL means loglikelihood; a Saturated Model is a model that assumes each data point has its own parameters; a Proposed Model has a number of explanatory parameters and an intercept; y_i is the actual number of collisions at site i; μ_i is the estimated number of collisions at site i; $n_{unt.}$ is the total number of untreated sites; $Var(Y_i)$ is the variance of collision frequency at site i.

3.2.2 Yearly Calibration Factor

Apart from road geometry properties and yearly traffic volumes, there are other confounding factors, such as weather patterns, roadway improvements, and general traffic safety trends, that cause annual fluctuations in collision frequencies but are not attributed to variables in the SPFs. Since SPFs are not able to capture all these factors (Persaud & Lyon, 2007), the yearly calibration factors (YCFs) were used to address this issue. The YCFs were calculated using **Equation (3-4)** as ratios between the sum of the observed number of collisions and the sum of the average number of collisions predicted using SPFs in the same year (Li, et al., 2015; Contini, 2015; Contini & El-Basyouny, 2016). The assumption of using the yearly calibration factor was that the confounding factors had a similar impact on all reference sites and treated sites. To obtain a more accurate prediction, the collision frequency predicted by SPFs was adjusted by multiplying the corresponding yearly calibration factor.

$$YCF_{cj} = \frac{\sum_{Allsites} N_{Observed,cj}}{\sum_{Allsites} N_{Predicted,cj}} \qquad (3\text{-}4)$$

where, YCF is the yearly calibration factor; $N_{Observed}$ is the observed number of collisions; $N_{Predicted}$ is the predicted average number of collisions; c is the collision type and/or severity; j is the year.

3.2.3 Before-and-After Evaluation with Empirical Bayes Method

In cases where the treated sites are selected for improvement because of unusually high crash frequencies, this constitutes a selection bias, which is also known as the regression-to-mean (RTM) effect (Highway Safety Manual, 2010). RTM refers to the random fluctuation in collision frequency, especially in the cases of extremely high/low collision occurrences, even if no countermeasure is implemented, the frequencies may also drop after a period of time, and vice-versa. As the safety effectiveness is the ratio of observed collision frequencies to expected number of collision frequencies, if RTM is not addressed in the evaluation, an overestimation or underestimation of the safety effects might occur. A before-and-after evaluation with the Empirical Bayes (EB) method, as proposed by Hauer (1997), which explicitly addresses the RTM effect, is commonly used to evaluate the safety effectiveness of treatments. The evaluation procedure is described below.

The first step is to calculate the expected number of collisions in the before-period for each site. The expected number of collisions in the before-period is calculated as a weighted combination of the predicted number of collisions in the before-period (from SPF) adjusted by the yearly calibration factor and the observed number of collisions in the before period. Equations for calculating the expected number and weighted adjustment factor are shown in **Equations (3-5)** and **(3-6)** below.

$$N_{Expected,B} = w * N_{Predicted,B} + (1 - w) * N_{Observed,B} \tag{3-5}$$

$$w = \frac{1}{1 + k * N_{Predicted,B}} \tag{3-6}$$

where, w is the weighted adjustment factor (between 0 and 1); $N_{Expected,B}$ is the expected number of collisions in the before-period; $N_{Predicted,B}$ is the predicted number of collisions in the before-period; $N_{Observed,B}$ is the observed number of collisions in the before-period; k is the overdispersion parameter estimated from SPF.

The second step is to calculate the expected number of collisions for the after-period. In order to account for variations in traffic volume and different period length, a multiplier is calculated by the ratio of the predicted before-period collisions to after-period collisions. The expected number of collisions can be obtained by multiplying the multiplier and the expected number of collisions for the before-period, which is calculated in the last step.

The third step is to calculate the overall odds ratio of collision reduction (θ) and the associated standard error ($SE(\theta)$) as seen in the equations below.

$$\theta = \frac{\frac{\sum_{Allsites} N_{Observed,A}}{\sum_{Allsites} N_{Expected,A}}}{1 + \frac{Var(\sum_{Allsites} N_{Observed,A})}{(\sum_{Allsites} N_{Expected,A})^2}} \quad (3\text{-}7)$$

$$Var\left(\sum_{Allsites} N_{Observed,A}\right) = \sum_{Allsites}\left[\left(\frac{N_{Predicted,A}}{N_{Predicted,B}}\right)^2 * N_{Expected,B} * (1-w)\right] \quad (3\text{-}8)$$

$$SE(\theta) = \sqrt{\frac{(\frac{\sum_{Allsites} N_{Observed,A}}{\sum_{Allsites} N_{Expected,A}})^2 * [\frac{1}{\sum_{Allsites} N_{Observed,A}} + \frac{Var(\sum_{Allsites} N_{Observed,A})}{(\sum_{Allsites} N_{Expected,A})^2}]}{1 + \frac{Var(\sum_{Allsites} N_{Observed,A})}{(\sum_{Allsites} N_{Expected,A})^2}}} \quad (3\text{-}9)$$

where, $N_{Expected,A}$ is the expected number of collisions in the after-period; $N_{Predicted,A}$ is the predicted number of collisions in the after-period (multiplied by the yearly calibration factor); $N_{Observed,A}$ is the observed number of collisions in the after-period.

Finally, the percent reduction and its statistical significance can be calculated as follows: Percent reduction in collisions = 100 × (1- θ) with a standard error of 100 × $SE(\theta)$. Positive collision reduction value means a decrease in collisions while a negative value means an increase. The ratio of the percent reduction and its standard error is the statistical significance. If this ratio is higher than 1.96, the collision reduction percentage is significant at 95% confidence level (Highway Safety Manual, 2010).

3.2.4 Calendar Years

Since DFSs under investigation were installed at different times (different months in subsequent years), new calendar years were generated for each intervention time period. For example, if the intervention time of one treated site is July 2017, and the available collision data spans the years between 2009-to-2018, the new calendar year of its before-period will be July-to-June for each of the before years from 2009 to June-2017 while the new calendar year in its after-period will be July-2017 to June-2018.

3.2.5 Economic Analysis

Economic analysis is performed to compare the benefits of potential collision countermeasures to its project costs. The Net Present Value (NPV) and Benefit-Cost Ratio (BCR) are commonly used to evaluate the economic effectiveness and feasibility of individual roadway projects. Compared with the NPV, BCR makes the relative desirability of a proposed project immediately evident to decision makes, so BCR is used in this study to justify the economic feasibility of installing DFSs. The procedures to conduct the economic analysis is presented in this section (Highway Safety Manual, 2010).

The first step in calculating the BCR is to convert the treatment effect into an annualized reduction or increase in collision frequency and then convert these reductions or increases into annual monetary value based on the average costs of corresponding collision severities as annual project benefits (Sayed, et al., 2004). Then, the second step is to convert the annual monetary value of benefits to a present value (PV, see **Equation (3-10)**). Finally, like in the former steps, present value of project costs needs to be calculated. After this, the BCR can be computed using **Equation (3-11)**.

$$PV = AV \times \left[\frac{(1+r)^{n_s} - 1}{r \times (1+r)^{n_s}}\right] \tag{3-10}$$

$$BCR = \frac{PV_{benefits}}{PV_{costs}} \tag{3-11}$$

where, AV is the annual value; r is the annual interest rate; n_s is the number of service years; $PV_{benefits}$ is the present value of project benefits; PV_{costs} is the present value of project costs.

3.3 Results and Discussions

3.3.1 SPFs and Yearly Calibration Factors

The local SPFs were developed by using the data and methodology described above. The models' goodness of fit was measured by two statistics; Pearson's χ^2 and residual deviance, which are shown in the **Table 3-2**.

Table 3-2 SPF Parameter Estimates and Goodness of fit measures by Collision Type/Severity and Starting Month

Collision Type/Severity	Starting Month	Parameter Estimate				Residual Deviance	Pearson's χ^2
		Intercept	ADT	Length	Dispersion Parameter		
Total	Jan.	-8.79	0.36**	0.77**	0.54	1470.68	2150.21
	Feb.	-8.80	0.36**	0.78**	0.54	1465.11	2154.80
	Mar.	-8.83	0.36**	0.78**	0.54	1460.28	2153.99
	Apr.	-8.82	0.36**	0.78**	0.55	1456.08	2148.05
	May.	-8.82	0.36**	0.78**	0.54	1456.57	2149.10
	Jun.	-8.83	0.36**	0.78**	0.54	1457.78	2149.05
	Jul.	-8.84	0.36**	0.78**	0.54	1456.45	2151.80
	Aug.	-8.83	0.36**	0.77**	0.54	1455.56	2146.90
	Sep.	-8.83	0.36**	0.77**	0.54	1451.01	2146.51
	Oct.	-8.81	0.36**	0.77**	0.54	1451.85	2139.75
	Nov.	-8.84	0.36**	0.77**	0.55	1452.72	2137.13
	Dec.	-8.85	0.36**	0.77**	0.54	1464.15	2138.68
PDO	Jan.	-8.64	0.34**	0.75**	0.54	1468.23	2102.96
	Feb.	-8.64	0.34**	0.76**	0.55	1463.78	2102.32
	Mar.	-8.67	0.34**	0.76**	0.55	1460.59	2101.75
	Apr.	-8.67	0.34**	0.76**	0.55	1458.09	2097.79
	May.	-8.67	0.34**	0.76**	0.55	1459.74	2098.09
	Jun.	-8.68	0.34**	0.76**	0.55	1461.56	2097.75
	Jul.	-8.69	0.34**	0.76**	0.54	1460.94	2100.21
	Aug.	-8.68	0.35**	0.75**	0.55	1459.94	2095.79
	Sep.	-8.68	0.35**	0.75**	0.55	1455.89	2095.40
	Oct.	-8.67	0.35**	0.75**	0.55	1460.68	2090.17
	Nov.	-8.70	0.35**	0.75**	0.55	1458.06	2088.51
	Dec.	-8.70	0.35**	0.75**	0.55	1465.63	2089.91
Injury	Jan.	-13.09	0.46**	0.94**	0.60	1324.50	1944.69
	Feb.	-13.12	0.46**	0.95**	0.58	1305.11	1940.55

	Mar.	-13.21	0.47**	0.95**	0.59	1302.16	1939.38
	Apr.	-13.15	0.46**	0.95**	0.57	1303.89	1937.07
	May.	-13.14	0.45**	0.96**	0.57	1287.05	1937.16
	Jun.	-13.19	0.45**	0.96**	0.57	1286.24	1940.07
	Jul.	-13.25	0.45**	0.96**	0.57	1286.64	1944.61
	Aug.	-13.24	0.45**	0.97**	0.57	1289.13	1941.21
	Sep.	-13.30	0.46**	0.97**	0.57	1292.51	1940.13
	Oct.	-13.18	0.45**	0.96**	0.57	1291.59	1930.24
	Nov.	-13.21	0.45**	0.96**	0.57	1298.84	1930.68
	Dec.	-13.21	0.45**	0.96**	0.58	1303.85	1923.08
Severe	Jan.	-13.06	0.47**	0.93**	0.58	1324.29	1957.60
	Feb.	-13.13	0.46**	0.95**	0.57	1306.24	1956.55
	Mar.	-13.21	0.47**	0.95**	0.57	1303.11	1956.19
	Apr.	-13.15	0.46**	0.95**	0.56	1304.29	1954.01
	May.	-13.14	0.45**	0.95**	0.56	1287.47	1954.66
	Jun.	-13.17	0.45**	0.96**	0.56	1285.78	1955.61
	Jul.	-13.23	0.46**	0.96**	0.55	1286.27	1959.12
	Aug.	-13.22	0.45**	0.96**	0.56	1288.93	1955.49
	Sep.	-13.25	0.46**	0.96**	0.56	1291.57	1953.28
	Oct.	-13.13	0.45**	0.95**	0.55	1289.94	1942.58
	Nov.	-13.16	0.46**	0.95**	0.55	1297.02	1943.15
	Dec.	-13.15	0.46**	0.95**	0.56	1302.93	1935.73
Speed-related	Jan.	-10.57	0.44**	0.85**	0.52	1615.89	2260.66
	Feb.	-10.60	0.43**	0.86**	0.52	1623.48	2260.20
	Mar.	-10.64	0.44**	0.86**	0.53	1616.25	2261.90
	Apr.	-10.63	0.44**	0.86**	0.53	1604.05	2256.73
	May.	-10.64	0.43**	0.86**	0.53	1605.83	2256.13
	Jun.	-10.64	0.44**	0.86**	0.53	1604.03	2256.32
	Jul.	-10.63	0.44**	0.86**	0.52	1599.17	2255.98
	Aug.	-10.61	0.44**	0.85**	0.53	1599.13	2248.80
	Sep.	-10.64	0.45**	0.85**	0.53	1594.35	2252.56
	Oct.	-10.61	0.45**	0.85**	0.53	1590.61	2244.27
	Nov.	-10.66	0.45**	0.85**	0.53	1582.84	2243.82
	Dec.	-10.64	0.44**	0.85**	0.53	1593.61	2244.59
Speed-related PDO	Jan.	-10.10	0.4**	0.81**	0.54	1610.00	2148.90
	Feb.	-10.11	0.4**	0.82**	0.54	1610.69	2141.28
	Mar.	-10.15	0.41**	0.82**	0.54	1608.97	2141.78
	Apr.	-10.15	0.4**	0.82**	0.55	1598.77	2139.15
	May.	-10.16	0.41**	0.82**	0.54	1602.36	2136.79

	Jun.	-10.15	0.41**	0.81**	0.54	1599.23	2134.82
	Jul.	-10.13	0.41**	0.81**	0.54	1595.65	2132.69
	Aug.	-10.12	0.41**	0.8**	0.54	1594.37	2127.42
	Sep.	-10.15	0.42**	0.8**	0.54	1591.91	2130.86
	Oct.	-10.13	0.42**	0.8**	0.54	1593.78	2125.62
	Nov.	-10.18	0.42**	0.8**	0.55	1583.05	2125.69
	Dec.	-10.16	0.42**	0.8**	0.54	1595.72	2123.75
Arterial	Jan.	-9.93	0.35**	0.9**	0.57	1216.52	1684.27
	Feb.	-9.99	0.35**	0.91**	0.57	1216.75	1690.86
	Mar.	-10.02	0.36**	0.91**	0.58	1212.01	1690.22
	Apr.	-9.98	0.35**	0.9**	0.58	1211.13	1683.63
	May.	-9.98	0.35**	0.9**	0.58	1211.97	1683.71
	Jun.	-10.02	0.35**	0.9**	0.57	1211.81	1685.87
	Jul.	-10.03	0.36**	0.9**	0.57	1211.68	1686.45
	Aug.	-10.03	0.36**	0.9**	0.57	1210.98	1684.15
	Sep.	-9.99	0.36**	0.9**	0.57	1204.72	1682.21
	Oct.	-9.95	0.36**	0.89**	0.57	1206.66	1677.33
	Nov.	-9.96	0.36**	0.89**	0.57	1205.39	1675.03
	Dec.	-9.94	0.36**	0.89**	0.57	1214.23	1674.31
Collector	Jan.	-9.68	0.68**	0.66**	0.29	269.79	301.34
	Feb.	-9.46	0.67**	0.64**	0.28	263.64	302.88
	Mar.	-9.63	0.68**	0.65**	0.28	264.73	303.86
	Apr.	-9.66	0.67**	0.65**	0.29	264.03	303.76
	May.	-9.67	0.67**	0.66**	0.28	263.46	303.50
	Jun.	-9.70	0.66**	0.67**	0.29	263.82	302.58
	Jul.	-9.62	0.65**	0.66**	0.29	263.44	301.49
	Aug.	-9.65	0.66**	0.66**	0.29	262.06	301.69
	Sep.	-9.72	0.66**	0.67**	0.30	262.86	302.05
	Oct.	-9.67	0.67**	0.66**	0.30	262.06	301.52
	Nov.	-9.66	0.67**	0.65**	0.32	264.97	300.11
	Dec.	-9.78	0.67**	0.66**	0.32	266.24	300.40

Note: *Significant at 95% level; **significant at 99% level

As shown in the table above, all the developed models fit the data and all the parameter estimates were significant at the 95% confidence level. The regression coefficients are all positive, indicating that factors such as segment length and ADT are positively associated with the number of collisions. All the shape parameters were highly significant, which validates the presence of overdispersion in the data. The goodness-of-fit results shows that the SPFs provide a good fit to the data as both

Residual Deviance and Pearson's χ^2 are lower than their respective critical values. The yearly calibration factors for each calendar year are shown in **Table 3-3**.

Table 3-3 Yearly Calibration Factors

Collision Type/Severity	Starting Month	Yearly Calibration Factors									
		'09	'10	'11	'12	'13	'14	'15	'16	'17	'18
Overall	Jan.	1.51	1.35	1.07	1.11	1.07	1.03	0.95	0.77	0.70	0.74
	Feb.	1.45	1.33	0.99	1.08	1.04	1.02	0.89	0.74	0.70	
	Mar.	1.44	1.32	0.98	1.08	1.06	1.04	0.86	0.74	0.72	
	Apr.	1.38	1.35	0.98	1.10	1.07	1.04	0.85	0.75	0.73	
	May.	1.37	1.35	0.99	1.11	1.06	1.04	0.84	0.74	0.74	
	Jun.	1.38	1.33	0.99	1.12	1.06	1.06	0.83	0.72	0.75	
	Jul.	1.38	1.32	0.99	1.13	1.07	1.05	0.84	0.70	0.77	
	Aug.	1.38	1.31	1.01	1.13	1.07	1.06	0.83	0.69	0.77	
	Sep.	1.38	1.31	1.02	1.12	1.07	1.04	0.83	0.71	0.76	
	Oct.	1.41	1.29	1.01	1.14	1.07	1.03	0.83	0.69	0.77	
	Nov.	1.41	1.26	1.02	1.16	1.07	1.04	0.82	0.69	0.78	
	Dec.	1.45	1.19	1.11	1.10	1.09	0.99	0.81	0.71	0.79	
PDO	Jan.	1.51	1.34	1.05	1.10	1.07	1.05	0.96	0.78	0.70	0.75
	Feb.	1.46	1.32	0.97	1.07	1.04	1.04	0.90	0.75	0.70	
	Mar.	1.45	1.32	0.95	1.07	1.07	1.06	0.87	0.75	0.72	
	Apr.	1.38	1.34	0.96	1.09	1.07	1.06	0.85	0.76	0.73	
	May.	1.37	1.34	0.97	1.11	1.06	1.06	0.84	0.75	0.74	
	Jun.	1.38	1.33	0.97	1.12	1.06	1.07	0.84	0.72	0.77	
	Jul.	1.38	1.31	0.97	1.13	1.07	1.07	0.84	0.70	0.78	
	Aug.	1.37	1.30	0.98	1.12	1.09	1.07	0.84	0.70	0.78	
	Sep.	1.38	1.30	1.00	1.13	1.09	1.05	0.85	0.71	0.77	
	Oct.	1.41	1.27	0.99	1.14	1.08	1.04	0.84	0.70	0.77	
	Nov.	1.40	1.25	1.00	1.16	1.08	1.05	0.84	0.70	0.78	
	Dec.	1.43	1.18	1.10	1.10	1.10	1.00	0.82	0.72	0.80	
Injury	Jan.	1.46	1.43	1.21	1.18	1.03	0.88	0.90	0.70	0.66	0.67
	Feb.	1.36	1.39	1.14	1.14	1.00	0.90	0.84	0.67	0.68	
	Mar.	1.38	1.37	1.16	1.11	1.02	0.88	0.84	0.66	0.69	
	Apr.	1.34	1.39	1.14	1.15	1.01	0.91	0.81	0.66	0.69	
	May.	1.35	1.40	1.14	1.14	1.02	0.91	0.83	0.64	0.69	
	Jun.	1.38	1.38	1.11	1.12	1.04	0.96	0.77	0.68	0.67	
	Jul.	1.42	1.34	1.14	1.10	1.03	0.94	0.77	0.65	0.71	

	Aug.	1.41	1.36	1.15	1.12	0.99	0.97	0.74	0.65	0.73	
	Sep.	1.41	1.38	1.16	1.11	0.96	0.96	0.74	0.66	0.73	
	Oct.	1.43	1.40	1.10	1.12	0.98	0.97	0.74	0.64	0.74	
	Nov.	1.50	1.36	1.12	1.11	0.97	0.97	0.71	0.65	0.74	
	Dec.	1.57	1.27	1.20	1.08	0.95	0.94	0.73	0.63	0.75	
Severe	Jan.	1.47	1.42	1.20	1.19	1.03	0.88	0.90	0.70	0.67	0.68
	Feb.	1.37	1.38	1.14	1.15	1.00	0.90	0.84	0.66	0.68	
	Mar.	1.39	1.36	1.16	1.11	1.03	0.87	0.84	0.65	0.70	
	Apr.	1.35	1.39	1.14	1.15	1.02	0.90	0.81	0.66	0.70	
	May.	1.35	1.39	1.14	1.14	1.02	0.91	0.84	0.63	0.70	
	Jun.	1.39	1.38	1.10	1.13	1.04	0.96	0.78	0.67	0.68	
	Jul.	1.42	1.35	1.14	1.11	1.03	0.94	0.77	0.65	0.71	
	Aug.	1.41	1.37	1.15	1.12	0.99	0.97	0.74	0.65	0.73	
	Sep.	1.41	1.38	1.16	1.11	0.97	0.95	0.75	0.66	0.74	
	Oct.	1.43	1.40	1.10	1.12	0.98	0.96	0.73	0.64	0.76	
	Nov.	1.49	1.35	1.12	1.11	0.97	0.97	0.71	0.65	0.75	
	Dec.	1.57	1.26	1.21	1.08	0.95	0.94	0.73	0.63	0.76	
Speed-related	Jan.	1.62	1.40	1.02	1.11	1.06	0.99	0.92	0.78	0.68	0.71
	Feb.	1.54	1.34	0.98	1.07	1.02	1.00	0.86	0.75	0.68	
	Mar.	1.54	1.32	0.98	1.07	1.04	1.01	0.84	0.75	0.69	
	Apr.	1.45	1.36	0.99	1.10	1.02	1.03	0.83	0.76	0.71	
	May.	1.44	1.35	1.01	1.10	1.01	1.03	0.83	0.74	0.72	
	Jun.	1.46	1.32	1.01	1.11	1.02	1.03	0.84	0.71	0.74	
	Jul.	1.46	1.32	1.00	1.13	1.03	1.02	0.86	0.68	0.75	
	Aug.	1.45	1.30	1.02	1.13	1.03	1.02	0.86	0.68	0.76	
	Sep.	1.47	1.28	1.03	1.14	1.03	1.01	0.85	0.69	0.74	
	Oct.	1.52	1.24	1.02	1.15	1.03	1.00	0.84	0.68	0.75	
	Nov.	1.51	1.20	1.05	1.16	1.03	1.02	0.83	0.68	0.76	
	Dec.	1.54	1.14	1.14	1.11	1.05	0.97	0.82	0.70	0.77	
Speed-related PDO	Jan.	1.63	1.37	1.00	1.09	1.06	1.02	0.94	0.79	0.68	0.72
	Feb.	1.56	1.31	0.94	1.06	1.03	1.02	0.87	0.77	0.68	
	Mar.	1.55	1.30	0.94	1.06	1.04	1.03	0.85	0.77	0.70	
	Apr.	1.45	1.32	0.96	1.08	1.04	1.05	0.84	0.78	0.72	
	May.	1.44	1.32	0.98	1.09	1.03	1.05	0.84	0.76	0.73	
	Jun.	1.46	1.29	0.98	1.10	1.03	1.05	0.85	0.72	0.76	
	Jul.	1.46	1.29	0.97	1.12	1.04	1.04	0.87	0.69	0.76	
	Aug.	1.44	1.27	0.99	1.12	1.05	1.04	0.88	0.68	0.77	

	Sep.	1.46	1.25	1.00	1.13	1.05	1.03	0.87	0.70	0.75	
	Oct.	1.51	1.20	1.01	1.16	1.04	1.02	0.86	0.69	0.76	
	Nov.	1.49	1.17	1.03	1.17	1.04	1.04	0.85	0.69	0.77	
	Dec.	1.51	1.12	1.12	1.11	1.07	0.98	0.84	0.71	0.78	
Speed-related Severe	Jan.	1.54	1.53	1.17	1.20	1.01	0.82	0.81	0.67	0.62	0.58
	Feb.	1.42	1.46	1.15	1.13	0.95	0.84	0.74	0.62	0.62	
	Mar.	1.42	1.43	1.19	1.11	0.96	0.82	0.76	0.62	0.62	
	Apr.	1.36	1.51	1.15	1.18	0.91	0.85	0.73	0.64	0.62	
	May.	1.37	1.51	1.16	1.15	0.90	0.86	0.76	0.62	0.62	
	Jun.	1.41	1.47	1.14	1.12	0.93	0.90	0.72	0.65	0.59	
	Jul.	1.46	1.44	1.15	1.11	0.92	0.88	0.73	0.61	0.64	
	Aug.	1.47	1.45	1.14	1.16	0.87	0.88	0.71	0.61	0.66	
	Sep.	1.51	1.41	1.15	1.14	0.87	0.86	0.71	0.62	0.66	
	Oct.	1.53	1.44	1.11	1.11	0.94	0.84	0.71	0.61	0.67	
	Nov.	1.61	1.36	1.15	1.10	0.93	0.85	0.69	0.63	0.65	
	Dec.	1.70	1.23	1.24	1.08	0.91	0.85	0.70	0.60	0.67	
Rear-end	Jan.	1.45	1.34	0.99	1.03	0.99	0.91	0.86	0.77	0.62	0.65
	Feb.	1.39	1.28	0.94	1.00	0.93	0.91	0.82	0.74	0.61	
	Mar.	1.39	1.25	0.94	1.02	0.93	0.91	0.83	0.73	0.62	
	Apr.	1.32	1.27	0.96	1.03	0.93	0.92	0.82	0.73	0.64	
	May.	1.31	1.27	0.97	1.03	0.93	0.92	0.83	0.70	0.66	
	Jun.	1.33	1.24	0.98	1.03	0.93	0.93	0.84	0.66	0.68	
	Jul.	1.34	1.24	0.97	1.04	0.94	0.92	0.87	0.62	0.69	
	Aug.	1.33	1.24	0.98	1.06	0.92	0.94	0.86	0.62	0.70	
	Sep.	1.35	1.22	1.00	1.04	0.94	0.92	0.86	0.64	0.68	
	Oct.	1.41	1.19	1.00	1.05	0.94	0.91	0.85	0.62	0.68	
	Nov.	1.43	1.15	1.03	1.04	0.94	0.93	0.84	0.63	0.68	
	Dec.	1.44	1.09	1.08	1.03	0.95	0.90	0.84	0.63	0.71	
Improper lane changing	Jan.	1.42	1.32	1.20	1.10	1.05	1.07	1.02	0.81	0.67	0.79
	Feb.	1.38	1.35	1.07	1.10	1.01	1.06	0.95	0.77	0.68	
	Mar.	1.36	1.37	1.04	1.07	1.07	1.09	0.92	0.74	0.71	
	Apr.	1.35	1.38	1.02	1.09	1.10	1.08	0.89	0.73	0.72	
	May.	1.33	1.40	1.00	1.13	1.09	1.06	0.89	0.72	0.74	
	Jun.	1.29	1.46	0.97	1.17	1.07	1.11	0.83	0.73	0.75	
	Jul.	1.30	1.44	0.98	1.13	1.09	1.12	0.81	0.71	0.78	
	Aug.	1.29	1.44	0.97	1.13	1.10	1.14	0.79	0.71	0.78	
	Sep.	1.29	1.44	0.99	1.12	1.11	1.11	0.82	0.70	0.78	

	Oct.	1.27	1.44	0.99	1.12	1.12	1.11	0.83	0.67	0.79	
	Nov.	1.29	1.42	0.96	1.16	1.10	1.11	0.84	0.66	0.80	
	Dec.	1.35	1.37	1.04	1.11	1.09	1.08	0.81	0.67	0.82	
Arterial	Jan.	1.51	1.36	1.07	1.11	1.06	1.01	0.95	0.77	0.69	0.73
	Feb.	1.45	1.33	0.99	1.08	1.03	1.01	0.88	0.74	0.69	
	Mar.	1.44	1.32	0.99	1.08	1.05	1.02	0.86	0.73	0.71	
	Apr.	1.37	1.35	0.99	1.10	1.05	1.03	0.84	0.74	0.73	
	May.	1.36	1.36	0.99	1.11	1.04	1.03	0.84	0.73	0.74	
	Jun.	1.37	1.34	0.99	1.12	1.05	1.04	0.83	0.71	0.75	
	Jul.	1.39	1.32	0.99	1.12	1.05	1.04	0.83	0.69	0.77	
	Aug.	1.38	1.31	1.00	1.12	1.05	1.05	0.83	0.69	0.77	
	Sep.	1.39	1.31	1.02	1.11	1.05	1.03	0.83	0.70	0.76	
	Oct.	1.42	1.29	1.01	1.13	1.06	1.03	0.83	0.68	0.76	
	Nov.	1.42	1.26	1.02	1.14	1.06	1.03	0.82	0.69	0.77	
	Dec.	1.47	1.19	1.11	1.10	1.07	0.99	0.81	0.70	0.78	
Collector	Jan.	1.49	1.26	1.03	1.15	1.12	1.12	0.85	0.71	0.68	0.72
	Feb.	1.42	1.27	0.96	1.12	1.09	1.10	0.81	0.67	0.67	
	Mar.	1.45	1.31	0.89	1.10	1.14	1.12	0.73	0.71	0.66	
	Apr.	1.43	1.28	0.90	1.13	1.15	1.10	0.76	0.72	0.64	
	May.	1.42	1.24	0.96	1.13	1.15	1.09	0.77	0.70	0.63	
	Jun.	1.41	1.26	0.95	1.14	1.16	1.08	0.77	0.69	0.65	
	Jul.	1.34	1.27	0.96	1.15	1.18	1.05	0.78	0.67	0.71	
	Aug.	1.32	1.27	0.99	1.11	1.22	1.01	0.79	0.65	0.74	
	Sep.	1.33	1.26	0.97	1.20	1.19	0.97	0.78	0.67	0.73	
	Oct.	1.33	1.24	0.97	1.25	1.14	0.98	0.75	0.69	0.75	
	Nov.	1.26	1.27	0.97	1.27	1.14	1.01	0.74	0.67	0.78	
	Dec.	1.31	1.19	1.16	1.14	1.16	0.93	0.74	0.68	0.81	

3.3.2 Overall Before-and-After Evaluation

The overall percentage of change in collisions and their statistical test ratio both by severity and type are shown in **Table 3-4**. Also, a comparison was conducted between the segments treated with DFS only and the segments with both DFS and MPE. In each computation, the adjusted yearly predicted number of collisions was calculated by using the segment length, new-calendar-year ADT, and corresponding yearly calibration factor. The overall percentage of reduced collisions, standard errors, statistical test ratios, and their lower and upper 95% confidence levels bound are shown in **Table 3-4**, categorized by collision type.

Table 3-4 Overall Before-and-After Evaluation Results

Collision Severity or Type	Collision Reduction (%)	Standard Error	Statistical Test Ratio	Lower Bound	Upper Bound
Total	36.10	3.63	9.93**	26.73	45.48
DFS only	33.34	4.42	7.54**	21.93	44.75
DFS and MPE	41.61	6.25	6.66**	25.49	57.74
Arterial	36.96	3.71	9.96**	27.39	46.53
Arterial with DFS only	34.70	4.53	7.66**	23.01	46.39
Arterial with DFS and MPE	41.29	6.34	6.51**	24.93	57.65
Collector	36.84	13.77	2.67**	1.31	72.37
Collector with DFS only	31.02	15.28	2.03*	1.07	60.97
Collector with DFS and MPE	87.62	17.71	4.95**	41.94	133.30
PDO	34.30	4.00	8.58**	23.98	44.61
Injury	36.46	9.85	3.7**	11.04	61.87
Severe	36.74	9.70	3.79**	11.71	61.77
Speed-related	38.19	4.48	8.53**	26.64	49.74
Speed-related PDO	34.69	5.05	6.87**	21.66	47.72
Speed-related Severe	44.87	10.81	4.15**	16.98	72.75
Rear-end	38.00	6.09	6.24**	22.28	53.72
Improper lane-changing	32.52	7.83	4.15**	12.32	52.72

Note: **Significant at 99% confidence level.

3.3.3 Economic Analysis

The first step of the benefit-cost ratio analysis is to convert the total collision reductions or increases into annual benefit or disadvantage using the average costs of corresponding collision severity. The average estimated costs of collisions vary depending on the type of costs included in the analysis as well as the method used to obtain these costs. In this study, three different collision costing methods were utilized (Captial Region Intersection Safety Partnership, 2018) – Direct Costs (DC), Human Capital (HC) costs and Willing-To-Pay (WTP) costs. DC uses costs that can be directly linked to the collision, including property damage costs, emergency services, medical expenses and costs associated with loss of time such as travel delay costs. HC consider the costs that are associated with the future net production that is lost to a society as a result of a collision. WTP Costs represent costs that a society is willing to pay to prevent or reduce the risks associated with the occurrence of collisions, particularly those crashes causing serious injuries and fatalities. Each method provided a different perspective on the type of costs that are incurred due to collision causing a serious injury or fatality. The estimated costs by each method, using data from Edmonton's capital region, is shown in **Table 3-5** (Captial Region Intersection Safety Partnership, 2018).

Table 3-5 Average Costs of each collision severity

Criterion	PDO	Severe
Direct Costs	$14,065	$50,025
Human Capital*	$14,065	$159,723
Willing-To-Pay*	$14,065	$270,909

*Includes direct costs

Benefit-cost ratios were then calculated using $6000 for each DFS and a 1.92% interest rate (i.e., this is the opportunity cost interest rate used by the City of Edmonton's procurement department). Two- and five- years were selected as service years respectively to compare the relative short and long-term benefits. The results of the economic analysis are shown in **Table 3-6**. As expected, as collision costs increased, larger BCRs were observed. Even if the analysis was based on the direct costs only, the BCR were computed at 8.2 and 19.8 for a 2- and 5- year service life. Regardless of the method used to estimate the collision costs, the results of the economic analysis showcase the cost-effectiveness of installing DFS in urban road environments.

Table 3-6 Results of the Benefit-Cost Analysis

Criterion	Severity	2-year Service Life		5-year Service Life	
		Benefits	BCR*	Benefits	BCR*
Direct Costs	PDO	$2,805,823.91	5.44	$6,819,440.25	13.22
	Severe	$1,405,263.93	2.72	$3,415,436.50	6.62
	Overall	$4,211,087.84	8.16	$10,234,876.76	19.84
Human Capital	PDO	$2,805,823.91	5.44	$6,819,440.25	13.22
	Severe	$4,486,816.00	8.70	$10,905,022.78	21.13
	Overall	$7,292,639.91	14.13	$17,724,463.04	34.35
Willingness-To-Pay	PDO	$2,805,823.91	5.44	$6,819,440.25	13.22
	Severe	$7,610,167.83	14.75	$18,496,201.65	35.85
	Overall	$10,415,991.74	20.19	$25,315,641.91	49.06

*BCR stands for benefit-to-cost ratio

3.3.4 Lessons Learned from existing DFS Deployment

Current DFS sites were selected based on collision history and local expertise, such as the distance from a school and historical collision frequencies and rates. In order to assist the City of Edmonton and other cities interested in identifying potential locations for future DFSs, it is of interest to further understand ways to prioritize the selection of future DFS locations. The impact that various road segment characteristics have on safety was investigated to identify which factors would affect the change in collision frequency before and after.

The percentage change in collision frequency is one of the best indicators of how effective a countermeasure is. However, findings in literature (Suissa, et al., 1989; Vickers, 2001) suggest the percentage of change from the baseline is not appropriate to use directly in the statistical analysis. The best way is to find the relationship between post-treatment values and the baseline as well as other explanatory variables and then convert the estimated values to a percentage of change using the baseline. In this case, the post-treatment values are the observed collisions in the after period while the baselines are the expected frequency of collisions (EB after, obtained from EB method) during the after-period. Similarly, a negative binomial distribution was also adopted to create the generalized linear model (GLM), which assumed the post-treatment values were over-dispersed. The function form of the model is shown below.

$$\ln\left(N_{Observed,A}\right) = \beta_0 + \beta_1 I_1 + \beta_2 I_2 + \cdots + \beta_n I_n + \alpha \ln(V) + \gamma \ln(L) \quad (3\text{-}12)$$

where, I_1, I_2, …, I_n are the independent variables related to road segment characteristics, including EB after, number of driving lanes, road type (arterial = 1, collector =0), presence of median, shoulder, pedestrian crossing, and roadside park (presence = 1, otherwise 0); V is the traffic volume (ADT) of the road segment; L is the length of the road segment (m); β_0, β_1, and $\beta_2 \cdots \beta_n$, α, and γ are the regression parameters.

After the observed collision frequencies in the post-treatment period are predicted using the proposed model, the percent change can be calculated by the following equation.

$$\Delta(\%) = \frac{N_{Expected,A} - N_{Observed,A}}{N_{Expected,A}} \times 100\% \qquad (3\text{-}13)$$

where $\Delta(\%)$ is the percent of change in collision frequencies, positive/negative means reduction/increase, respectively; $N_{Expected,A}$ is the expected collision frequency during the after-period assuming there is no DFS intervention and it can be obtained from the EB method.

These models were estimated using the SAS GENMOD procedure (SAS Institute, 2012), which uses maximum likelihood estimation. SAS GENMOD uses scaled deviance (SD) and Pearson χ^2 (**Equation (3-3)**) to assess the goodness of fit. The SD computation is shown in **Equation (3-14)**.

$$SD = 2\sum_{i=1}^{n}[y_i \ln\left(\frac{y_i}{\mu_i}\right) - (y_i + k)\ln(\frac{y_i + k}{\mu_i + k})] \qquad (3\text{-}14)$$

where, y_i is the observed collision frequency on segment *i*; μ_i is the predicted collision frequency on segment *i*.

When creating the models, insignificant variables were removed in a backwards stepwise process to find the model with the best fit. The GLM analysis was repeated for all the collision categories and the results are summarized in Appendix A. The category of collector segments treated with both DFS and MPE was not included as there were only two of them.

All the collision types show that the reduced frequency of collisions is significantly related to the expected collision frequency, assuming an absence of DFSs, and segments with a higher expected number of collisions are observed to experience a higher reduction in collision frequency. Except on collector segments, the presence of a shoulder significantly reduces the frequency of collisions; this could be attributed to the limited number of treated collector segments. And when the shoulder is represented with a negative sign, it indicates the presence of shoulder is usually associated with improved safety levels as it provides an additional margin for recovery from errors. The ADT has a significant impact on all four collision types as they are positively correlated, meaning when the ADT is represented with a positive sign it can be expected to cause a higher frequency of collisions. Segment length is another important factor in site selection, though it does not have a significant impact on collectors. However, segment length does not have a significant impact towards reducing collisions whenever the segment has already been treated with MPE.

3.4 Summary

This chapter describes all the utilized methods and corresponding results of Phase I. The before-and-after Empirical Bayes method was used to evaluate the safety effectiveness of DFSs on urban roads using data provided by the City of Edmonton. To estimate the change in collisions, locally developed SPFs and yearly calibration factors for different collision severities and types were used. Statistically significant reductions were observed for all of collision severities (i.e., PDO, Injury and Severe) and types (i.e., Speed-related, Rear-end and Improper lane changing). The reductions ranged from 32.5% to 44.9%, with the highest percentage reduction in collisions being observed for severe speed-related collisions, followed by the total speed-related collisions. As the initial purpose of installing DFS was to improve compliance to speed limits, these findings are both intuitive and expected. Previous studies only showed that DFSs were effective in reducing speed in specific locations, while results of this study confirmed their effectiveness for improving road safety. The economic analysis indicated that it is worthwhile to invest in installing citywide DFSs in urban cities.

Additionally, the before-and-after EB evaluation was repeated on urban arterial and collector roads in the City of Edmonton. Local SPFs and YCFs were again constructed accordingly based on different categories. A comparison was investigated between sites treated with only DFS and with both DFS and MPE. The results verified that DFS was able to reduce collisions at treated sites. The reduced number of collisions were estimated at 31.02% on collector segments with DFS only, and 41.61% on segments treated with both DFS and MPE. Collector segments with both DFS and MPE showed an 87.62% reduction, but the sample size of this category was too small and cannot be considered conclusive. In the other two categories (i.e., Total and Arterial), reductions resulting from both DFS and MPE were higher than DFS only. Also, the study by (Li, et al., 2015)suggested MPE can lead to an overall reduction in collision frequency on urban arterials by approximately 14.5%. As a result, it can be concluded that the combined use of these two treatments is more effective for improving traffic safety than using only either DFS or MPE. Overall, the results strongly indicate that DFSs were more effective for improving safety on arterials compared to collectors.

Finally, to explore the factors that might influence the selection of future DFS locations, a generalized linear model for each type of collision was created. The observed frequency of collisions after the intervention was chosen as the dependent variable, the evaluation results showed that the expected number of collisions during the after-period with the absence of DFS was the most significant factor. Traffic volume (ADT), presence of a shoulder, and segment length were also identified as significant factors influencing the selection of future DFS locations. Future research may take advantage of this study's findings to determine the optimal strategy for placing new DFSs, which can then provide the basis for the future expansion of a DFS system in urban environments.

Chapter 4. CITYWIDE IMPLEMENTATION STRATEGY

Based on the results found in Chapter 3, it was established that DFS is able to significantly reduce the collision frequencies for all collision severities and types. It also has a high benefit-to-cost ratio that is into the double digits indicating this countermeasure is well worth the investment. However, like most projects, resources are limited thus an optimal strategy for deploying DFSs is required to avoid unnecessary spending.

This chapter introduces a site selection framework developed for locating DFSs. Section 4.1 provides an overview of the framework and describes the procedures for recommending DFS sites. Section 4.2 elaborates on the methodologies behind this framework, including the explanation of the location selection criteria (4.2.1), introduction of the geostatistical method for estimating ADT data (4.2.2), formulation of the objective function (4.2.3), and the algorithm utilized to obtain the optimal solutions (4.2.4). The results are shown in Section 4.3 with Section 4.4 summarizing the work done in Phase II. The lists of all the selected sites' information are shown in Appendices B, C and D.

4.1 An Overview of DFS Location Allocation Framework

In this framework, the segmentation units for the candidate sites are the same as those used in Chapter 3. Typically, location allocation problems require that the whole demand surface be discretized into equal units as candidate sites (i.e., equal road length segments), however, this cannot be done in this research for the following reasons:

- All the SPFs and YCFs used in this research were developed based on the segments split by the rules introduced in Chapter 3;
- The location information provided for each collision point is not accurate as it only identifies a general location as being on a segment of road between two intersections. If the road segment were to be spit into smaller equal length units, there would be many zero collision recordings for each new unit. This means that the SPFs would not accurately model the relationship between road properties and geometry to the number of collisions.

To address these limitations, the candidate sites used in this framework are the same as the ones used in Chapter 3. To find the optimal installation sites for DFSs, two factors are considered within the framework. The first and top priority is the safety effectiveness (i.e. collision frequency reductions) that can be obtained from a certain implementation strategy. This factor is overwhelmingly considered in many site selection works that pertain to traffic safety countermeasures and/or facilities (Kim, et al., 2016; Jin, et al., 2014; Dell'Olmo, et al., 2014; Kwon, 2015). To quantify the expected collision frequency reductions for each candidate site, the Equivalent-Property-Damage-Only (EPDO) method was used to make a fair comparison between candidate sites by removing the collision severity and initial collision frequencies biases. This method is a weighting system where severe collisions receive the highest weightings and PDO collisions receive the least. Prior to estimating the expected safety effectiveness, the ADT value was interpolated using a geostatistical method for each site, which is critical to the whole framework. The EPDO and ADT estimation methods are introduced in Sections 4.2.1 and 4.2.2.

The coverage of vulnerable road users and facilities is the second factor that needs to be included in the DFS site selection process (Li, et al., 2017). For this study, vulnerable users and areas are represented by school zones, playgrounds, bus stops, and senior residences which are combined together as a factor to be utilized in the framework (Kim, et al., 2016; Li, et al., 2017; Li, et al., 2019).

In order to integrate these two factors into the site selection process, the level of importance between the two factors needs to be adjusted by using a trade-off criterion. The criterion is determined by applying weights to them, where the greater the weight is applied, the more importance is placed on that factor. For each of the different criterion, there are two scenarios to be considered. The all-new scenario is one where all existing DFSs are hypothetically relocated optimally within the study area and then used to assess the existing deployment strategy. The expansion scenario is where the framework will suggest optimal sites for expanding an existing DFS network with a predetermined number of new DFS units. The overall process of the DFS location allocation framework is shown in **Figure 4-1.** This figure also depicts required tasks to be conducted along with their corresponding sections for detailed discussions.

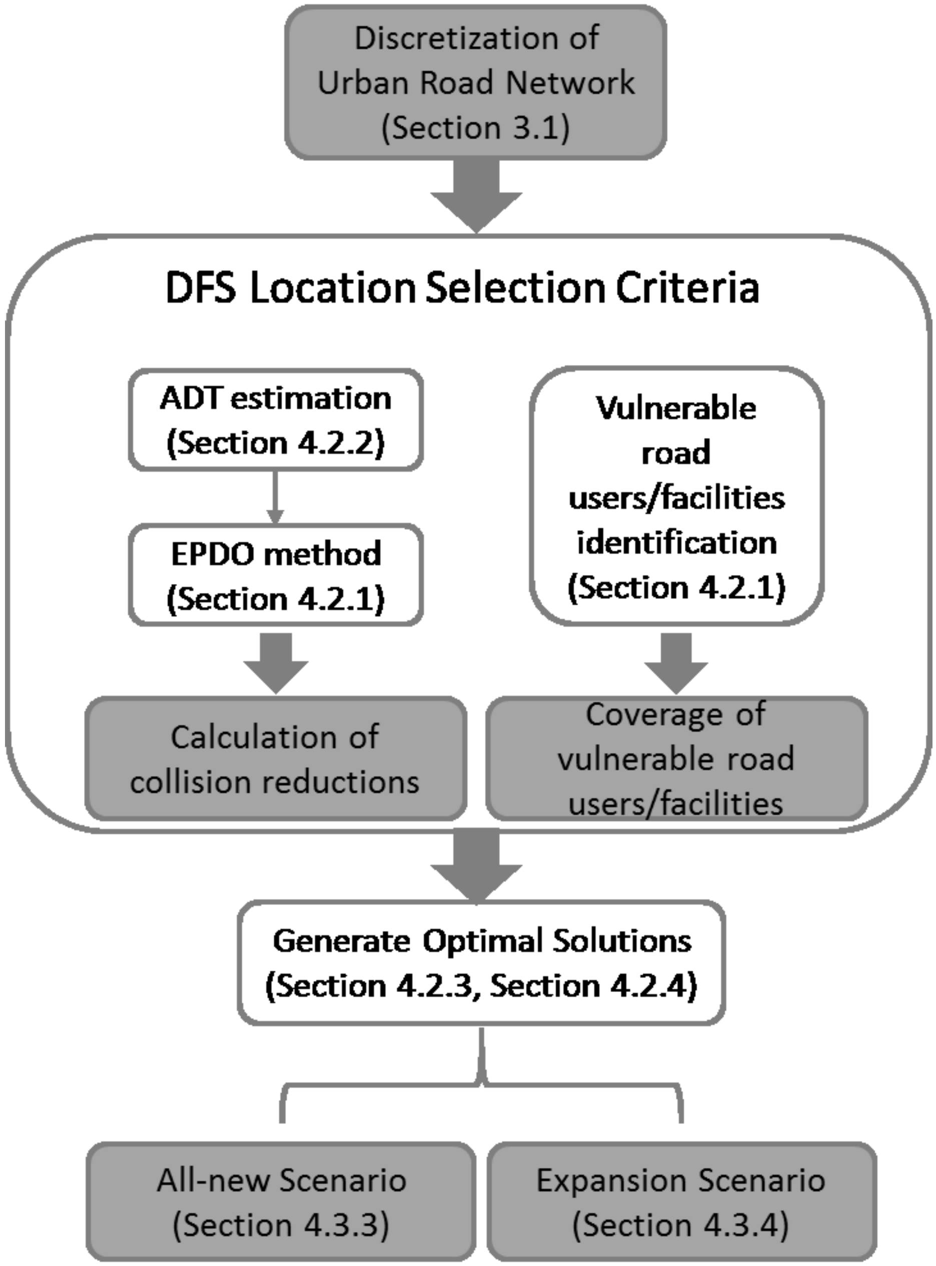


Figure 4-1 Overview of the framework

4.2 Methodology

4.2.1 Location Selection Criteria

Traffic Safety (EPDO)

Using the same methods and calculations as outlined in Chapter 3, the EPDO collision reduction for each site is calculated for each candidate site. Collisions for each candidate site were divided into two severity categories - PDO and Severe, and the collision reduction is found for both (Section 3.1). Section 3.2 detailed how to obtain the expected number of collisions using the EB-method with the collision reduction ratios provided in Section 3.3.2. Once the expected collision reductions for both severities are found, they are then multiplied by the Equivalent-Property-Damage-Only (EPDO) weights and summed. An EPDO weight is defined as the ratio between the costs of a certain severity of a collision to a PDO collision (Federal Highway Administration, 2004). **Figure 4-2** is a flowchart showing the workflow for the computational process of this step.

In order to use the EB-method to calculate the expected collision frequencies, the corresponding ADT data for that road segment is required. However, as was identified in Section 3.1, ADT data is not always available for every segment. To fill in the missing ADT data, the Spatial Statistical method Kriging was utilized to spatially interpolate the missing ADT data for each year. Details of this step is outlined in Section 4.2.2.

Vulnerable Road Users & Facilities

In this framework, the presence of bus stops, nearby schools, playgrounds, and senior residences were taken into account as a vulnerable facility or source of vulnerable users. **Figure 4-3** is a map showing the location of all these vulnerable facilities. The Geographic Information System software named ArcGIS developed by Esri (ESRI, 2019) was used to process the relevant spatial data with their built-in spatial analysis tool. The details of this procedure are outlined in the following sections.

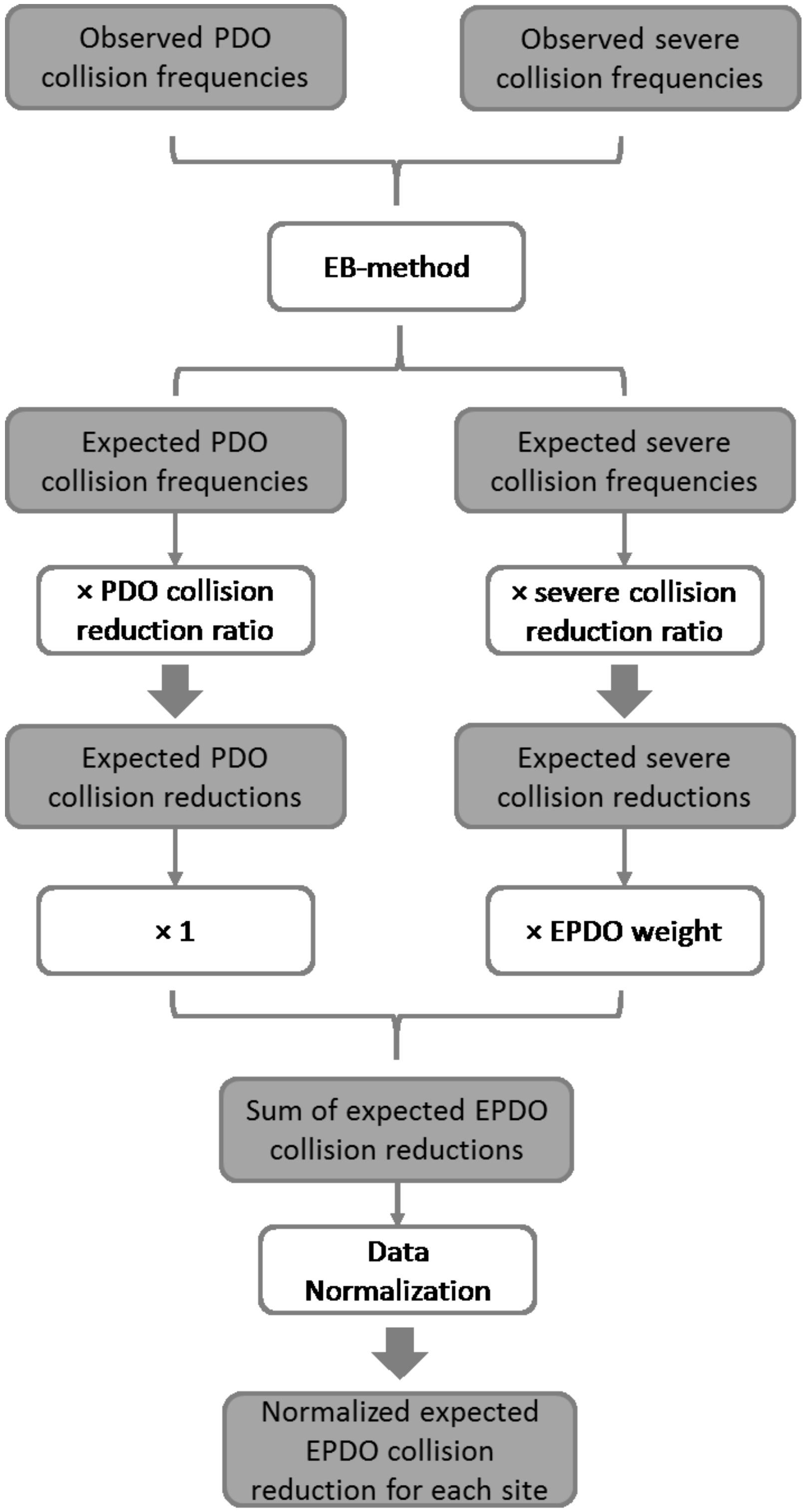


Figure 4-2 Workflow of Calculating EPDO collision reductions

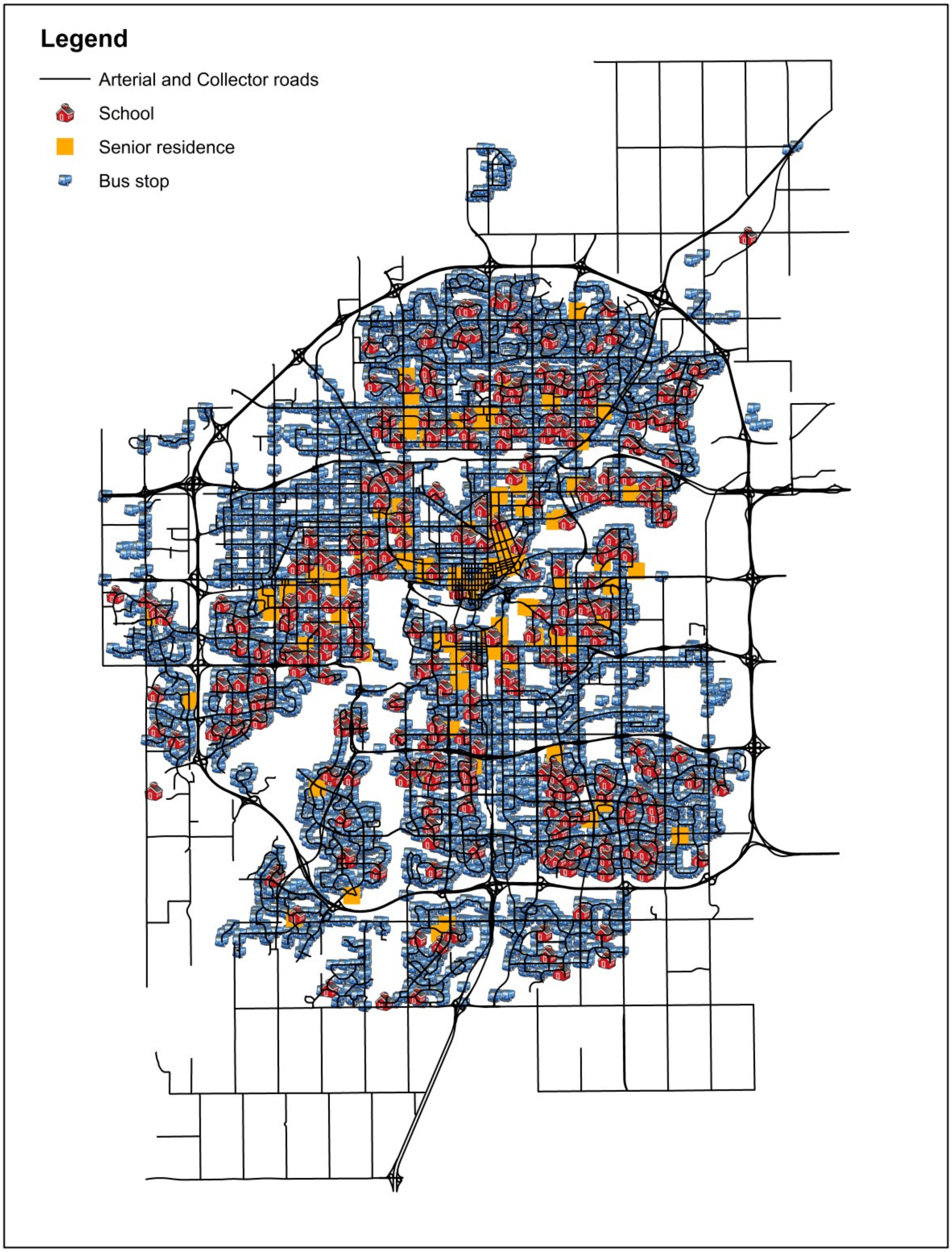


Figure 4-3 Map of the vulnerable road users/facilities

In ArcGIS, all the bus stops were assigned to their located road segments. Any road segments with a speed limit equal to or under 30 km/hr are assumed to be near vulnerable road users/facilities, such as schools and playgrounds. For senior residences, a 500-meter distance threshold was used to label road segments as being nearby a senior residence. Each of these three variables were binary values, indicating they were either present or not. For each candidate segment, these three variables are summed to obtain a coverage value, thus the minimum coverage value would be 0 and the maximum would be 3. Outlined below are the following steps for this procedure.

Step 1: Map the segments with speed limits under or equal to 30 km/h, locations of senior residences, and bus stops;

Step 2: Use the Intersection Tool provided in ArcGIS to intersect the segments where the speed limit is under or equal to 30 km/h with all the candidate segments. Intersected segments are considered close to schools, playgrounds or other vulnerable road users/facilities and their attribute of coverage for schools/playgrounds would be set to 1, otherwise 0.

Step 3: Use the Network Analyst Tool – OD Cost Matrix provided in ArcGIS to calculate the actual network distance between each senior residence and segment. Check the distances for all segments, if the distance is less than or equal to 500 meters, then that segment is considered close to a senior residence. If a segment is identified to be close to at least one senior residence, the attribute of coverage for senior residences can be covered by the DFS in that segment would be set to 1, otherwise 0.

Step 4: Use the Spatial Join Tool provided in ArcGIS to assign the bus stops information into their located segments and count the number of bus stops located in each segment. If a segment has at least one bus stops, the attribute of coverage for bus stops located on that segment would be set to 1, otherwise 0.

Step 5: Add the results obtained in steps 2, 3, and 4 together for each candidate site. The maximum final value of coverage for vulnerable road users/facilities would be 3 and the minimum would be 0.

Step 6: Normalize the results obtained in step 5 between 0 and 1 for all segments.

Both EPDO collision reductions and coverage of vulnerable road users/facilities were normalized between 0 and 1 to convert them into a dimensionless term to enforce a fair comparison. A weighted value was proposed to allow decision-makers to adjust the level of importance on these two factors based on their specific needs. To find the optimal strategy for deploying DFSs in the city, the Greedy Algorithm was utilized to iteratively update the demand surfaces (i.e., safety conditions and coverage of vulnerable road users/facilities in each segment) by locating one DFS at a time and then compare the segments' objective values while under a series of constraints. Details, including the usage of the weight value, the objective function formulation, and work logic of the greedy algorithm are presented in Sections 4.2.3 and 4.2.4.

4.2.2 Average Daily Traffic (ADT) Estimation via Kriging

Traffic volumes is an extremely important piece of information used by transportation engineers and planners when making decisions. This study relies on traffic volume data as key variable for the calculation of a candidate road segment's collision reductions as introduced in Section 4.2.1.

A variety of techniques have been implemented to estimate traffic counts. Each method takes known traffic counts and uses additional information (e.g., land use, time-steps, road geometry attributes, etc.,) to make a prediction (Selby & Kockelman, 2011). These estimates can be separated into future-year and present-year predictions. Future-year predictions use current and past traffic count data to estimate the traffic count at a future date. On the other hand, current-year predictions use the traffic data available to estimate traffic counts at unmeasured locations. For this study, ADT data is available at various locations for every year, therefore the current-year prediction method was used to interpolate yearly ADT values at unmeasured road segments.

Kriging is one of the most commonly used geostatistical interpolation techniques that also account for the uncertainty of the estimation. Kriging predicts the values at unsampled locations from the weighted average of nearby measured observations. Weights are determined based on their distance from the unsampled location and their closeness to each other. Commonly used variants of the kriging method are Simple Kriging (SK), Ordinary Kriging (OK) and Regression or Universal Kriging (RK or UK). The main difference between SK and OK estimation methods is that SK assumes a constant and known mean over the sampling domain, while OK assumes an unknown and constant mean. RK or UK are quite similar interpolation techniques that model the trend or drift component of the variable using available observations. The basic equation of kriging is given as:

$$Z^*(X_0) = \sum_{i=1}^{n} \lambda_i Z(X_i) \tag{4-1}$$

Where, $Z^*(X_0)$ is the estimated value at location X_0, $Z(X_i)$ is the measured observations at sampling site X_i, λ_i is the kriging weight and n is the number of sampling location within search neighborhood. Kriging weights for each sampling location is estimated based on the parameters of the semivariogram model, introduced in the following paragraphs, and the relative distance of the specific point with other sampling points and the unknown point (Lichtenstern, 2013; Kwon & Fu, 2017). For this study, Ordinary Kriging (OK) was used.

The semivariogram models are used for linear interpolation via Kriging. Constructing a good quality semivariograms for each year is critical as it determines the accuracy of estimation results. The semivariogram is the plot of the expected value of the semivariance of the variable of interest. It is a statistic that shows how the level of similarity between two known points decrease as their separation distance increases (Olea, 2006). The semivariance value can be calculated by taking the average of the squared difference of two measurements in a study domain separated by a specific and defined lag distance. The formula generally used for semivariogram estimation is shown below:

$$\gamma(h) = \frac{1}{2n(h)} \sum_{i=1}^{n(h)} [z(x_i + h) - z(x_i)]^2 \tag{4-2}$$

Here, γ(h) is the semivariance value. $z(x_i + h)$ and $z(x_i)$ are two measurements taken at location x_i and $(x_i + h)$ which are separated with a lag distance, h. **Figure 4-4** shows a typical semivariogram plot. Here, $C(h)$ is the covariance value, that measures the similarity of the measurements. For a specific lag distance, the summation of semivariance and covariance is equal to the total variance value in the study domain.

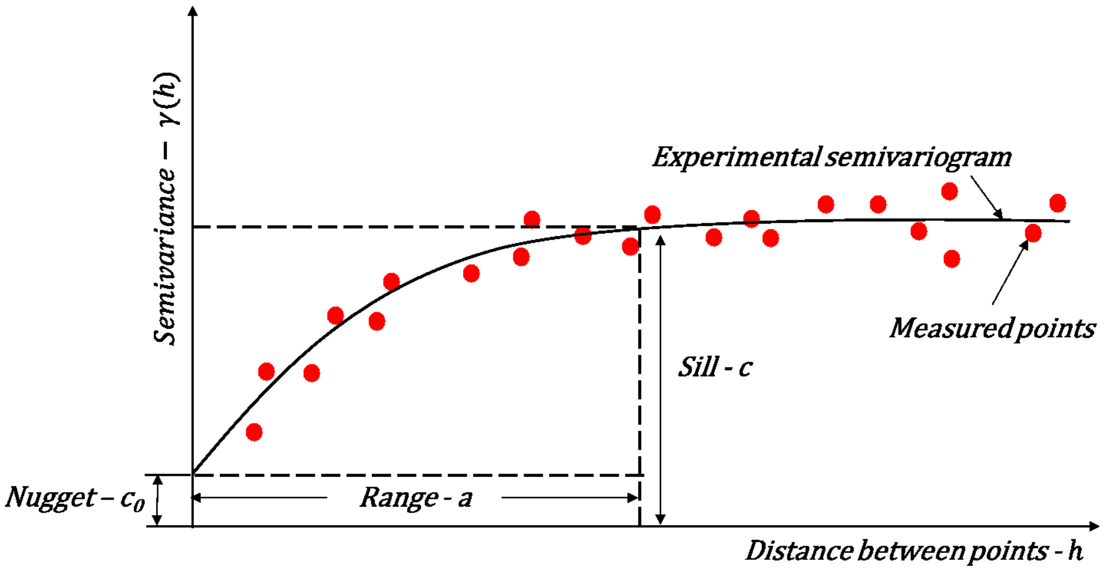


Figure 4-4 A typical semivariogram with parameters (modified and adopted from Flatman, et al., 1987)

Three basic parameters associated with semivariograms are the range, nugget and sill. According to theory, the semivariogram value at the origin should be zero, but due to measurement errors, the value of the semivariogram at the origin could differ significantly from zero and this is known as the nugget effect. The semivariance value at which the semivariogram levels off is known as the sill parameter. Generally, the partial sill is encountered in the semivariogram analysis as the difference between the actual sill value and nugget effect. The lag distance at which the semivariogram reaches the sill value is known as the spatial range of autocorrelation. Autocorrelation is considered to be zero beyond this spatial range. Three model forms commonly used for semivariogram modeling is considered during this analysis (Bohling, 2005; Olea, 2006; Solana-Gutiérrez & Merino-de-Miguel, 2011). The model types along with their equations are given below:

Spherical model:
$$\gamma(h) = \begin{cases} c * \left(1.5\left(\frac{h}{a}\right) - 0.5\left(\frac{h}{a}\right)^3\right), \text{if } h \leq a \\ c, \quad \text{otherwise} \end{cases}$$

Gaussian model:
$$\gamma(h) = c * (1 - e^{(\frac{-3h^2}{a^2})})$$

Exponential model:
$$\gamma(h) = c * (1 - e^{(\frac{-3h}{a})})$$

Here, h = lag distance, a = spatial range of continuity and c = sill.

After the semivariograms are constructed for each year, OK is used to interpolate the ADT values for all the unmeasured road segments. In order to assure the accuracy of interpolated results, cross validation is a geostatistical jargon that describes a unique verification process in which each observation is removed to produce an estimate at the same location of removal (Olea 2006). The error is calculated by taking the difference between observed vs estimated value at each known point and the same process continues until all observations are compared with estimated values. The semivariogram model developed is then tested using some statistical measures including mean standardized error (MSE) and/or root mean squared standardized error (RMSSE) to represent its robustness by examining, for instance, how closely the fitted model predicts the measured values. The workflow of the entire procedures of applying OK to interpolate ADT is shown in **Figure 4-5**.

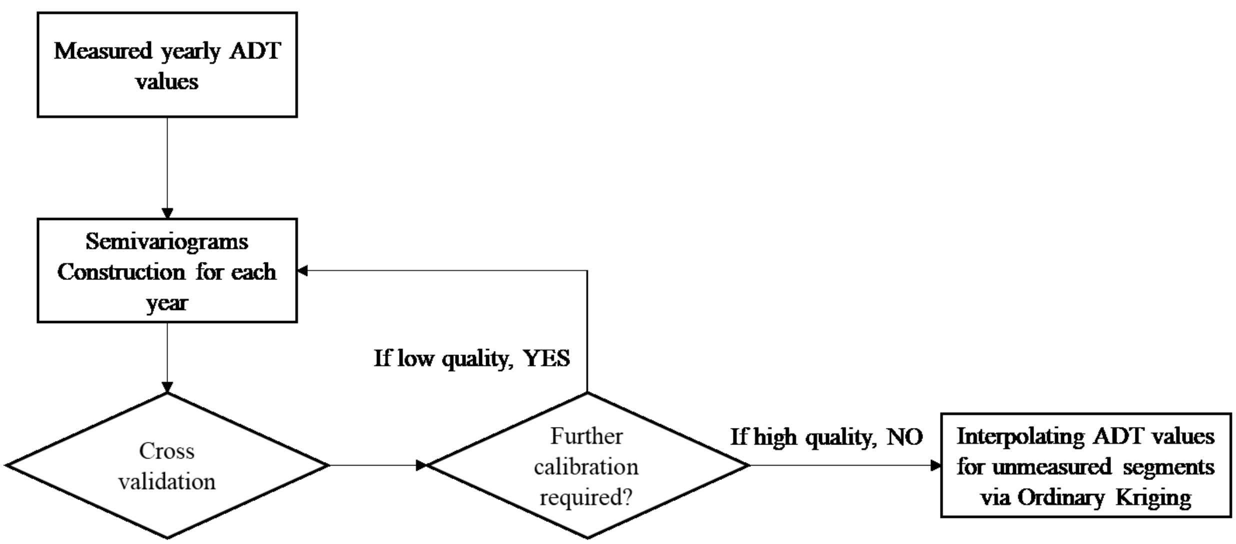


Figure 4-5 Workflow of ADT Estimation using Ordinary Kriging

4.2.3 Problem Formulation

Once the estimated ADT values for all candidate road segments have been calculated, the expected EPDO collision reductions and coverage of vulnerable road users/facilities can now be determined via the GIS analysis method outlined in Section 4.2.1. We propose that multiple DFSs be allowed to be installed on the same road segment, based on its length, however no literature that studied the halo effect of DFSs were found. Thus, based on the halo effect study of MPE (Gouda & El-

Basyouny, 2017) a 1-kilometer distance was set as the distance interval between DFSs as both MPE and DFS have a lot of similarities between them, and that study was also conducted in the same city. The objective function of locating DFSs is shown as **Equation (4-3)**.

$$Maximize: Obj = w_s * \sum_{i=1}^{n_{cad}} \sum_{m=1}^{n_{max}} s_i * s_i^m * {\Delta_{EPDO}}_i^m + (1 - w_s) * \sum_{i=1}^{n_{cad}} s_i * Cvg_i \tag{4-3}$$

Subject to:

$$\sum_{i=1}^{n_{cad}} \sum_{m=1}^{n_{max}} \boldsymbol{s_i * s_i^m \leq B}, \qquad \forall \boldsymbol{i} \tag{1}$$

$$\boldsymbol{s_i \in \{0, 1\}} \tag{2}$$

$$\boldsymbol{s_i^m \in \{0, 1\}} \tag{3}$$

$$\boldsymbol{0 \leq w_s \leq 1} \tag{4}$$

Where, Obj is the objective value of all the selected sites by integrating collision reductions (first term) and coverage of vulnerable road users/facilities (second term); w_s is the weight value (usually between 0 and 1) allowing users to place different levels of importance between the two factors; n_{cad} represents the total number of candidate sites; s_i is a binary decision variable (0 or 1) that controls the selection of the i^{th} candidate site, if s_i is equal to 1, it means the i^{th} candidate site is included, otherwise no; n_{max} represents the maximum number of DFSs that can be located in one road segment; s_i^m is a second decision variable representing whether the m^{th} DFS is located in the i^{th} candidate site; ${\Delta_{EPDO}}_i^m$ means the normalized collision reduction after putting the m^{th} DFS into the i^{th} candidate site; Cvg_i is the normalized coverage of vulnerable road users/facilities of the i^{th} candidate site; B is the total available budget (i.e., the total number of DFSs that will be located). Other constraints include:

1. if one segment is longer than one kilometer or shorter than 100 meters, it will be excluded from the body of candidate sites for selection. The majority of the road lengths are about one kilometer, and in terms of the real engineering concerns, Edmonton's city blocks are usually around 100 meters (City of Edmonton, 2019), thus the reasoning for segments with lengths longer than one kilometer or shorter than 100 meters were excluded from the candidate sites.
2. highway road segments are also excluded since DFSs mainly target reducing collisions on arterial and collector roads.

4.2.4 Optimization via Greedy Algorithm

As mentioned above, greedy algorithm is utilized as the solution algorithm in this framework. The greedy algorithm is any algorithm that follows the problem-solving heuristic of making the locally optimal choice at each stage with the intent of finding a global optimum (Cormen, et al., 1990). In many problems, a greedy strategy does not usually produce an optimal solution, but a greedy heuristic may yield locally optimal solutions that approximate a globally optimal solution in a reasonable amount of time. In our case, since the two factors in the objective function can be calculated in a deterministic way for each candidate site, the greedy algorithm was deemed suitable for application and thus implemented herein to find the optimal solutions. The workflow of the greedy algorithm is shown in **Figure 4-6**.

4.3 Results and Discussions

In this section, results of the ADT estimation including the semivariograms and the kriged maps that show all the interpolated ADTs are shown in Sections 4.3.1 and 4.3.2, respectively. By using the site selection framework, the optimal DFS deployment strategies for two scenarios using three weight values are explained in Sections 4.3.3 and 4.3.4.

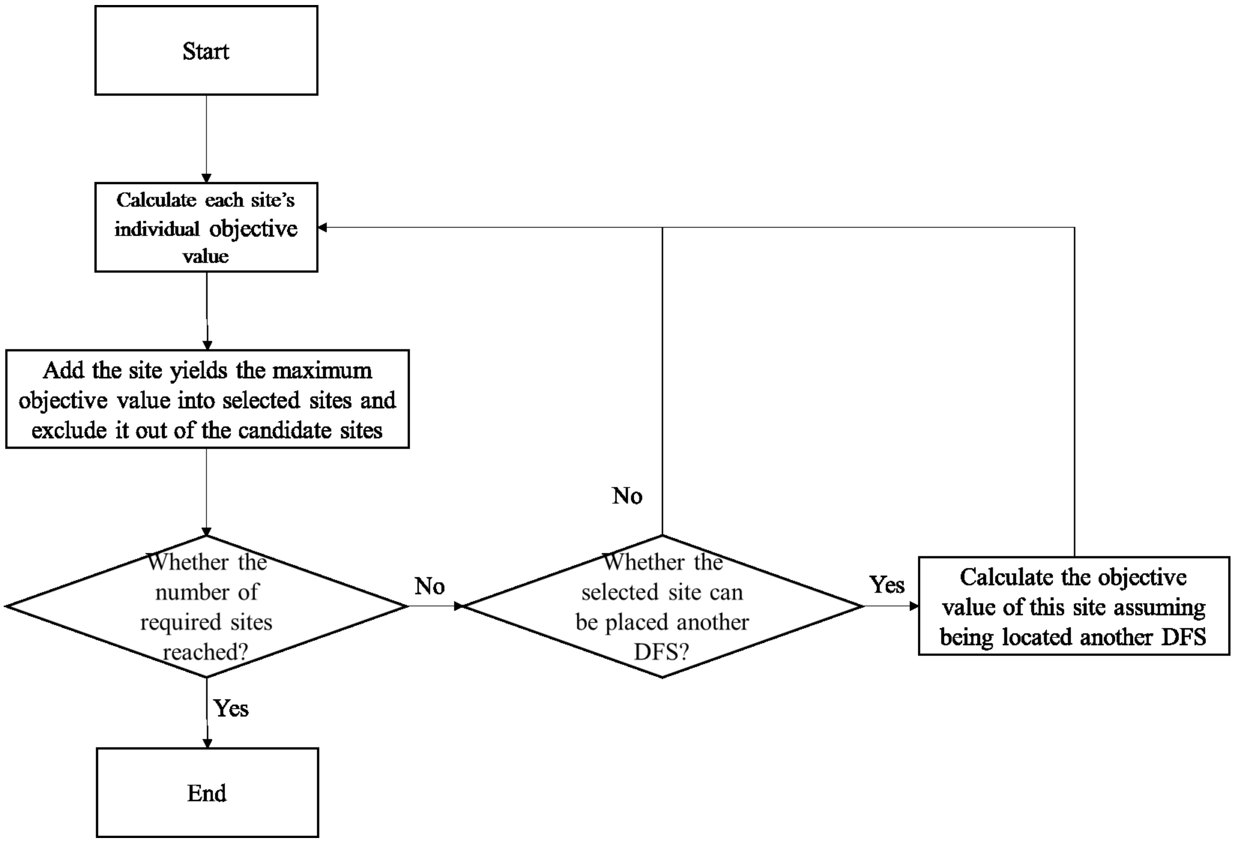


Figure 4-6 Workflow of the greedy algorithm

4.3.1 Semivariograms

As mentioned in the section 4.1, the quality of the semivariograms are crucial for the accuracy of the ADT estimation results. In this study, two statistical measures, namely, the Mean Standardized Error (MSE), and Root Mean Square Standardized Error (RMSSE) from the cross validation of the results were used to determine its accuracy. The Equations for MSE and RMSSE are shown as follows.

$$MSE = \frac{\sum_{i=1}^{n}(\hat{Z}(z_i) - Z(z_i))/\hat{\sigma}(z_i)}{n} \tag{4-4}$$

$$RMSSE = \sqrt{\frac{\sum_{i=1}^{n}[\frac{\hat{Z}(z_i) - Z(z_i)}{\hat{\sigma}(z_i)}]^2}{n}} \tag{4-5}$$

The closer MSE is to 0 and RMSSE is to 1, the higher the accuracy of the estimated results. Typically, a minimum of 30 sample points is required to construct an accurate semivariogram though more sample points tend to result in higher accuracy levels (Olea, 2006). A summary of all the available ADT data points over the years is shown in **Table 4-1**.

Since the number of available data points in 2017 does not meet the minimum threshold, 2017 was excluded in the ADT estimation step and omitted in the expected collision reductions computation. The semivariograms were constructed within ArcGIS (ESRI, 2019) and the resulting semivariogram plots are shown below in **Figure 4-7** and the semivariogram models' details and their cross validation results are shown in the **Table 4-2**.

Table 4-1 Summary of available ADT data points

Year	Number of available data points
2009	425
2010	494
2011	581
2012	521
2013	700
2014	905
2015	1175
2016	1037
2017	8
2018	239

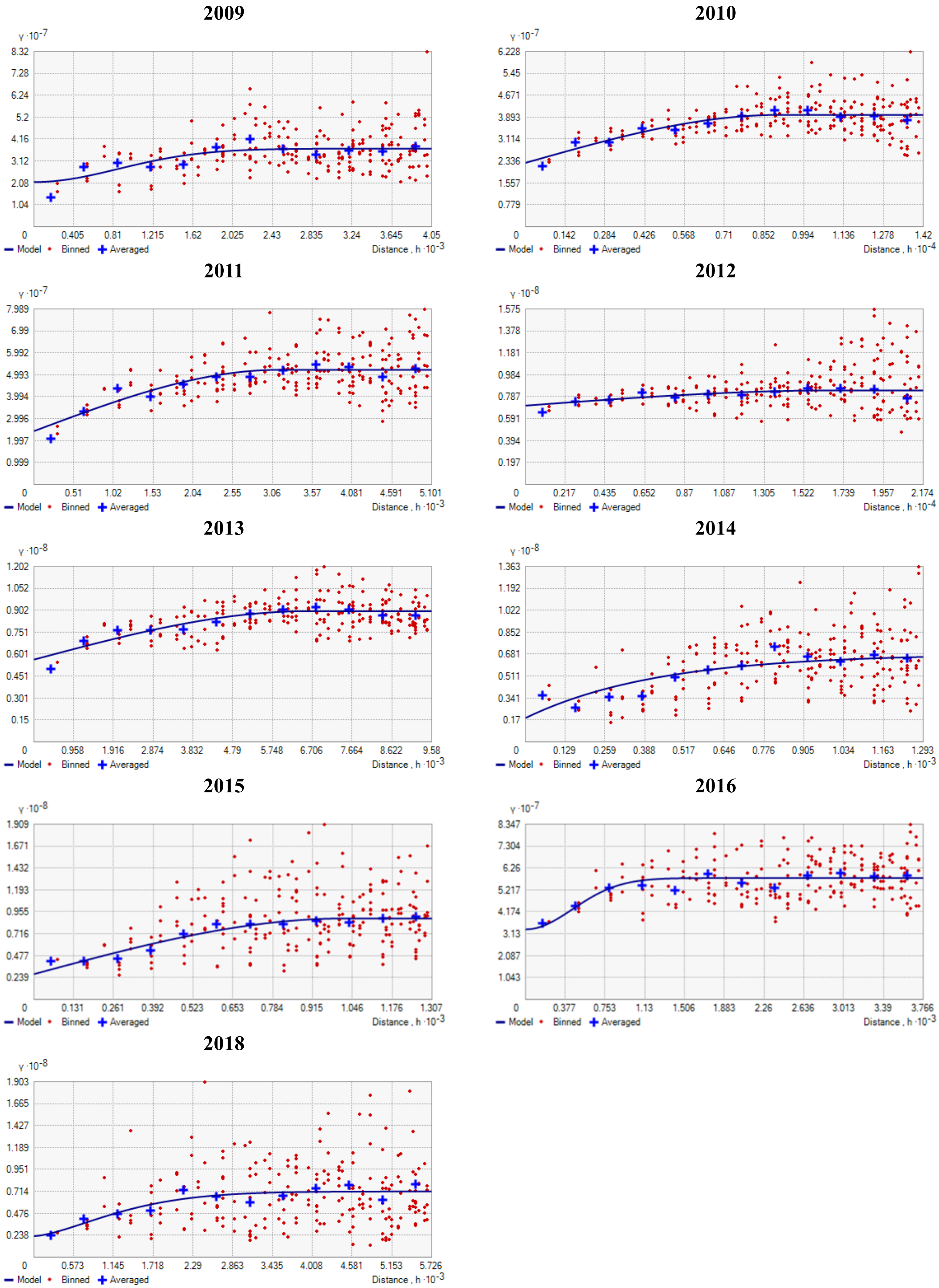


Figure 4-7 Semivariograms of ADTs in 2009 – 2018

Table 4-2 Summary of yearly ADT semivariogram models

Year	Model	Partial Sill	Range	Nugget	MSE	RMSSE
2009	Gaussian	15,852,949	2101.747	21,222,809	-0.00378	0.99703
2010	Spherical	17,016,233	9043.457	22,725,419	0.007596	1.020923
2011	Spherical	27,876,692	3139.66	24,318,105	0.004031	1.115397
2012	Spherical	13,629,084	16869.01	70,817,339	-0.00232	0.998993
2013	Spherical	33,132,531	6576.977	56,446,149	0.001857	1.008961
2014	Exponential	49,873,513	1292.681	18,642,927	-0.00496	1.1039
2015	Spherical	60,418,880	1017.751	27,786,960	-0.00948	1.040402
2016	Gaussian	24,419,174	1087.64	33,403,420	0.003751	1.009619
2018	Exponential	56,214,359	4411.691	17,909,720	-0.00637	1.008195

By examining the semivariograms' shapes, model parameters, and cross validation results, it can be concluded that all of them are of good quality and their corresponding estimation results are deemed reliable.

4.3.2 Estimated ADT Values

With these accurate semivariogram models, Ordinary Kriging (OK) was used to interpolate the missing ADT values for each year. The maps of the estimated ADT distributions from 2009 to 2018 excluding 2017 are shown in **Figure 4-8**.

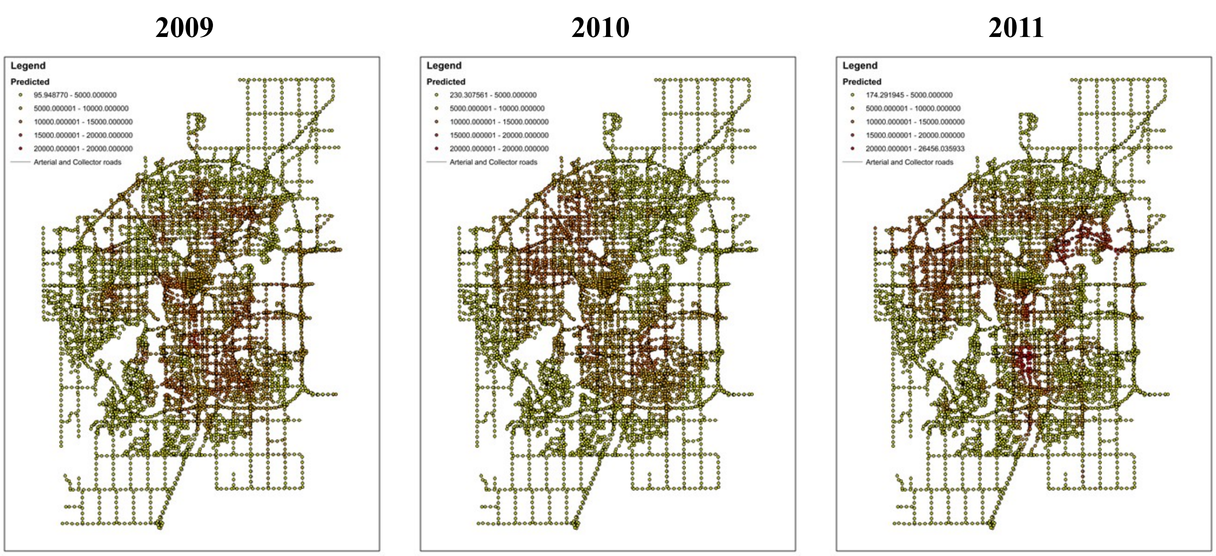


Figure 4-8 Estimated ADT data in the city road network

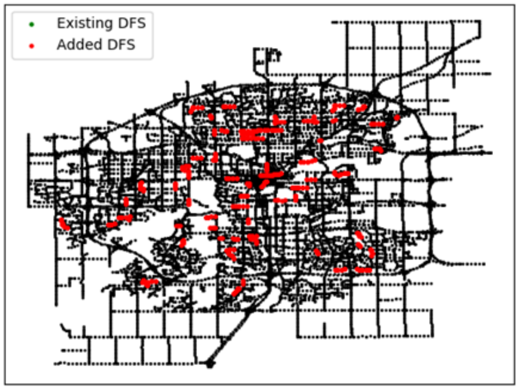
By examining the semivariogram models' calibrated parameters and the estimated ADT results, the ADT pattern of each year is different from each other. As semivariogram models are data sensitive (Bohling, 2005), different data availabilities and spatial distribution have an impact on the model development process (Olea, 2006). However, the results also indicate that a semivariogram model constructed in one year cannot be directly used to interpolate ADT values for another year. Thus, the long-term ADT data and semivariogram analysis are needed to better interpolate unmeasured points. After all the estimated ADT values were interpolated, each segment's corresponding collision reduction was calculated through the methods outlined in Section 4.1.

4.3.3 All-New Scenario Implementation Strategies

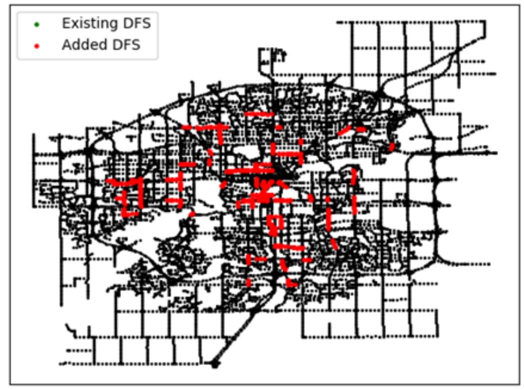
The all-new scenario is a hypothetical simulation of relocating all existing DFSs in the study area with the purpose of comparing the objective value of the existing deployment with that of the theoretical optimal deployment strategy. The results can be used to assess the current deployment strategy of DFSs and benchmark an optimal criterion.

In this study, three different weights were used to generate strategies by placing different importance on safety effectiveness (Δ_{EPDO}) and coverage of vulnerable road users/facilities (Cvg). The total budget constraint was assumed to be equivalent to the number of existing DFSs currently in place (i.e., 142) in the City of Edmonton. The optimization formulated earlier was implemented to locate DFSs such that traffic safety and coverage of vulnerable facilities and users can be maximized. The optimal sites locations generated via greedy algorithm are shown in the **Figure 4-9**.

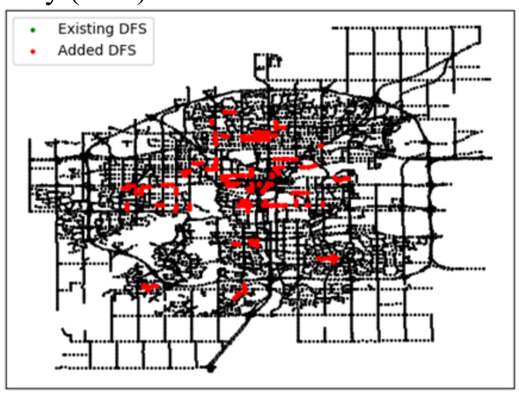
From **Figure 4-9**, it can be observed that the distribution of the selected DFS sites change based on the weightings applied to each of the factors. As the weight applied to the safety effectiveness (Δ_{EPDO}) increases, so does the preference for locating DFSs at high collision sites. By contrast, as the weighting value is reduced, then the preference shifts to cover more sites identified as vulnerable facilities or zones with vulnerable users. Some of the selected sites street views of the 0.5-weight value are shown in **Figure 4-10** to portray how well the proposed optimizer has delineated locations that are prone to accidents (e.g., sites 1 and 2) and vulnerable facilities (e.g., sites 3 and 4).



Considering $\boldsymbol{Cvg}$ Only (w=0)

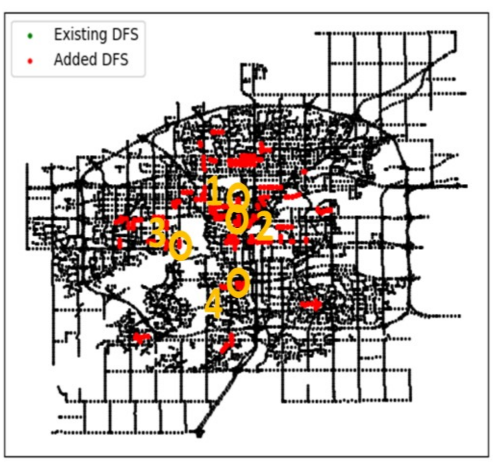


Considering $\Delta_{\boldsymbol{EPDO}}$ Only (w=1)



Equally considering both (w=0.5)

Figure 4-9 Selected sites distribution of all-new scenario



Site1

Site2

Site3

Site4

Figure 4-10 Street view of some selected sites of all-new scenario

Using the existing deployment as a point of reference, **Figure 4-10** shows how the level of improvements in percentage (negative value means decrease) on the reduction of collisions and coverage of vulnerable road users/facilities change as the weights changes.

As expected, as the weight value increases (i.e., more importance is placed on collision reduction), the level of improvement for collision reduction increases while the coverage of vulnerable road users/facilities decreases, and vice versa. The results of this comparison show that the current DFS deployment strategy focuses more on zones with high collision rates but still has room for improvement if the optimal deployment strategy is adopted.

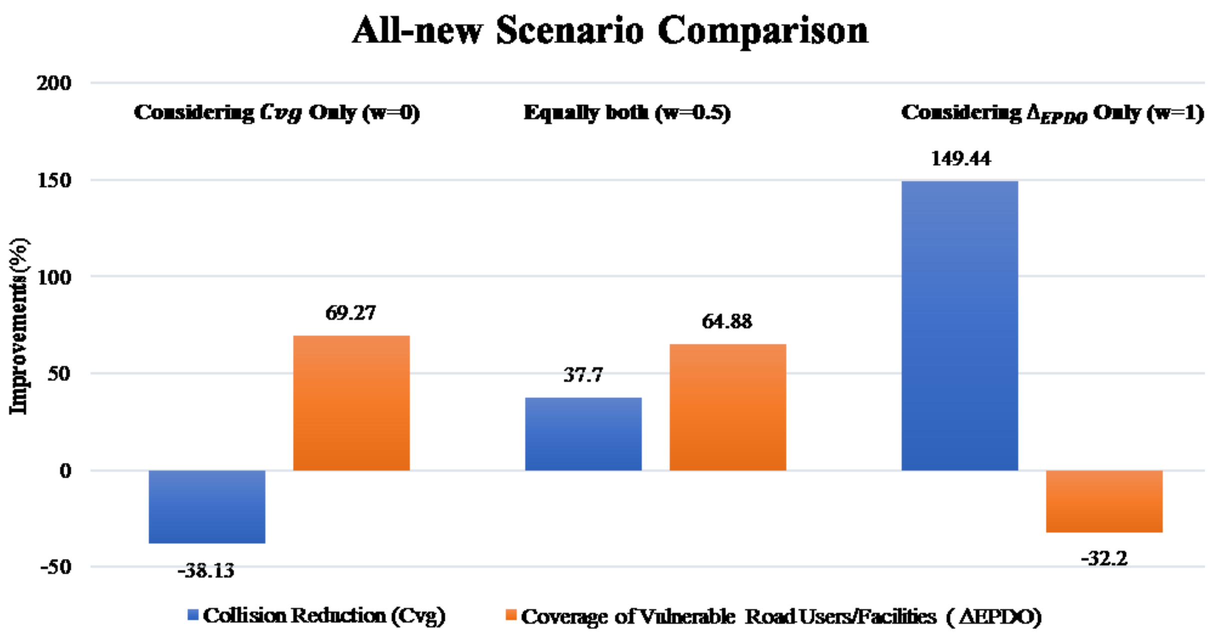
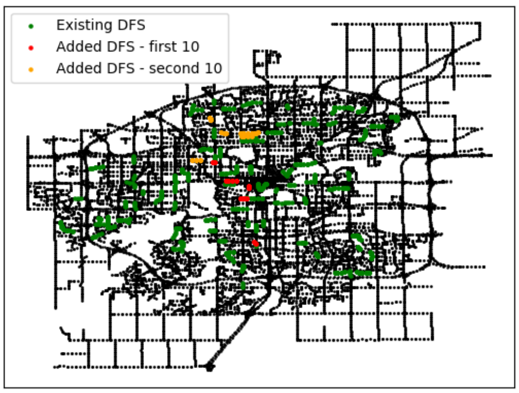


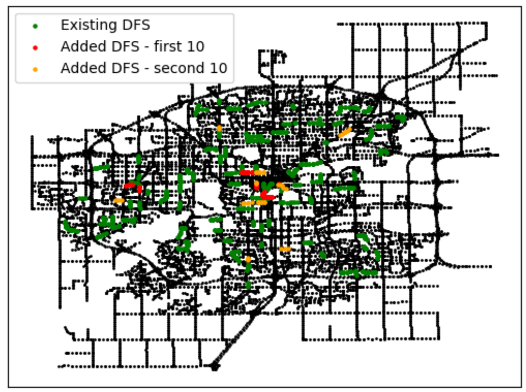
Figure 4-10 Comparison of the improvements by changing weight values of all-new scenario

4.3.4 Expansion Scenario Implementation Strategies

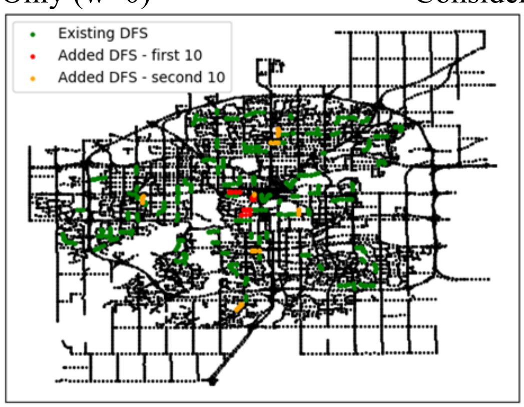
While the results from the all-new scenario show that the current deployment can be improved, relocating the entire set of existing DFSs is not an economically feasible option as it entails a laborious and timely endeavour. Therefore, this section details a way to expand the system by adding more DFSs to the existing deployment scheme. The optimization procedure introduced earlier has been modified to reflect the changes in the base condition. The objective function was evaluated at each iteration by considering the fixed DFSs throughout the entire optimization process. Identical optimization parameters and weighting schemes were used to generated locations solutions. The location of the selected sites for an additional 10 and 20 DFSs are shown in **Figure 4-11** and **Figure 4-12** displays some of the street views of the selected sites of the expansion scenarios using the weight value of 0.5. This further confirms that the results generated from this framework fit our expectations as some of the sites are near schools, playgrounds, and senior residences while others were placed in areas with a high collision frequency.



Considering Cvg Only (w=0)



Considering Δ_{EPDO} Only (w=1)



Equally considering both (w=0.5)

Figure 4-11 Sites selected for 10 future DFSs

Figure 4-12 Street view of some selected sites of expansion scenarios

Similar to the all-new scenario, the same trend in the distribution of selected sites based on the weightings can be seen in this expansion scenario. As before, the level of improvements based on weightings were found for both examples of adding 10 or 20 additional DFSs and are shown in **Figure 4-13**. Again, these statistics follow the same trend that was observed with the all-new scenario, with the only difference being that there were no negative improvement values.

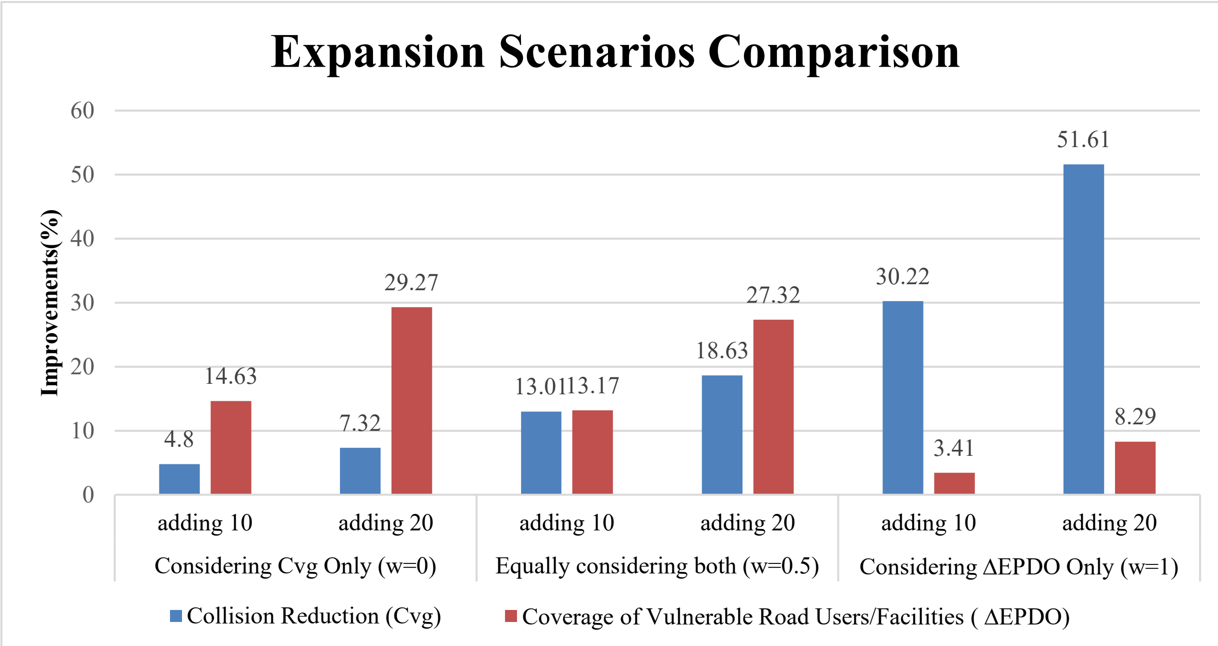


Figure 4-13 Comparison of the improvements by changing weight values of expansion scenarios

4.4 Summary

This chapter expanded the discussion on the site selection framework for a citywide DFS implementation strategy. Spatial interpolation of ADT via kriging was first conducted in this chapter, wherein the semivariogram models and their cross-validation results ensured the reliability of the estimated results. The EPDO method utilized the estimated ADTs to calculate the expected collision reductions for each candidate site as a result of installing a DFS. Another location selection criterion considering vulnerable road users/facilities were spatially processed and distributed to each site via ArcGIS.

Results from the all-new and expansion scenarios optimized via greedy algorithm were discussed. The findings suggested that the framework proposed and developed therein was able to provide reliable deployment strategies based on different weighting schemes such that DFS planners would have a freedom to adjust the level of importance (i.e., traffic safety vs facilities coverage) based on their needs.

This was supported by the results from the improvement comparisons and the sites that were selected based on which factor was deemed more important. As the weight value increased from 0 to 1, the level of importance is shifted in favor of reducing collisions over coverage of vulnerable road users/facilities. This means that segments or areas with a high collision frequency have a greater chance of being selected as a site for future DFS intervention. The opposite is true when the weight value decreases from 1 to 0, favoring coverage of vulnerable road users/facilities over collision reduction, thus making school zones, playgrounds, and senior residences a more favorable site for DFS intervention. In either case, the level of improvement will be the greatest for the factor deemed the most important. If the weighting was set to 0.5, giving each an equal level of importance, then improvement levels will be somewhere in between the maximum and minimum extremes.

Overall, the findings of this chapter suggest that the proposed DFS location allocation framework is easy and convenient to implement, and therefore suitable for real-world applications.

Chapter 5. CONCLUSIONS AND FUTURE RESEARCH

This chapter provides a summary of the thesis and highlights the major findings and the contributions of the work presented herein. The limitations of this thesis are also discussed in this chapter along with recommendations for future research.

5.1 Overview of Research

Speeding is a major contributing factor for traffic collisions and its dangers are often underestimated by the general public. Many countermeasures have been implemented in order to improve the level of traffic safety for the road users. One of the countermeasures is the Driver Feedback Sign (DFS) and has been in use around the world for some time, yet its safety impacts remains unknown. Therefore, the first primary objective of this thesis was to first conduct a safety assessment of DFSs, quantify its safety effectiveness, and determine the benefit-cost ratio through a case study. Factors that could potentially affect the safety impact of DFSs were also identified which may help in the selection of future DFS installation sites.

Since the provision of optimal DFS implementation strategies is considered equally important, a new location allocation framework was also developed. This framework enables transportation agencies to adjust the weighting values for factors based on their unique needs and concerns. The recommended sites determined by the framework aligned with our expectations for the reduction in collisions and the level of coverage for vulnerable road users/facilities. In both cases, the reductions and coverage area are improved when using the results from the framework. Visual verification of the optimally generated sites further validates the goodness of locations selected for DFS installation.

5.2 Main Findings of Research

Phase I: Traffic Safety Assessment of DFSs

- A before-and-after Empirical Bayes (EB) evaluation of DFSs was conducted on urban roads using data provided by the City of Edmonton. To estimate the change in collisions, locally developed SPFs and yearly calibration factors for different collision severities and types were used. Statistically significant reductions were observed for all of collision severities (i.e., PDO, Injury and Severe) and types (i.e., Speed-related, Rear-end and Improper lane changing). The reductions ranged from 32.5% to 44.9%, with the highest percentage reduction in collisions being observed for severe speed-related collisions, followed by the total speed-related collisions. As the initial purpose of installing DFS was to improve compliance to speed limits, these findings are both intuitive and expected. Previous studies only showed that DFSs were effective in reducing speed in specific locations, while the results of this study confirmed their effectiveness for improving overall road safety. The economic analysis indicated that it is worthwhile to invest in installing citywide DFSs in urban cities.

- The EB evaluation of DFSs was repeated on urban arterial and collector roads in the City of Edmonton. A comparison investigation was also conducted between sites treated with only DFSs and those with both DFSs and MPEs. The results verified that DFSs were able to reduce collisions at all categories of treated sites. The reduced number of collisions were estimated to be 31.02% on collector segments utilizing only DFS, and 41.61% on segments treated with both DFS and MPE. Collector segments with both DFS and MPE showed an 87.62% reduction, but the sample size of this category was too small for it to be conclusive. The Total and Arterial categories saw higher reductions when both DFSs and MPEs were used together as compared to using only DFSs. Also, the previous study (Li, et al., 2015) suggested MPEs can lead to around 14.5% overall reduction in collision frequency on urban arterials by itself. As a result, it can be concluded that the combined use of these two treatments is more effective for improving traffic safety than using only either DFS or MPE. Overall, the results strongly indicate that DFSs were more effective for improving safety on arterial roads as compared to collector roads.
- To explore factors that might influence the selection of future DFS locations, a generalized linear model was created for each type of collision. For this model, the dependent variable is the number of collisions observed after the DFS intervention was installed at the site. The results of the evaluation showed that the initial number of collisions was the most significant factor. Other factors such as traffic volume (ADT), presence of a shoulder, and segment lengths were also identified as significant factors that can influence the selection process for future DFS sites. Future research may take advantage of this study's findings

to determine the optimal strategy for placing new DFSs and in turn provide the basis for the future expansion of a DFS system in an urban environment.

Phase II: Development of Citywide DFS Implementation Strategies

- Missing ADT data in each year (except for 2017 because of limited available observed data) were interpolated using kriging for each candidate segment. Semivariograms were developed using well adopted statistical measures to check its accuracy. Robustness of the developed models and ADTs interpolated over a large urban network were validated and further attested the applicability of the geostatistical method to fill large spatial gaps.
- A site selection framework was developed to recommend optimal DFS deployment strategies. The all-new scenario results reveal that the current DFS deployment in the city of Edmonton focus more on areas with a high collision frequency. The differences between the suggested optimal locations and current locations indicate the benefits obtained from DFSs can be improved significantly by redesigning the current deployment. The collision reductions and coverage of vulnerable road users/facilities can be improved by up to 149.4% or 69.27% respectively if the level of importance was assigned accordingly.
- The expansion scenario results in a list of optimal sites that can be considered for future DFSs. The change in the location distributions and improvements based on different weight values given to them matched the expectations and the real situation as observed in the city. Collision reductions can be improved by up to 30.22% or 51.61% when adding 10 or 20 more DFSs respectively, while the coverage of vulnerable road users/facilities can be improved by up to 14.63% or 29.27% likewise.

5.3 Research Contributions

There are six major contributions in this research as summarized below:

- **Evaluation of DFSs and its impact on traffic safety:** Before this research, very limited literature existed on the safety impacts (i.e., collision reduction) of DFSs based on a long-term and large-scale implementation in an urban setting. Previous studies mainly focused on the speed changes resulting from DFSs within specific areas, while the research work of this thesis is the first to show that it has a definitive impact on reducing different types and severities of collisions as a whole for urban areas (i.e., arterials and collectors). This gap in the safety impact of DFS has now been addressed.

- **Economic analysis of the DFS program:** There is currently no studies related to the monetary benefits of DFSs. In this research, with the knowledge of the safety effectiveness of DFSs, economic analysis further investigated its benefit-cost ratio based on a 2-year and 5-year time horizon. The results indicate that DFS has a high benefit-cost ratio, making this countermeasure worthy of further investments.
- **Identification of the influencing factors of DFS installation.** Comparisons of DFS safety impact in different road and intervention types were conducted in Section 3.3.4. Arterials may benefit more from DFSs as compared to collectors, and combined use of DFS and MPE can lead to higher effectiveness. Calibrated results of the before-and-after change model from Section 3.3.4 indicate segments with higher traffic volume, initial collision frequencies, longer segment length, and shoulders are expected to benefit more from DFSs. These can be used as parts of the future DFS site selection criteria.
- **Investigation on interpolating the unmeasured traffic volume data.** Traffic volume measurements needs substantial time and manpower commitments, thus the availability of these data is quite limited. This thesis utilizes a well-known spatial statistical method, known as Kriging, to interpolate ADT values at unmeasured locations throughout the whole city road network. Furthermore, it is the first paper to use a long-term and large dataset to prove the feasibility of this interpolation method, however this topic still needs further investigation.
- **Development of a new DFS location allocation framework:** A location-allocation framework for optimizing the spatial design was proposed for DFS. The method developed provide decision makers with the freedom to simulate and optimize their DFS network by balancing the needs of the road users, vulnerable facilities, and traffic safety in locating DFS over an urban road network.
- **Establishment of DFS sitting guidelines.** Two distinct optimization scenarios with three weighting schemes for each were considered and optimal deployment strategies were provided accordingly. The all-new scenario results benchmark the system optimal implementation strategies and expansion to assess the current deployment work. The

expansion scenario results provide the optimal sites for installing additional future DFSs in order to improve the overall collision reductions and coverage of vulnerable road users/facilities. Proposed weight values can be adjusted by transportation authorities to study the tradeoffs between the two factors.

5.4 Future Research

This thesis validated the safety effects of DFSs on a city-wide level. A site selection framework has been developed to provide a system optimal implementation strategy for future DFS locations. However, it is still unknown how many DFSs would be required in urban areas. In addition, Section 3.3.4 indicates that the combined use of MPE and DFS can lead to higher safety effectiveness. Nevertheless, the site selection framework does not take this into account and the combined use of DFS, MPE, ISD and other countermeasures may alter the location allocation strategies. The research can therefore be further extended in several directions as follows:

- From the safety assessment results, it is evident that as more DFSs are added into the road network, the higher the benefits that can be obtained from the new deployment. However, there may be a diminishing return to the safety benefit as more and more DFSs are added and eventually the improvements would benefit coverage levels more than improvements to safety. Since there are limited resources for expanding the DFS program, it is meaningful to investigate the optimal density or optimal number of DFSs needed in the future.

- In Section 3.3.4, the comparison of the safety effectiveness between treated sites with DFS only and both DFS and MPE indicates that the safety effectiveness obtained from the combined use of both these countermeasures is higher than if using either one by itself. However, the accurate mutual effects between them are unknown. Since the city is planning to expand existing ISD, MPE and DFS programs to make the city safer, it is necessary to create a comprehensive system that would take these three countermeasures together into considerations when the expansion strategy is in its planning phase. This means the system optimal implementation strategy would be generated by not separating these countermeasures into individual parts but integrating them together as a whole.

- To better interpolate ADT values at unmeasured locations, more advanced kriging variants such as universal kriging or kriging with external drifts, should be explored to take account for additional covariates to improve the model performance. The semivariogram models can also further be investigated to explore the relationship between the variables of the study areas and the calibration parameters. This has the potential of obtaining a greater level of accuracy of the estimation results.

As summarized above, additional research will contribute to further expanding a new body of knowledge for developing sustainable DFS location allocation strategies and will improve the effectiveness and efficiency of future traffic safety programs.

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Appendix A Results of GLM analysis

	Intercept	EB after	Road Type	Shoulder	Pedestrian Crossing	ADT	Segment Length	Dispersion Parameter	Pearson's χ^2	Scaled Deviance	df
Total	-6.98	0.05**	-	-0.92*	-	0.51**	0.47**	0.18	76.84	88.07	81
Total with DFS only	-6.74	0.05**	-	-1.14*	-	0.45**	0.52*	0.21	69.25	69.30	59
Total with DFS and MPE	-4.86	0.07**	-	-1.23**	-	0.60*	-	0	16.28	16.81	18
Arterial	-6.91	0.05**	NA	-1.14*	-	0.52**	0.45*	0.18	55.86	66.26	61
Arterial with DFS only	-6.52	0.05**	NA	-1.87*	-	0.45*	0.49*	0.18	46.97	52.57	41
Arterial with DFS and MPE	0.71	0.07**	NA	-0.89*	-	-	-	0	15.55	16.01	17
Collector	-0.9747	0.53**	NA	-	-	-	-	0	13.53	14.97	18
Collector with DFS only	-0.82	0.49**	NA	-	-	-	-	-	10.95	12.49	16

Appendix B Selected Locations for All-New Scenario

Table A-1 Selected Sites by Considering Coverage of Vulnerable Road Users/Facilities Only (w=0)

Road Name	Direction	Road Type	Start Point	End Point	Δ_{EPDO}	Cvg	#DFS
132 AV NW	EBD	Collector-Residential	(32667.3,5940040.0)	(32013.9,5940040.0)	0.571	3	1
135 AV NW	EBD	Collector-Residential	(34081.9,5940570.0)	(33640.1,5940560.0)	0.665	3	1
144 AV [EB-S] NW	EBD	Collector-Residential	(34632.2,5941580.0)	(34255.5,5941580.0)	0.499	3	1
MCQUEEN RD NW	NBD	Collector-Residential	(28548.5,5935520.0)	(28398.5,5935970.0)	0.301	3	1
87 AV NW	EBD	Arterial-Class D (Non-Truck Route Low speeds)	(32359.4,5932330.0)	(31977.5,5932330.0)	0.867	3	1
87 AV NW	WBD	Arterial-Class D (Non-Truck Route Low speeds)	(32359.4,5932330.0)	(31977.5,5932330.0)	0.801	3	1
102 AV NW	EBD	Collector-Residential	(31731.3,5934570.0)	(31099.2,5934560.0)	0.977	3	1
102 AV NW	WBD	Collector-Residential	(31731.3,5934570.0)	(31099.2,5934560.0)	0.608	3	1
106 ST [NB-S] NW	NBD	Collector-Residential	(32916.0,5926840.0)	(32786.3,5927000.0)	0.308	3	1
106 ST [SB-S] NW	SBD	Collector-Residential	(32916.0,5926840.0)	(32786.3,5927000.0)	0.338	3	1
110 ST NW	NBD	Collector-Residential	(32468.4,5933580.0)	(32466.3,5933930.0)	0.528	3	1
110 ST NW	SBD	Collector-Residential	(32468.4,5933580.0)	(32466.3,5933930.0)	0.365	3	1
114 AV NW	EBD	Collector-Residential	(30398.2,5936860.0)	(30286.6,5936850.0)	0.137	3	1
114 AV NW	WBD	Collector-Residential	(30398.2,5936860.0)	(30286.6,5936850.0)	0.137	3	1
115 AV NW	EBD	Collector-Residential	(29504.9,5937020.0)	(29059.9,5937020.0)	0.203	3	1
115 AV NW	WBD	Collector-Residential	(29504.9,5937020.0)	(29059.9,5937020.0)	0.203	3	1
129 ST NW	NBD	Collector-Residential	(30188.6,5942060.0)	(30085.8,5942260.0)	0.289	3	1
129 ST NW	SBD	Collector-Residential	(30188.6,5942060.0)	(30085.8,5942260.0)	0.224	3	1
132 AV NW	WBD	Collector-Residential	(32667.3,5940040.0)	(32013.9,5940040.0)	0.379	3	1
134 AV NW	EBD	Collector-Residential	(32664.1,5940350.0)	(32007.0,5940350.0)	0.348	3	1
134 AV NW	WBD	Collector-Residential	(32664.1,5940350.0)	(32007.0,5940350.0)	0.382	3	1
134A AV NW	EBD	Collector-Residential	(33022.3,5940480.0)	(32828.0,5940360.0)	0.236	3	1
134A AV NW	WBD	Collector-Residential	(33022.3,5940480.0)	(32828.0,5940360.0)	0.203	3	1
134B AV NW	EBD	Collector-Residential	(31110.7,5940340.0)	(30779.2,5940500.0)	0.199	3	1

134B AV NW	WBD	Collector-Residential	(31110.7,5940340.0)	(30779.2,5940500.0)	0.199	3	1
135 AV NW	WBD	Collector-Residential	(34081.9,5940570.0)	(33640.1,5940560.0)	0.412	3	1
135 AV NW	EBD	Collector-Residential	(33399.9,5940560.0)	(33022.3,5940480.0)	0.243	3	1
135 AV NW	WBD	Collector-Residential	(33399.9,5940560.0)	(33022.3,5940480.0)	0.378	3	1
142 ST NW	NBD	Collector-Residential	(28806.5,5931400.0)	(28802.6,5931880.0)	0.285	3	1
142 ST NW	SBD	Collector-Residential	(28806.5,5931400.0)	(28802.6,5931880.0)	0.220	3	1
167 ST NW	NBD	Collector-Residential	(25818.2,5933270.0)	(25889.0,5934070.0)	0.361	3	1
167 ST NW	SBD	Collector-Residential	(25818.2,5933270.0)	(25889.0,5934070.0)	0.396	3	1
40 AV [EB-S] NW	EBD	Collector-Residential	(31812.3,5927080.0)	(31669.2,5927080.0)	0.217	3	1
40 AV [EB-S] NW	EBD	Collector-Residential	(31669.2,5927080.0)	(31465.6,5927100.0)	0.165	3	1
40 AV [WB-S] NW	WBD	Collector-Residential	(32786.3,5927000.0)	(32548.5,5927090.0)	0.242	3	1
40 AV [WB-S] NW	WBD	Collector-Residential	(31812.3,5927080.0)	(31669.2,5927080.0)	0.154	3	1
42 AV NW	EBD	Collector-Residential	(32910.8,5927430.0)	(32492.0,5927460.0)	0.423	3	1
42 AV NW	WBD	Collector-Residential	(32910.8,5927430.0)	(32492.0,5927460.0)	0.423	3	1
65 ST NW	NBD	Collector-Residential	(37725.7,5935030.0)	(37694.6,5935310.0)	0.201	3	1
65 ST NW	SBD	Collector-Residential	(37725.7,5935030.0)	(37694.6,5935310.0)	0.264	3	1
91 ST NW	NBD	Collector-Residential	(35321.8,5931810.0)	(35316.6,5932420.0)	0.645	3	1
91 ST NW	SBD	Collector-Residential	(35321.8,5931810.0)	(35316.6,5932420.0)	0.510	3	1
94 ST NW	NBD	Collector-Residential	(34032.4,5941340.0)	(34078.9,5941620.0)	0.383	3	1
94 ST NW	SBD	Collector-Residential	(34032.4,5941340.0)	(34078.9,5941620.0)	0.350	3	1
94 ST NW	NBD	Collector-Residential	(34082.2,5941630.0)	(34063.6,5942110.0)	0.403	3	1
94 ST NW	SBD	Collector-Residential	(34082.2,5941630.0)	(34063.6,5942110.0)	0.604	3	1
95 AV NW	EBD	Collector-Residential	(35969.6,5933350.0)	(35090.0,5933340.0)	0.375	3	1
95 AV NW	WBD	Collector-Residential	(35969.6,5933350.0)	(35090.0,5933340.0)	0.341	3	1
99 AV NW	EBD	Collector-Residential	(32466.3,5933930.0)	(32344.0,5933930.0)	0.197	3	1
99 AV NW	WBD	Collector-Residential	(32466.3,5933930.0)	(32344.0,5933930.0)	0.136	3	1
ALLAN DR SW	NBD	Collector-Residential	(26739.3,5921770.0)	(26201.5,5921640.0)	0.212	3	1
ALLAN DR SW	SBD	Collector-Residential	(26739.3,5921770.0)	(26201.5,5921640.0)	0.212	3	1
ALLAN DR SW	NBD	Collector-Residential	(26201.5,5921640.0)	(26281.0,5921260.0)	0.152	3	1
ALLAN DR SW	SBD	Collector-Residential	(26201.5,5921640.0)	(26281.0,5921260.0)	0.152	3	1

AUSTIN LINK SW	NBD	Collector-Residential	(26021.4,5921990.0)	(25978.4,5921710.0)	0.200	3	1
AUSTIN LINK SW	SBD	Collector-Residential	(26021.4,5921990.0)	(25978.4,5921710.0)	0.230	3	1
FULTON RD NW	EBD	Collector-Residential	(37937.4,5934860.0)	(38536.9,5935110.0)	0.260	3	1
FULTON RD NW	WBD	Collector-Residential	(37937.4,5934860.0)	(38536.9,5935110.0)	0.260	3	1
MCQUEEN RD NW	SBD	Collector-Residential	(28548.5,5935520.0)	(28398.5,5935970.0)	0.259	3	1
MCQUEEN RD NW	NBD	Collector-Residential	(28398.5,5935970.0)	(28771.7,5936020.0)	0.312	3	1
MCQUEEN RD NW	SBD	Collector-Residential	(28398.5,5935970.0)	(28771.7,5936020.0)	0.312	3	1
RUTHERFORD RD SW	NBD	Collector-Residential	(31568.1,5920310.0)	(31823.8,5920990.0)	0.396	3	1
RUTHERFORD RD SW	SBD	Collector-Residential	(31568.1,5920310.0)	(31823.8,5920990.0)	0.396	3	1
111 ST [SB-S] SW	SBD	Arterial-Class C (Truck Route Low speeds)	(32111.1,5921930.0)	(32126.4,5921470.0)	1.428	2	1
112 AV NW	WBD	Arterial-Class C (Truck Route Low speeds)	(36519.8,5936760.0)	(35611.3,5936620.0)	1.159	2	1
127 ST NW	NBD	Arterial-Class C (Truck Route Low speeds)	(30378.5,5940030.0)	(30374.8,5940500.0)	1.969	2	1
82 AV [EB-S] NW	EBD	Arterial-Class C (Truck Route Low speeds)	(34708.7,5931810.0)	(34082.0,5931810.0)	2.727	2	1
FORT RD [SB-S] NW	SBD	Arterial-Class C (Truck Route Low speeds)	(36746.3,5939180.0)	(36864.5,5939280.0)	0.997	2	1
142 ST NW	NBD	Arterial-Class D (Non-Truck Route Low speeds)	(28783.8,5934660.0)	(28773.0,5935390.0)	0.493	2	1
149 ST NW	SBD	Arterial-Class D (Non-Truck Route Low speeds)	(27981.4,5933260.0)	(27975.6,5933950.0)	1.708	2	1
101 AV NW	WBD	Collector-Residential	(36504.5,5934400.0)	(36004.8,5934400.0)	0.254	2	1
106 ST [NB-S] NW	NBD	Collector-Residential	(32922.7,5926580.0)	(32916.0,5926840.0)	0.343	2	1
106 ST [SB-S] NW	SBD	Collector-Residential	(32922.7,5926580.0)	(32916.0,5926840.0)	0.544	2	1
109 ST NW	NBD	Collector-Residential	(32391.0,5929130.0)	(32387.8,5929500.0)	0.293	2	1
109 ST NW	SBD	Collector-Residential	(32391.0,5929130.0)	(32387.8,5929500.0)	0.293	2	1
11A AV NW	EBD	Collector-Residential	(38334.8,5923290.0)	(37744.4,5923230.0)	0.397	2	1
11A AV NW	WBD	Collector-Residential	(38334.8,5923290.0)	(37744.4,5923230.0)	0.520	2	1
12 AV NW	EBD	Collector-Residential	(39849.6,5923260.0)	(39076.2,5923310.0)	0.770	2	1
12 AV NW	WBD	Collector-Residential	(39849.6,5923260.0)	(39076.2,5923310.0)	0.393	2	1
127 ST NW	NBD	Collector-Residential	(30398.2,5936860.0)	(30393.9,5937600.0)	0.832	2	1
129 AV NW	WBD	Collector-Residential	(33290.4,5939510.0)	(32831.4,5939520.0)	0.306	2	1
129 AV NW	EBD	Collector-Residential	(32831.4,5939520.0)	(32011.1,5939510.0)	0.361	2	1
135 AV NW	WBD	Collector-Residential	(34397.3,5940450.0)	(34081.9,5940570.0)	0.309	2	1
139 AV NW	EBD	Collector-Residential	(40636.1,5941280.0)	(39960.6,5941290.0)	0.815	2	1

139 AV NW	WBD	Collector-Residential	(40636.1,5941280.0)	(39960.6,5941290.0)	0.692	2	1
139 ST NW	NBD	Collector-Residential	(28926.0,5942810.0)	(29057.6,5943270.0)	0.424	2	1
144 AV [EB-S] NW	EBD	Collector-Residential	(36128.9,5941670.0)	(35817.6,5941710.0)	0.442	2	1
144 AV [WB-S] NW	WBD	Collector-Residential	(36617.8,5941500.0)	(36412.1,5941570.0)	0.266	2	1
144 AV [WB-S] NW	WBD	Collector-Residential	(37771.6,5941720.0)	(37560.5,5941620.0)	0.404	2	1
160 AV NW	WBD	Collector-Residential	(29585.1,5943260.0)	(29057.6,5943270.0)	0.314	2	1
162 AV NW	EBD	Collector-Residential	(38242.6,5943590.0)	(37663.6,5943550.0)	0.242	2	1
162 AV NW	EBD	Collector-Residential	(31531.3,5943480.0)	(30924.4,5943400.0)	0.624	2	1
162 AV NW	WBD	Collector-Residential	(31531.3,5943480.0)	(30924.4,5943400.0)	0.853	2	1
165 ST NW	NBD	Collector-Residential	(26039.6,5932970.0)	(26040.0,5933260.0)	0.413	2	1
172 ST NW	NBD	Collector-Residential	(25148.8,5929450.0)	(25184.5,5929790.0)	0.368	2	1
175 ST NW	NBD	Collector-Residential	(24934.6,5931320.0)	(24955.4,5932000.0)	0.832	2	1
21 ST NW	NBD	Collector-Residential	(41445.4,5942030.0)	(41548.9,5942120.0)	0.265	2	1
31 AV NW	EBD	Collector-Residential	(31509.5,5925760.0)	(31105.6,5925690.0)	0.412	2	1
31 AV NW	WBD	Collector-Residential	(31509.5,5925760.0)	(31105.6,5925690.0)	0.452	2	1
37 ST NW	NBD	Collector-Residential	(39956.4,5925020.0)	(39918.2,5925790.0)	0.672	2	1
37 ST NW	SBD	Collector-Residential	(39956.4,5925020.0)	(39918.2,5925790.0)	0.799	2	1
40 AV [EB-S] NW	EBD	Collector-Residential	(30864.4,5927140.0)	(30647.6,5927130.0)	0.267	2	1
44 ST NW	SBD	Collector-Residential	(39332.8,5927240.0)	(39068.7,5927820.0)	0.409	2	1
51 AV NW	WBD	Collector-Residential	(30383.2,5928470.0)	(30123.3,5928450.0)	0.219	2	1
53 AV [WB-S] NW	WBD	Collector-Residential	(28298.6,5928700.0)	(28044.7,5928680.0)	0.312	2	1
57 AV NW	EBD	Collector-Residential	(24285.6,5928950.0)	(23873.4,5928810.0)	0.312	2	1
57 AV NW	WBD	Collector-Residential	(24285.6,5928950.0)	(23873.4,5928810.0)	0.331	2	1
59A ST NW	NBD	Collector-Residential	(37577.3,5942940.0)	(37663.6,5943550.0)	0.246	2	1
59A ST NW	SBD	Collector-Residential	(37577.3,5942940.0)	(37663.6,5943550.0)	0.246	2	1
63 AV NW	WBD	Collector-Residential	(30439.7,5929810.0)	(29829.1,5929650.0)	0.278	2	1
64 AV NW	EBD	Collector-Residential	(25184.5,5929790.0)	(24538.0,5929670.0)	0.472	2	1
72 ST NW	NBD	Collector-Residential	(36333.3,5941600.0)	(36460.1,5942070.0)	0.772	2	1
72 ST NW	SBD	Collector-Residential	(36460.1,5942070.0)	(36457.0,5942210.0)	0.210	2	1
76 AV NW	WBD	Collector-Residential	(32368.0,5931150.0)	(31454.2,5931140.0)	0.718	2	1

ABBOTTSFIELD RD NW	EBD	Collector-Residential	(40507.6,5937910.0)	(40159.0,5938200.0)	0.695	2	1
BELLAMY HILL NW	NBD	Arterial-Class D (Non-Truck Route Low speeds)	(33229.2,5933570.0)	(33561.1,5934200.0)	2.017	2	1
BELLAMY HILL NW	SBD	Arterial-Class D (Non-Truck Route Low speeds)	(33229.2,5933570.0)	(33561.1,5934200.0)	2.017	2	1
BRINTNELL BLVD NW	NBD	Collector-Residential	(39161.5,5943050.0)	(39496.8,5943490.0)	0.249	2	1
BRINTNELL BLVD NW	SBD	Collector-Residential	(39161.5,5943050.0)	(39496.8,5943490.0)	0.249	2	1
BULYEA RD NW	NBD	Collector-Residential	(28363.1,5926250.0)	(28461.2,5926940.0)	0.298	2	1
HEMINGWAY RD NW	NBD	Collector-Residential	(21364.1,5928420.0)	(21076.0,5928880.0)	0.312	2	1
HEMINGWAY RD NW	SBD	Collector-Residential	(21076.0,5928880.0)	(21010.7,5929460.0)	0.423	2	1
MILL WOODS RD E NW	NBD	Collector-Residential	(39260.9,5926160.0)	(39163.9,5926460.0)	0.277	2	1
MILL WOODS RD E NW	SBD	Collector-Residential	(39260.9,5926160.0)	(39163.9,5926460.0)	0.268	2	1
MILL WOODS RD NW	NBD	Collector-Residential	(36658.2,5925230.0)	(36650.4,5925360.0)	0.435	2	1
MILL WOODS RD NW	SBD	Collector-Residential	(36650.4,5925360.0)	(36538.9,5925600.0)	0.250	2	1
SADDLEBACK RD NW	NBD	Collector-Residential	(31408.3,5924960.0)	(31515.7,5924680.0)	0.422	2	1
SADDLEBACK RD NW	SBD	Collector-Residential	(31218.4,5925280.0)	(31408.3,5924960.0)	0.278	2	1
101 ST [SB-S] NW	SBD	Arterial-Class C (Truck Route Low speeds)	(33547.8,5936230.0)	(33545.3,5936350.0)	0.413	2	1
101 ST NW	NBD	Arterial-Class C (Truck Route Low speeds)	(33556.3,5934930.0)	(33555.9,5935100.0)	0.446	2	1
101 ST NW	SBD	Arterial-Class C (Truck Route Low speeds)	(33556.3,5934930.0)	(33555.9,5935100.0)	0.630	2	1
101 ST NW	NBD	Arterial-Class C (Truck Route Low speeds)	(33552.4,5935510.0)	(33550.1,5935870.0)	0.779	2	1
101 ST NW	SBD	Arterial-Class C (Truck Route Low speeds)	(33552.4,5935510.0)	(33550.1,5935870.0)	0.779	2	1
103A AV [EB-S] NW	EBD	Arterial-Class C (Truck Route Low speeds)	(33680.6,5934920.0)	(33556.3,5934930.0)	0.130	2	1
103A AV [EB-S] NW	EBD	Arterial-Class C (Truck Route Low speeds)	(33836.6,5934950.0)	(33722.2,5934930.0)	0.157	2	1
103A AV [WB-S] NW	WBD	Arterial-Class C (Truck Route Low speeds)	(33984.3,5934990.0)	(33836.6,5934950.0)	0.196	2	1
103A AV [WB-S] NW	WBD	Arterial-Class C (Truck Route Low speeds)	(33836.6,5934950.0)	(33722.2,5934930.0)	0.158	2	1
103A AV NW	EBD	Arterial-Class C (Truck Route Low speeds)	(34214.9,5935060.0)	(33984.3,5934990.0)	0.410	2	1
103A AV NW	WBD	Arterial-Class C (Truck Route Low speeds)	(34214.9,5935060.0)	(33984.3,5934990.0)	0.379	2	1
103A AV NW	EBD	Arterial-Class C (Truck Route Low speeds)	(34447.9,5935130.0)	(34214.9,5935060.0)	0.271	2	1
103A AV NW	WBD	Arterial-Class C (Truck Route Low speeds)	(34447.9,5935130.0)	(34214.9,5935060.0)	0.271	2	1
104 AV NW	EBD	Arterial-Class C (Truck Route Low speeds)	(33434.6,5934930.0)	(33191.3,5934930.0)	0.291	2	1
Total							**142**

Table A- 2 Selected Sites by Equally Considering two factors (w=0.5)

Road Name	Direction	Road Type	Start Point	End Point	Δ_{EPDO}	Cvg	#DFS
109 ST [SB-S] NW	SBD	Arterial-Class C (Truck Route Low speeds)	(32583.0,5933660.0)	(32581.6,5933930.0)	3.625	2	1
149 ST [SB-S] NW	SBD	Arterial-Class D (Non-Truck Route Low speeds)	(27920.5,5931100.0)	(27985.3,5931910.0)	5.292	1	1
STONY PLAIN RD [WB-S] NW	WBD	Arterial-Class C (Truck Route Low speeds)	(25396.1,5934340.0)	(25003.0,5934350.0)	5.187	1	1
109 ST [SB-S] NW	SBD	Arterial-Class C (Truck Route Low speeds)	(32581.6,5933930.0)	(32580.3,5934100.0)	2.811	2	1
82 AV [EB-S] NW	EBD	Arterial-Class C (Truck Route Low speeds)	(34708.7,5931810.0)	(34082.0,5931810.0)	2.727	2	1
102 AV NW	EBD	Collector-Residential	(31731.3,5934570.0)	(31099.2,5934560.0)	0.977	3	1
87 AV NW	EBD	Arterial-Class D (Non-Truck Route Low speeds)	(32359.4,5932330.0)	(31977.5,5932330.0)	0.867	3	1
87 AV NW	WBD	Arterial-Class D (Non-Truck Route Low speeds)	(32359.4,5932330.0)	(31977.5,5932330.0)	0.801	3	1
135 AV NW	EBD	Collector-Residential	(34081.9,5940570.0)	(33640.1,5940560.0)	0.665	3	1
91 ST NW	NBD	Collector-Residential	(35321.8,5931810.0)	(35316.6,5932420.0)	0.645	3	1
102 AV NW	WBD	Collector-Residential	(31731.3,5934570.0)	(31099.2,5934560.0)	0.608	3	1
94 ST NW	SBD	Collector-Residential	(34082.2,5941630.0)	(34063.6,5942110.0)	0.604	3	1
132 AV NW	EBD	Collector-Residential	(32667.3,5940040.0)	(32013.9,5940040.0)	0.571	3	1
82 AV [EB-S] NW	EBD	Arterial-Class D (Non-Truck Route Low speeds)	(32363.2,5931800.0)	(31786.0,5931780.0)	2.268	2	1
110 ST NW	NBD	Collector-Residential	(32468.4,5933580.0)	(32466.3,5933930.0)	0.528	3	1
91 ST NW	SBD	Collector-Residential	(35321.8,5931810.0)	(35316.6,5932420.0)	0.510	3	1
144 AV [EB-S] NW	EBD	Collector-Residential	(34632.2,5941580.0)	(34255.5,5941580.0)	0.499	3	1
109 ST [SB-S] NW	SBD	Arterial-Class C (Truck Route Low speeds)	(32580.3,5934110.0)	(32584.7,5934340.0)	2.197	2	1
42 AV NW	EBD	Collector-Residential	(32910.8,5927430.0)	(32492.0,5927460.0)	0.423	3	1
42 AV NW	WBD	Collector-Residential	(32910.8,5927430.0)	(32492.0,5927460.0)	0.423	3	1
135 AV NW	WBD	Collector-Residential	(34081.9,5940570.0)	(33640.1,5940560.0)	0.412	3	1
94 ST NW	NBD	Collector-Residential	(34082.2,5941630.0)	(34063.6,5942110.0)	0.403	3	1
167 ST NW	SBD	Collector-Residential	(25818.2,5933270.0)	(25889.0,5934070.0)	0.396	3	1
RUTHERFORD RD SW	NBD	Collector-Residential	(31568.1,5920310.0)	(31823.8,5920990.0)	0.396	3	1
RUTHERFORD RD SW	SBD	Collector-Residential	(31568.1,5920310.0)	(31823.8,5920990.0)	0.396	3	1
94 ST NW	NBD	Collector-Residential	(34032.4,5941340.0)	(34078.9,5941620.0)	0.383	3	1
134 AV NW	WBD	Collector-Residential	(32664.1,5940350.0)	(32007.0,5940350.0)	0.382	3	1

132 AV NW	WBD	Collector-Residential	(32667.3,5940040.0)	(32013.9,5940040.0)	0.379	3	1
135 AV NW	WBD	Collector-Residential	(33399.9,5940560.0)	(33022.3,5940480.0)	0.378	3	1
95 AV NW	EBD	Collector-Residential	(35969.6,5933350.0)	(35090.0,5933340.0)	0.375	3	1
110 ST NW	SBD	Collector-Residential	(32468.4,5933580.0)	(32466.3,5933930.0)	0.365	3	1
167 ST NW	NBD	Collector-Residential	(25818.2,5933270.0)	(25889.0,5934070.0)	0.361	3	1
94 ST NW	SBD	Collector-Residential	(34032.4,5941340.0)	(34078.9,5941620.0)	0.350	3	1
134 AV NW	EBD	Collector-Residential	(32664.1,5940350.0)	(32007.0,5940350.0)	0.348	3	1
95 AV NW	WBD	Collector-Residential	(35969.6,5933350.0)	(35090.0,5933340.0)	0.341	3	1
106 ST [SB-S] NW	SBD	Collector-Residential	(32916.0,5926840.0)	(32786.3,5927000.0)	0.338	3	1
82 AV [WB-S] NW	WBD	Arterial-Class D (Non-Truck Route Low speeds)	(32363.2,5931800.0)	(31785.9,5931800.0)	2.065	2	1
MCQUEEN RD NW	NBD	Collector-Residential	(28398.5,5935970.0)	(28771.7,5936020.0)	0.312	3	1
MCQUEEN RD NW	SBD	Collector-Residential	(28398.5,5935970.0)	(28771.7,5936020.0)	0.312	3	1
106 ST [NB-S] NW	NBD	Collector-Residential	(32916.0,5926840.0)	(32786.3,5927000.0)	0.308	3	1
MCQUEEN RD NW	NBD	Collector-Residential	(28548.5,5935520.0)	(28398.5,5935970.0)	0.301	3	1
129 ST NW	NBD	Collector-Residential	(30188.6,5942060.0)	(30085.8,5942260.0)	0.289	3	1
BELLAMY HILL NW	NBD	Arterial-Class D (Non-Truck Route Low speeds)	(33229.2,5933570.0)	(33561.1,5934200.0)	2.017	2	1
BELLAMY HILL NW	SBD	Arterial-Class D (Non-Truck Route Low speeds)	(33229.2,5933570.0)	(33561.1,5934200.0)	2.017	2	1
142 ST NW	NBD	Collector-Residential	(28806.5,5931400.0)	(28802.6,5931880.0)	0.285	3	1
65 ST NW	SBD	Collector-Residential	(37725.7,5935030.0)	(37694.6,5935310.0)	0.264	3	1
FULTON RD NW	EBD	Collector-Residential	(37937.4,5934860.0)	(38536.9,5935110.0)	0.260	3	1
FULTON RD NW	WBD	Collector-Residential	(37937.4,5934860.0)	(38536.9,5935110.0)	0.260	3	1
MCQUEEN RD NW	SBD	Collector-Residential	(28548.5,5935520.0)	(28398.5,5935970.0)	0.259	3	1
135 AV NW	EBD	Collector-Residential	(33399.9,5940560.0)	(33022.3,5940480.0)	0.243	3	1
40 AV [WB-S] NW	WBD	Collector-Residential	(32786.3,5927000.0)	(32548.5,5927090.0)	0.242	3	1
127 ST NW	NBD	Arterial-Class C (Truck Route Low speeds)	(30378.5,5940030.0)	(30374.8,5940500.0)	1.969	2	1
134A AV NW	EBD	Collector-Residential	(33022.3,5940480.0)	(32828.0,5940360.0)	0.236	3	1
AUSTIN LINK SW	SBD	Collector-Residential	(26021.4,5921990.0)	(25978.4,5921710.0)	0.230	3	1
129 ST NW	SBD	Collector-Residential	(30188.6,5942060.0)	(30085.8,5942260.0)	0.224	3	1
142 ST NW	SBD	Collector-Residential	(28806.5,5931400.0)	(28802.6,5931880.0)	0.220	3	1
40 AV [EB-S] NW	EBD	Collector-Residential	(31812.3,5927080.0)	(31669.2,5927080.0)	0.217	3	1

ALLAN DR SW	NBD	Collector-Residential	(26739.3,5921770.0)	(26201.5,5921640.0)	0.212	3	1
ALLAN DR SW	SBD	Collector-Residential	(26739.3,5921770.0)	(26201.5,5921640.0)	0.212	3	1
134A AV NW	WBD	Collector-Residential	(33022.3,5940480.0)	(32828.0,5940360.0)	0.203	3	1
115 AV NW	EBD	Collector-Residential	(29504.9,5937020.0)	(29059.9,5937020.0)	0.203	3	1
115 AV NW	WBD	Collector-Residential	(29504.9,5937020.0)	(29059.9,5937020.0)	0.203	3	1
65 ST NW	NBD	Collector-Residential	(37725.7,5935030.0)	(37694.6,5935310.0)	0.201	3	1
AUSTIN LINK SW	NBD	Collector-Residential	(26021.4,5921990.0)	(25978.4,5921710.0)	0.200	3	1
134B AV NW	EBD	Collector-Residential	(31110.7,5940340.0)	(30779.2,5940500.0)	0.199	3	1
134B AV NW	WBD	Collector-Residential	(31110.7,5940340.0)	(30779.2,5940500.0)	0.199	3	1
99 AV NW	EBD	Collector-Residential	(32466.3,5933930.0)	(32344.0,5933930.0)	0.197	3	1
109 ST [NB-S] NW	NBD	Arterial-Class C (Truck Route Low speeds)	(32577.1,5935510.0)	(32576.7,5936330.0)	3.643	1	1
109 ST [SB-S] NW	SBD	Arterial-Class C (Truck Route Low speeds)	(32584.7,5934340.0)	(32584.0,5934570.0)	1.908	2	1
40 AV [EB-S] NW	EBD	Collector-Residential	(31669.2,5927080.0)	(31465.6,5927100.0)	0.165	3	1
40 AV [WB-S] NW	WBD	Collector-Residential	(31812.3,5927080.0)	(31669.2,5927080.0)	0.154	3	1
ALLAN DR SW	NBD	Collector-Residential	(26201.5,5921640.0)	(26281.0,5921260.0)	0.152	3	1
ALLAN DR SW	SBD	Collector-Residential	(26201.5,5921640.0)	(26281.0,5921260.0)	0.152	3	1
114 AV NW	EBD	Collector-Residential	(30398.2,5936860.0)	(30286.6,5936850.0)	0.137	3	1
114 AV NW	WBD	Collector-Residential	(30398.2,5936860.0)	(30286.6,5936850.0)	0.137	3	1
99 AV NW	WBD	Collector-Residential	(32466.3,5933930.0)	(32344.0,5933930.0)	0.136	3	1
170 ST [SB-S] NW	SBD	Arterial-Class C (Truck Route Low speeds)	(25502.7,5933310.0)	(25509.6,5933710.0)	5.191	0	1
109 ST NW	NBD	Arterial-Class C (Truck Route Low speeds)	(32368.0,5931150.0)	(32363.2,5931800.0)	1.730	2	1
149 ST NW	SBD	Arterial-Class D (Non-Truck Route Low speeds)	(27981.4,5933260.0)	(27975.6,5933950.0)	1.708	2	1
109 ST [SB-S] NW	SBD	Arterial-Class C (Truck Route Low speeds)	(32577.1,5935510.0)	(32565.3,5936330.0)	3.435	1	1
82 AV [WB-S] NW	WBD	Arterial-Class C (Truck Route Low speeds)	(34708.7,5931810.0)	(34082.0,5931810.0)	1.673	2	1
109 ST NW	SBD	Arterial-Class C (Truck Route Low speeds)	(32368.0,5931150.0)	(32363.2,5931800.0)	1.662	2	1
STONY PLAIN RD NW	EBD	Arterial-Class D (Non-Truck Route Low speeds)	(27739.3,5934350.0)	(27156.4,5934350.0)	1.553	2	1
107 AV NW	EBD	Arterial-Class C (Truck Route Low speeds)	(31600.0,5935500.0)	(30758.4,5935440.0)	3.279	1	1
STONY PLAIN RD NW	WBD	Arterial-Class D (Non-Truck Route Low speeds)	(27739.3,5934350.0)	(27156.4,5934350.0)	1.519	2	1
118 AV NW	EBD	Arterial-Class C (Truck Route Low speeds)	(35286.7,5937640.0)	(34463.9,5937630.0)	1.457	2	1
118 AV NW	WBD	Arterial-Class C (Truck Route Low speeds)	(35286.7,5937640.0)	(34463.9,5937630.0)	1.457	2	1

109 ST NW	NBD	Arterial-Class C (Truck Route Low speeds)	(32363.2,5931800.0)	(32362.1,5931940.0)	1.441	2	1
127 ST NW	SBD	Arterial-Class C (Truck Route Low speeds)	(30379.9,5939520.0)	(30378.5,5940030.0)	1.437	2	1
111 ST [SB-S] SW	SBD	Arterial-Class C (Truck Route Low speeds)	(32111.1,5921930.0)	(32126.4,5921470.0)	1.428	2	1
107 AV NW	WBD	Arterial-Class C (Truck Route Low speeds)	(32577.1,5935510.0)	(31723.7,5935500.0)	3.100	1	1
75 ST [SB-S] NW	SBD	Arterial-Class C (Truck Route Low speeds)	(36943.1,5931860.0)	(36947.3,5932170.0)	1.344	2	1
109 ST NW	SBD	Arterial-Class C (Truck Route Low speeds)	(32363.2,5931800.0)	(32362.1,5931940.0)	1.281	2	1
118 AV NW	EBD	Arterial-Class C (Truck Route Low speeds)	(34463.9,5937630.0)	(33967.2,5937630.0)	1.271	2	1
118 AV NW	WBD	Arterial-Class C (Truck Route Low speeds)	(34463.9,5937630.0)	(33967.2,5937630.0)	1.271	2	1
109 ST [SB-S] NW	SBD	Arterial-Class C (Truck Route Low speeds)	(32362.1,5931940.0)	(32359.9,5932230.0)	1.213	2	1
JASPER AV NW	EBD	Arterial-Class D (Non-Truck Route Low speeds)	(31488.2,5934330.0)	(31100.5,5934330.0)	1.210	2	1
137 AV [EB-S] NW	EBD	Arterial-Class C (Truck Route Low speeds)	(33571.3,5940860.0)	(32814.4,5940850.0)	1.180	2	1
82 AV NW	WBD	Arterial-Class C (Truck Route Low speeds)	(33500.4,5931800.0)	(33319.9,5931800.0)	1.161	2	1
112 AV NW	WBD	Arterial-Class C (Truck Route Low speeds)	(36519.8,5936760.0)	(35611.3,5936620.0)	1.159	2	1
75 ST [NB-S] NW	NBD	Arterial-Class C (Truck Route Low speeds)	(36955.1,5931830.0)	(36947.3,5932170.0)	1.151	2	1
95 ST NW	SBD	Arterial-Class D (Non-Truck Route Low speeds)	(34221.8,5935790.0)	(34000.5,5936450.0)	1.150	2	1
82 AV [EB-S] NW	EBD	Arterial-Class C (Truck Route Low speeds)	(33910.8,5931800.0)	(33739.6,5931800.0)	1.148	2	1
127 ST NW	SBD	Arterial-Class C (Truck Route Low speeds)	(30378.5,5940030.0)	(30374.8,5940500.0)	1.102	2	1
97 ST NW	SBD	Arterial-Class C (Truck Route Low speeds)	(33883.2,5935390.0)	(33818.2,5935640.0)	1.100	2	1
GATEWAY BLVD NW	NBD	Arterial-Class D (Non-Truck Route Low speeds)	(33488.4,5931910.0)	(33425.7,5932430.0)	1.100	2	1
GATEWAY BLVD NW	SBD	Arterial-Class D (Non-Truck Route Low speeds)	(33488.4,5931910.0)	(33425.7,5932430.0)	1.100	2	1
149 ST NW	NBD	Arterial-Class D (Non-Truck Route Low speeds)	(27981.4,5933260.0)	(27975.6,5933950.0)	1.086	2	1
95 ST NW	NBD	Arterial-Class D (Non-Truck Route Low speeds)	(34221.8,5935790.0)	(34000.5,5936450.0)	1.084	2	1
66 ST [SB-S] NW	SBD	Arterial-Class D (Non-Truck Route Low speeds)	(37541.6,5924710.0)	(37551.3,5924960.0)	1.083	2	1
132 AV NW	EBD	Collector-Residential	(33635.0,5940040.0)	(32840.8,5940040.0)	1.072	2	1
87 AV [EB-S] NW	EBD	Arterial-Class D (Non-Truck Route Low speeds)	(27172.0,5931910.0)	(26778.9,5931910.0)	1.066	2	1
101 ST NW	SBD	Arterial-Class D (Non-Truck Route Low speeds)	(33560.0,5934350.0)	(33559.2,5934480.0)	1.054	2	1
111 ST [NB-S] SW	NBD	Arterial-Class C (Truck Route Low speeds)	(32137.3,5921930.0)	(32145.8,5921420.0)	1.040	2	1
66 ST [NB-S] NW	NBD	Arterial-Class D (Non-Truck Route Low speeds)	(37583.4,5925190.0)	(37559.5,5925610.0)	1.018	2	1
127 ST NW	SBD	Arterial-Class C (Truck Route Low speeds)	(30374.8,5940500.0)	(30373.7,5940700.0)	1.003	2	1
127 ST NW	NBD	Arterial-Class C (Truck Route Low speeds)	(30379.9,5939520.0)	(30378.5,5940030.0)	1.000	2	1

FORT RD [SB-S] NW	SBD	Arterial-Class C (Truck Route Low speeds)	(36746.3,5939180.0)	(36864.5,5939280.0)	0.997	2	1
82 AV NW	EBD	Arterial-Class C (Truck Route Low speeds)	(32542.3,5931800.0)	(32363.2,5931800.0)	0.990	2	1
100 AV NW	EBD	Arterial-Class C (Truck Route Low speeds)	(25048.6,5934050.0)	(24695.5,5933960.0)	2.717	1	1
STONY PLAIN RD NW	EBD	Arterial-Class D (Non-Truck Route Low speeds)	(31097.5,5934920.0)	(30760.1,5934990.0)	0.976	2	1
127 ST NW	NBD	Arterial-Class C (Truck Route Low speeds)	(30374.8,5940500.0)	(30373.7,5940700.0)	0.971	2	1
101 ST NW	NBD	Arterial-Class D (Non-Truck Route Low speeds)	(33560.0,5934350.0)	(33559.2,5934480.0)	0.963	2	1
82 AV NW	EBD	Arterial-Class C (Truck Route Low speeds)	(34082.0,5931810.0)	(33910.8,5931800.0)	0.961	2	1
JAMES MOWATT TR [NB-S] SW	NBD	Arterial-Class C (Truck Route Low speeds)	(32149.5,5921350.0)	(32156.4,5920990.0)	0.959	2	1
100 AV NW	EBD	Arterial-Class D (Non-Truck Route Low speeds)	(26337.6,5934120.0)	(25897.7,5934120.0)	0.954	2	1
82 AV [WB-S] NW	WBD	Arterial-Class C (Truck Route Low speeds)	(36130.5,5931820.0)	(35926.4,5931820.0)	0.940	2	1
28 AV NW	WBD	Collector-Residential	(37821.2,5925200.0)	(37623.7,5925190.0)	0.928	2	1
111 AV NW	WBD	Arterial-Class C (Truck Route Low speeds)	(30401.1,5936330.0)	(29844.3,5936320.0)	0.911	2	1
132 AV NW	WBD	Collector-Residential	(33635.0,5940040.0)	(32840.8,5940040.0)	0.900	2	1
28 AV NW	WBD	Arterial-Class D (Non-Truck Route Low speeds)	(37561.3,5925190.0)	(36689.2,5925190.0)	0.891	2	1
105 ST NW	NBD	Arterial-Class D (Non-Truck Route Low speeds)	(33073.3,5934350.0)	(33071.6,5934580.0)	0.889	2	1
111 AV NW	EBD	Arterial-Class C (Truck Route Low speeds)	(30401.1,5936330.0)	(29844.3,5936320.0)	0.878	2	1
111 AV NW	WBD	Arterial-Class C (Truck Route Low speeds)	(34477.3,5936600.0)	(33990.3,5936480.0)	0.874	2	1
137 AV [WB-S] NW	WBD	Arterial-Class C (Truck Route Low speeds)	(33617.9,5940880.0)	(32819.5,5940870.0)	0.874	2	1
87 AV [WB-S] NW	WBD	Arterial-Class D (Non-Truck Route Low speeds)	(27167.9,5931920.0)	(26755.7,5931920.0)	0.871	2	1
100 ST [NB-S] NW	NBD	Arterial-Class D (Non-Truck Route Low speeds)	(33787.3,5934370.0)	(33772.6,5934500.0)	0.867	2	1
162 AV NW	WBD	Collector-Residential	(31531.3,5943480.0)	(30924.4,5943400.0)	0.853	2	1
82 AV NW	EBD	Arterial-Class C (Truck Route Low speeds)	(33500.4,5931800.0)	(33319.9,5931800.0)	0.832	2	1
127 ST NW	NBD	Collector-Residential	(30398.2,5936860.0)	(30393.9,5937600.0)	0.832	2	1
175 ST NW	NBD	Collector-Residential	(24934.6,5931320.0)	(24955.4,5932000.0)	0.832	2	1
175 ST NW	SBD	Collector-Residential	(24934.6,5931320.0)	(24955.4,5932000.0)	0.832	2	1
Total							**142**

Table A-3 Selected Sites by Considering Collision Reduction Only(w=1)

Road Name	Direction	Road Type	Start Point	End Point	Δ_{EPDO}	Cvg	#DFS
149 ST [SB-S] NW	SBD	Arterial-Class D (Non-Truck Route Low speeds)	(27920.5,5931100.0)	(27985.3,5931910.0)	5.292	1	1
170 ST [SB-S] NW	SBD	Arterial-Class C (Truck Route Low speeds)	(25502.7,5933310.0)	(25509.6,5933710.0)	5.191	0	1
STONY PLAIN RD [WB-S] NW	WBD	Arterial-Class C (Truck Route Low speeds)	(25396.1,5934340.0)	(25003.0,5934350.0)	5.187	1	1
CONNORS RD [NB-S] NW	NBD	Arterial-Class C (Truck Route Low speeds)	(34149.4,5933950.0)	(33983.7,5934200.0)	4.221	0	1
109 ST [NB-S] NW	NBD	Arterial-Class C (Truck Route Low speeds)	(32577.1,5935510.0)	(32576.7,5936330.0)	3.643	1	1
109 ST [SB-S] NW	SBD	Arterial-Class C (Truck Route Low speeds)	(32583.0,5933660.0)	(32581.6,5933930.0)	3.625	2	1
109 ST [SB-S] NW	SBD	Arterial-Class C (Truck Route Low speeds)	(32577.1,5935510.0)	(32565.3,5936330.0)	3.435	1	1
107 AV NW	EBD	Arterial-Class C (Truck Route Low speeds)	(31600.0,5935500.0)	(30758.4,5935440.0)	3.279	1	1
107 AV NW	WBD	Arterial-Class C (Truck Route Low speeds)	(32577.1,5935510.0)	(31723.7,5935500.0)	3.100	1	1
109 ST [SB-S] NW	SBD	Arterial-Class C (Truck Route Low speeds)	(32581.6,5933930.0)	(32580.3,5934100.0)	2.811	2	1
82 AV [EB-S] NW	EBD	Arterial-Class C (Truck Route Low speeds)	(34708.7,5931810.0)	(34082.0,5931810.0)	2.727	2	1
100 AV NW	EBD	Arterial-Class C (Truck Route Low speeds)	(25048.6,5934050.0)	(24695.5,5933960.0)	2.717	1	1
105 ST NW	NBD	Arterial-Class C (Truck Route Low speeds)	(33004.0,5932820.0)	(33080.9,5933180.0)	2.665	0	1
QUEEN ELIZABETH PARK RD NW	NBD	Arterial-Class D (Non-Truck Route Low speeds)	(33579.8,5932500.0)	(32982.1,5932750.0)	2.556	0	1
QUEEN ELIZABETH PARK RD NW	SBD	Arterial-Class D (Non-Truck Route Low speeds)	(33579.8,5932500.0)	(32982.1,5932750.0)	2.556	0	1
107 AV NW	EBD	Arterial-Class C (Truck Route Low speeds)	(32577.1,5935510.0)	(31723.7,5935500.0)	2.459	1	1
34 AV [EB-S] NW	EBD	Arterial-Class C (Truck Route Low speeds)	(34557.4,5926150.0)	(34133.4,5926190.0)	2.448	0	1
127 ST [SB-S] NW	SBD	Arterial-Class C (Truck Route Low speeds)	(30365.1,5940900.0)	(30366.8,5941140.0)	2.413	1	1
111 ST [SB-S] NW	SBD	Arterial-Class C (Truck Route Low speeds)	(32108.7,5924700.0)	(32105.7,5924940.0)	2.325	1	1
104 ST NW	SBD	Arterial-Class C (Truck Route Low speeds)	(33349.7,5929020.0)	(33331.5,5929560.0)	2.277	1	1
82 AV [EB-S] NW	EBD	Arterial-Class D (Non-Truck Route Low speeds)	(32363.2,5931800.0)	(31786.0,5931780.0)	2.268	2	1
107 AV NW	EBD	Arterial-Class C (Truck Route Low speeds)	(33057.1,5935510.0)	(32577.1,5935510.0)	2.251	1	1
82 AV NW	WBD	Arterial-Class C (Truck Route Low speeds)	(33131.4,5931800.0)	(32743.5,5931800.0)	2.199	1	1
109 ST [SB-S] NW	SBD	Arterial-Class C (Truck Route Low speeds)	(32580.3,5934110.0)	(32584.7,5934340.0)	2.197	2	1
87 AV [EB-S] NW	EBD	Arterial-Class D (Non-Truck Route Low speeds)	(24473.0,5932100.0)	(24062.4,5932140.0)	2.195	1	1
FORT RD [SB-S] NW	SBD	Arterial-Class C (Truck Route Low speeds)	(37682.8,5940080.0)	(38261.2,5940840.0)	2.145	1	1

CONNORS RD [SB-S] NW	SBD	Arterial-Class C (Truck Route Low speeds)	(34417.9,5933460.0)	(33939.5,5934060.0)	2.141	0	1
97 ST NW	SBD	Arterial-Class C (Truck Route Low speeds)	(33627.9,5938330.0)	(33625.9,5938730.0)	2.132	1	1
75 ST [NB-S] NW	NBD	Arterial-Class C (Truck Route Low speeds)	(36986.0,5929000.0)	(36977.1,5929980.0)	2.122	1	1
107 AV NW	WBD	Arterial-Class C (Truck Route Low speeds)	(33057.1,5935510.0)	(32577.1,5935510.0)	2.120	1	1
50 ST [SB-S] NW	SBD	Arterial-Class C (Truck Route Low speeds)	(38536.7,5934060.0)	(38534.3,5934400.0)	2.114	1	1
82 AV [WB-S] NW	WBD	Arterial-Class D (Non-Truck Route Low speeds)	(32363.2,5931800.0)	(31785.9,5931800.0)	2.065	2	1
50 ST [NB-S] NW	NBD	Arterial-Class D (Non-Truck Route Low speeds)	(38538.8,5934810.0)	(38534.1,5935550.0)	2.045	1	1
99 ST NW	NBD	Arterial-Class C (Truck Route Low speeds)	(34107.4,5928520.0)	(34098.1,5929330.0)	2.036	1	1
34 AV [WB-S] NW	WBD	Arterial-Class C (Truck Route Low speeds)	(34120.3,5926210.0)	(33768.3,5926210.0)	2.025	0	1
137 AV [EB-S] NW	EBD	Arterial-Class C (Truck Route Low speeds)	(30785.8,5940850.0)	(30372.7,5940840.0)	2.023	1	1
170 ST [NB-S] NW	NBD	Arterial-Class C (Truck Route Low speeds)	(25509.6,5933710.0)	(25521.9,5934080.0)	2.021	1	1
BELLAMY HILL NW	NBD	Arterial-Class D (Non-Truck Route Low speeds)	(33229.2,5933570.0)	(33561.1,5934200.0)	2.017	2	1
BELLAMY HILL NW	SBD	Arterial-Class D (Non-Truck Route Low speeds)	(33229.2,5933570.0)	(33561.1,5934200.0)	2.017	2	1
GROAT RD [NB-S] NW	NBD	Arterial-Class D (Non-Truck Route Low speeds)	(30513.3,5933580.0)	(30642.1,5934020.0)	1.997	0	1
170 ST [NB-S] NW	NBD	Arterial-Class C (Truck Route Low speeds)	(25575.7,5931160.0)	(25519.8,5931850.0)	1.996	0	1
VICTORIA TR [SB-S] NW	SBD	Arterial-Class D (Non-Truck Route Low speeds)	(40849.6,5938280.0)	(40903.7,5938690.0)	1.981	1	1
127 ST NW	NBD	Arterial-Class C (Truck Route Low speeds)	(30378.5,5940030.0)	(30374.8,5940500.0)	1.969	2	1
82 AV NW	EBD	Arterial-Class C (Truck Route Low speeds)	(33131.4,5931800.0)	(32743.5,5931800.0)	1.966	1	1
STONY PLAIN RD [WB-S] NW	WBD	Arterial-Class C (Truck Route Low speeds)	(23868.6,5934330.0)	(23490.3,5934320.0)	1.957	1	1
137 AV [WB-S] NW	WBD	Arterial-Class C (Truck Route Low speeds)	(30372.7,5940840.0)	(29747.9,5940840.0)	1.940	1	1
109 ST [SB-S] NW	SBD	Arterial-Class C (Truck Route Low speeds)	(32584.7,5934340.0)	(32584.0,5934570.0)	1.908	2	1
153 AV [EB-S] NW	EBD	Arterial-Class D (Non-Truck Route Low speeds)	(32936.5,5942480.0)	(31987.7,5942480.0)	1.870	1	1
111 ST [SB-S] NW	SBD	Arterial-Class D (Non-Truck Route Low speeds)	(32125.0,5924120.0)	(32109.2,5924640.0)	1.854	1	1
100 AV NW	EBD	Arterial-Class C (Truck Route Low speeds)	(24637.5,5933950.0)	(23879.2,5933900.0)	1.838	0	1
99 ST NW	SBD	Arterial-Class C (Truck Route Low speeds)	(34107.4,5928520.0)	(34098.1,5929330.0)	1.827	1	1
114 ST [SB-S] NW	SBD	Arterial-Class D (Non-Truck Route Low speeds)	(31454.2,5931140.0)	(31446.7,5931620.0)	1.806	1	1
137 AV [WB-S] NW	WBD	Arterial-Class D (Non-Truck Route Low speeds)	(39127.2,5940660.0)	(38876.8,5940640.0)	1.772	1	1
CALGARY TR NW	SBD	Arterial-Class C (Truck Route Low speeds)	(33526.2,5928180.0)	(33522.9,5928470.0)	1.761	0	1
CALGARY TR NW	NBD	Arterial-Class C (Truck Route Low speeds)	(33526.2,5928180.0)	(33522.9,5928470.0)	1.761	0	1

PARSONS RD SW	NBD	Arterial-Class C (Truck Route Low speeds)	(34564.4,5921940.0)	(34567.1,5921470.0)	1.743	1	1
PARSONS RD SW	SBD	Arterial-Class C (Truck Route Low speeds)	(34564.4,5921940.0)	(34567.1,5921470.0)	1.743	1	1
GATEWAY BLVD NW	NBD	Arterial-Class C (Truck Route Low speeds)	(33720.2,5927670.0)	(33717.3,5928470.0)	1.742	1	1
GATEWAY BLVD NW	SBD	Arterial-Class C (Truck Route Low speeds)	(33720.2,5927670.0)	(33717.3,5928470.0)	1.742	1	1
107 AV NW	WBD	Arterial-Class C (Truck Route Low speeds)	(31600.0,5935500.0)	(30758.4,5935440.0)	1.730	1	1
109 ST NW	NBD	Arterial-Class C (Truck Route Low speeds)	(32368.0,5931150.0)	(32363.2,5931800.0)	1.730	2	1
170 ST [SB-S] NW	SBD	Arterial-Class C (Truck Route Low speeds)	(25507.1,5932510.0)	(25510.5,5933270.0)	1.710	0	1
149 ST NW	SBD	Arterial-Class D (Non-Truck Route Low speeds)	(27981.4,5933260.0)	(27975.6,5933950.0)	1.708	2	1
105 ST NW	NBD	Arterial-Class D (Non-Truck Route Low speeds)	(33079.6,5933570.0)	(33074.3,5934110.0)	1.701	1	1
97 ST NW	SBD	Arterial-Class C (Truck Route Low speeds)	(33637.8,5937680.0)	(33627.9,5938330.0)	1.690	1	1
97 ST NW	NBD	Arterial-Class C (Truck Route Low speeds)	(33627.9,5938330.0)	(33625.9,5938730.0)	1.680	1	1
82 AV [WB-S] NW	WBD	Arterial-Class C (Truck Route Low speeds)	(34708.7,5931810.0)	(34082.0,5931810.0)	1.673	2	1
109 ST NW	SBD	Arterial-Class C (Truck Route Low speeds)	(32368.0,5931150.0)	(32363.2,5931800.0)	1.662	2	1
SASKATCHEWAN DR NW	EBD	Arterial-Class D (Non-Truck Route Low speeds)	(33297.6,5932390.0)	(32379.3,5932450.0)	1.652	1	1
CALGARY TR NW	SBD	Arterial-Class C (Truck Route Low speeds)	(33522.7,5928510.0)	(33349.7,5929020.0)	1.645	1	1
CALGARY TR NW	NBD	Arterial-Class C (Truck Route Low speeds)	(33522.7,5928510.0)	(33349.7,5929020.0)	1.645	1	1
107 AV NW	WBD	Arterial-Class C (Truck Route Low speeds)	(33552.4,5935510.0)	(33071.9,5935510.0)	1.643	1	1
170 ST [NB-S] NW	NBD	Arterial-Class C (Truck Route Low speeds)	(25528.5,5934340.0)	(25492.5,5934580.0)	1.634	0	1
82 ST NW	SBD	Arterial-Class C (Truck Route Low speeds)	(35295.1,5936620.0)	(35291.8,5937130.0)	1.623	1	1
69 AV [EB-S] NW	EBD	Arterial-Class D (Non-Truck Route Low speeds)	(25242.3,5930240.0)	(24496.0,5930070.0)	1.619	1	1
WALTERDALE HILL NW	EBD	Arterial-Class C (Truck Route Low speeds)	(32379.3,5932450.0)	(32982.1,5932750.0)	1.614	0	1
WALTERDALE HILL NW	WBD	Arterial-Class C (Truck Route Low speeds)	(32379.3,5932450.0)	(32982.1,5932750.0)	1.614	0	1
75 ST [SB-S] NW	SBD	Arterial-Class C (Truck Route Low speeds)	(36979.2,5929060.0)	(36977.1,5929980.0)	1.591	1	1
170 ST [NB-S] NW	NBD	Arterial-Class C (Truck Route Low speeds)	(25519.8,5931950.0)	(25519.5,5932320.0)	1.567	0	1
127 ST [NB-S] NW	NBD	Arterial-Class C (Truck Route Low speeds)	(30372.7,5940840.0)	(30366.8,5941140.0)	1.566	1	1
66 ST [SB-S] NW	SBD	Arterial-Class D (Non-Truck Route Low speeds)	(37426.5,5926030.0)	(37226.6,5926960.0)	1.561	0	1
CALGARY TR NW	SBD	Arterial-Class C (Truck Route Low speeds)	(33504.0,5927740.0)	(33526.2,5928180.0)	1.558	1	1
CALGARY TR NW	NBD	Arterial-Class C (Truck Route Low speeds)	(33504.0,5927740.0)	(33526.2,5928180.0)	1.558	1	1
170 ST [SB-S] NW	SBD	Arterial-Class C (Truck Route Low speeds)	(25491.4,5931200.0)	(25512.9,5931920.0)	1.554	1	1

STONY PLAIN RD NW	EBD	Arterial-Class D (Non-Truck Route Low speeds)	(27739.3,5934350.0)	(27156.4,5934350.0)	1.553	2	1
99 ST NW	SBD	Collector-Industrial (Adjoining lots zoned > 50% Industrial)	(34395.7,5923390.0)	(34198.6,5924000.0)	1.548	1	1
GROAT RD [SB-S] NW	SBD	Arterial-Class C (Truck Route Low speeds)	(29716.3,5936360.0)	(29717.9,5936800.0)	1.537	0	1
178 ST [NB-S] NW	NBD	Arterial-Class D (Non-Truck Route Low speeds)	(24480.6,5930080.0)	(24535.6,5930780.0)	1.535	1	1
ELLERSLIE RD [WB-S] SW	WBD	Arterial-Class C (Truck Route Low speeds)	(34965.8,5921460.0)	(34567.1,5921470.0)	1.521	1	1
STONY PLAIN RD NW	WBD	Arterial-Class D (Non-Truck Route Low speeds)	(27739.3,5934350.0)	(27156.4,5934350.0)	1.519	2	1
99 ST NW	NBD	Collector-Industrial (Adjoining lots zoned > 50% Industrial)	(34395.7,5923390.0)	(34198.6,5924000.0)	1.515	1	1
153 AV [EB-S] NW	EBD	Arterial-Class D (Non-Truck Route Low speeds)	(33562.2,5942480.0)	(32936.5,5942480.0)	1.515	1	1
WHITEMUD DR [EB-S] NW	EBD	Arterial-Class C (Truck Route Low speeds)	(28730.5,5930170.0)	(28730.5,5930170.0)	1.513	0	1
85 ST NW	SBD	Collector-Residential	(35926.4,5931820.0)	(35871.9,5932420.0)	1.492	1	1
178 ST [NB-S] NW	NBD	Arterial-Class D (Non-Truck Route Low speeds)	(24542.9,5931390.0)	(24507.9,5932050.0)	1.477	1	1
137 AV [EB-S] NW	EBD	Arterial-Class C (Truck Route Low speeds)	(29557.6,5940830.0)	(28966.4,5940830.0)	1.473	1	1
170 ST [SB-S] NW	SBD	Arterial-Class C (Truck Route Low speeds)	(25497.1,5931980.0)	(25502.9,5932320.0)	1.458	0	1
118 AV NW	EBD	Arterial-Class C (Truck Route Low speeds)	(35286.7,5937640.0)	(34463.9,5937630.0)	1.457	2	1
118 AV NW	WBD	Arterial-Class C (Truck Route Low speeds)	(35286.7,5937640.0)	(34463.9,5937630.0)	1.457	2	1
137 AV [EB-S] NW	EBD	Arterial-Class C (Truck Route Low speeds)	(34077.3,5940870.0)	(33879.8,5940870.0)	1.447	0	1
178 ST [SB-S] NW	SBD	Arterial-Class D (Non-Truck Route Low speeds)	(24533.7,5932480.0)	(24503.0,5932910.0)	1.446	1	1
109 ST NW	NBD	Arterial-Class C (Truck Route Low speeds)	(32363.2,5931800.0)	(32362.1,5931940.0)	1.441	2	1
127 ST NW	SBD	Arterial-Class C (Truck Route Low speeds)	(30379.9,5939520.0)	(30378.5,5940030.0)	1.437	2	1
111 ST [SB-S] SW	SBD	Arterial-Class C (Truck Route Low speeds)	(32111.1,5921930.0)	(32126.4,5921470.0)	1.428	2	1
82 ST NW	NBD	Arterial-Class C (Truck Route Low speeds)	(35295.1,5936620.0)	(35291.8,5937130.0)	1.424	1	1
34 AV [EB-S] NW	EBD	Arterial-Class C (Truck Route Low speeds)	(34081.6,5926190.0)	(33728.9,5926200.0)	1.412	0	1
100 AV NW	EBD	Arterial-Class C (Truck Route Low speeds)	(25521.8,5934110.0)	(25395.3,5934110.0)	1.411	1	1
170 ST [SB-S] NW	SBD	Arterial-Class C (Truck Route Low speeds)	(25509.6,5933710.0)	(25499.4,5933850.0)	1.407	1	1
63 AV [WB-S] NW	WBD	Arterial-Class C (Truck Route Low speeds)	(34063.3,5929790.0)	(33570.6,5929790.0)	1.405	1	1
127 ST NW	SBD	Arterial-Class C (Truck Route Low speeds)	(30383.8,5938940.0)	(30383.4,5939180.0)	1.402	0	1
ST ALBERT TR [SB-S] NW	SBD	Arterial-Class C (Truck Route Low speeds)	(29827.0,5937610.0)	(29709.6,5937950.0)	1.378	1	1

50 ST [NB-S] NW	NBD	Arterial-Class C (Truck Route Low speeds)	(38597.2,5930370.0)	(38588.9,5931180.0)	1.374	1	1
137 AV [EB-S] NW	EBD	Arterial-Class D (Non-Truck Route Low speeds)	(39131.0,5940640.0)	(38833.7,5940640.0)	1.367	1	1
178 ST [SB-S] NW	SBD	Arterial-Class D (Non-Truck Route Low speeds)	(24466.8,5930110.0)	(24520.2,5930780.0)	1.365	1	1
107 AV NW	EBD	Arterial-Class C (Truck Route Low speeds)	(33552.4,5935510.0)	(33071.9,5935510.0)	1.349	1	1
50 ST [SB-S] NW	SBD	Arterial-Class C (Truck Route Low speeds)	(38564.7,5931610.0)	(38552.4,5932240.0)	1.349	1	1
111 AV [WB-S] NW	WBD	Arterial-Class C (Truck Route Low speeds)	(33424.8,5936350.0)	(32926.0,5936350.0)	1.348	1	1
82 AV [WB-S] NW	WBD	Arterial-Class C (Truck Route Low speeds)	(33910.8,5931800.0)	(33739.6,5931800.0)	1.344	1	1
75 ST [SB-S] NW	SBD	Arterial-Class C (Truck Route Low speeds)	(36943.1,5931860.0)	(36947.3,5932170.0)	1.344	2	1
170 ST [NB-S] NW	NBD	Arterial-Class C (Truck Route Low speeds)	(25521.8,5934110.0)	(25528.5,5934340.0)	1.341	0	1
34 AV [WB-S] NW	WBD	Arterial-Class C (Truck Route Low speeds)	(35404.1,5925960.0)	(34866.1,5926010.0)	1.340	1	1
82 AV [EB-S] NW	EBD	Arterial-Class C (Truck Route Low speeds)	(33319.9,5931800.0)	(33131.4,5931800.0)	1.318	1	1
97 ST NW	NBD	Arterial-Class C (Truck Route Low speeds)	(33637.8,5937680.0)	(33627.9,5938330.0)	1.314	1	1
137 AV [WB-S] NW	WBD	Arterial-Class C (Truck Route Low speeds)	(28539.8,5940840.0)	(28175.0,5940830.0)	1.311	1	1
23 AV [WB-S] NW	WBD	Arterial-Class D (Non-Truck Route Low speeds)	(35873.3,5924470.0)	(35491.2,5924450.0)	1.309	1	1
75 ST [SB-S] NW	SBD	Arterial-Class C (Truck Route Low speeds)	(36982.2,5928270.0)	(36986.0,5929000.0)	1.309	1	1
23 AV [WB-S] NW	WBD	Arterial-Class C (Truck Route Low speeds)	(33114.6,5924670.0)	(32620.5,5924670.0)	1.307	1	1
34 AV [EB-S] NW	EBD	Arterial-Class C (Truck Route Low speeds)	(35372.5,5925940.0)	(34858.7,5926000.0)	1.302	1	1
111 AV [WB-S] NW	WBD	Arterial-Class C (Truck Route Low speeds)	(28772.6,5936310.0)	(27956.9,5936310.0)	1.300	1	1
75 ST [NB-S] NW	NBD	Arterial-Class C (Truck Route Low speeds)	(36974.3,5930380.0)	(36970.4,5930730.0)	1.298	1	1
82 ST NW	NBD	Arterial-Class C (Truck Route Low speeds)	(35275.0,5939010.0)	(35275.3,5939220.0)	1.294	0	1
106 ST NW	SBD	Arterial-Class D (Non-Truck Route Low speeds)	(32956.2,5933580.0)	(32953.8,5933930.0)	1.294	1	1
127 ST NW	SBD	Arterial-Class C (Truck Route Low speeds)	(30383.0,5939230.0)	(30379.9,5939520.0)	1.289	1	1
75 ST [NB-S] NW	NBD	Arterial-Class C (Truck Route Low speeds)	(36977.1,5929980.0)	(36974.3,5930380.0)	1.285	1	1
109 ST NW	SBD	Arterial-Class C (Truck Route Low speeds)	(32363.2,5931800.0)	(32362.1,5931940.0)	1.281	2	1
99 ST NW	NBD	Collector-Industrial (Adjoining lots zoned > 50% Industrial)	(34198.6,5924000.0)	(34145.3,5924390.0)	1.276	1	1
118 AV NW	EBD	Arterial-Class C (Truck Route Low speeds)	(34463.9,5937630.0)	(33967.2,5937630.0)	1.271	2	1
118 AV NW	WBD	Arterial-Class C (Truck Route Low speeds)	(34463.9,5937630.0)	(33967.2,5937630.0)	1.271	2	1
149 ST NW	NBD	Arterial-Class D (Non-Truck Route Low speeds)	(27968.9,5934570.0)	(27963.4,5935170.0)	1.263	0	1
111 AV [EB-S] NW	EBD	Arterial-Class C (Truck Route Low speeds)	(28721.3,5936310.0)	(27956.9,5936310.0)	1.262	1	1

104 ST NW	SBD	Arterial-Class C (Truck Route Low speeds)	(33331.5,5929560.0)	(33330.0,5929770.0)	1.259	1	1
87 AV [EB-S] NW	EBD	Arterial-Class D (Non-Truck Route Low speeds)	(27985.3,5931910.0)	(27172.0,5931910.0)	1.258	1	1
Total							**142**

Appendix C Selected Locations for Expansion Scenario (adding 10)

Table B-1 Selected Sites by Considering Coverage of Vulnerable Road Users/Facilities Only (w=0)

Road Name	Direction	Road Type	Start Point	End Point	Δ_{EPDO}	Cvg	#DFS
87 AV NW	EBD	Arterial-Class D (Non-Truck Route Low speeds)	(32359.4,5932330.0)	(31977.5,5932330.0)	0.867	3	1
87 AV NW	WBD	Arterial-Class D (Non-Truck Route Low speeds)	(32359.4,5932330.0)	(31977.5,5932330.0)	0.801	3	1
102 AV NW	EBD	Collector-Residential	(31731.3,5934570.0)	(31099.2,5934560.0)	0.977	3	1
102 AV NW	WBD	Collector-Residential	(31731.3,5934570.0)	(31099.2,5934560.0)	0.608	3	1
106 ST [NB-S] NW	NBD	Collector-Residential	(32916.0,5926840.0)	(32786.3,5927000.0)	0.308	3	1
106 ST [SB-S] NW	SBD	Collector-Residential	(32916.0,5926840.0)	(32786.3,5927000.0)	0.338	3	1
110 ST NW	NBD	Collector-Residential	(32468.4,5933580.0)	(32466.3,5933930.0)	0.528	3	1
110 ST NW	SBD	Collector-Residential	(32468.4,5933580.0)	(32466.3,5933930.0)	0.365	3	1
114 AV NW	EBD	Collector-Residential	(30398.2,5936860.0)	(30286.6,5936850.0)	0.137	3	1
114 AV NW	WBD	Collector-Residential	(30398.2,5936860.0)	(30286.6,5936850.0)	0.137	3	1
Total							**10**

Table B- 2 Selected Sites by Equally Considering two factors (w=0.5)

Road Name	Direction	Road Type	Start Point	End Point	Δ_{EPDO}	Cvg	#DFS
109 ST [SB-S] NW	SBD	Arterial-Class C (Truck Route Low speeds)	(32583.0,5933660.0)	(32581.6,5933930.0)	3.625	2	1
109 ST [SB-S] NW	SBD	Arterial-Class C (Truck Route Low speeds)	(32581.6,5933930.0)	(32580.3,5934100.0)	2.811	2	1
102 AV NW	EBD	Collector-Residential	(31731.3,5934570.0)	(31099.2,5934560.0)	0.977	3	1
87 AV NW	EBD	Arterial-Class D (Non-Truck Route Low speeds)	(32359.4,5932330.0)	(31977.5,5932330.0)	0.867	3	1
87 AV NW	WBD	Arterial-Class D (Non-Truck Route Low speeds)	(32359.4,5932330.0)	(31977.5,5932330.0)	0.801	3	1
91 ST NW	NBD	Collector-Residential	(35321.8,5931810.0)	(35316.6,5932420.0)	0.645	3	1
102 AV NW	WBD	Collector-Residential	(31731.3,5934570.0)	(31099.2,5934560.0)	0.608	3	1
94 ST NW	SBD	Collector-Residential	(34082.2,5941630.0)	(34063.6,5942110.0)	0.604	3	1
82 AV [EB-S] NW	EBD	Arterial-Class D (Non-Truck Route Low speeds)	(32363.2,5931800.0)	(31786.0,5931780.0)	2.268	2	1

110 ST NW	NBD	Collector-Residential	(32468.4,5933580.0)	(32466.3,5933930.0)	0.528	3	1
Total							**10**

Table B-3 Selected Sites by Considering Collision Reduction Only(w=1)

Road Name	**Direction**	**Road Type**	**Start Point**	**End Point**	Δ_{EPDO}	Cvg	**#DFS**
170 ST [SB-S] NW	SBD	Arterial-Class C (Truck Route Low speeds)	(25502.7,5933310.0)	(25509.6,5933710.0)	5.191	0	1
CONNORS RD [NB-S] NW	NBD	Arterial-Class C (Truck Route Low speeds)	(34149.4,5933950.0)	(33983.7,5934200.0)	4.221	0	1
109 ST [SB-S] NW	SBD	Arterial-Class C (Truck Route Low speeds)	(32583.0,5933660.0)	(32581.6,5933930.0)	3.625	2	1
107 AV NW	WBD	Arterial-Class C (Truck Route Low speeds)	(32577.1,5935510.0)	(31723.7,5935500.0)	3.100	1	1
109 ST [SB-S] NW	SBD	Arterial-Class C (Truck Route Low speeds)	(32581.6,5933930.0)	(32580.3,5934100.0)	2.811	2	1
100 AV NW	EBD	Arterial-Class C (Truck Route Low speeds)	(25048.6,5934050.0)	(24695.5,5933960.0)	2.717	1	1
105 ST NW	NBD	Arterial-Class C (Truck Route Low speeds)	(33004.0,5932820.0)	(33080.9,5933180.0)	2.665	0	1
QUEEN ELIZABETH PARK RD NW	NBD	Arterial-Class D (Non-Truck Route Low speeds)	(33579.8,5932500.0)	(32982.1,5932750.0)	2.556	0	1
QUEEN ELIZABETH PARK RD NW	SBD	Arterial-Class D (Non-Truck Route Low speeds)	(33579.8,5932500.0)	(32982.1,5932750.0)	2.556	0	1
107 AV NW	EBD	Arterial-Class C (Truck Route Low speeds)	(32577.1,5935510.0)	(31723.7,5935500.0)	2.459	1	1
Total							**10**

Appendix D Selected Locations for Expansion Scenario (adding 20)

Table C-1 Selected Sites by Considering Coverage of Vulnerable Road Users/Facilities Only (w=0)

Road Name	Direction	Road Type	Start Point	End Point	Δ_{EPDO}	Cvg	#DFS
87 AV NW	EBD	Arterial-Class D (Non-Truck Route Low speeds)	(32359.4,5932330.0)	(31977.5,5932330.0)	0.867	3	1
87 AV NW	WBD	Arterial-Class D (Non-Truck Route Low speeds)	(32359.4,5932330.0)	(31977.5,5932330.0)	0.801	3	1
102 AV NW	EBD	Collector-Residential	(31731.3,5934570.0)	(31099.2,5934560.0)	0.977	3	1
102 AV NW	WBD	Collector-Residential	(31731.3,5934570.0)	(31099.2,5934560.0)	0.608	3	1
106 ST [NB-S] NW	NBD	Collector-Residential	(32916.0,5926840.0)	(32786.3,5927000.0)	0.308	3	1
106 ST [SB-S] NW	SBD	Collector-Residential	(32916.0,5926840.0)	(32786.3,5927000.0)	0.338	3	1
110 ST NW	NBD	Collector-Residential	(32468.4,5933580.0)	(32466.3,5933930.0)	0.528	3	1
110 ST NW	SBD	Collector-Residential	(32468.4,5933580.0)	(32466.3,5933930.0)	0.365	3	1
114 AV NW	EBD	Collector-Residential	(30398.2,5936860.0)	(30286.6,5936850.0)	0.137	3	1
114 AV NW	WBD	Collector-Residential	(30398.2,5936860.0)	(30286.6,5936850.0)	0.137	3	1
115 AV NW	EBD	Collector-Residential	(29504.9,5937020.0)	(29059.9,5937020.0)	0.203	3	1
115 AV NW	WBD	Collector-Residential	(29504.9,5937020.0)	(29059.9,5937020.0)	0.203	3	1
129 ST NW	NBD	Collector-Residential	(30188.6,5942060.0)	(30085.8,5942260.0)	0.289	3	1
129 ST NW	SBD	Collector-Residential	(30188.6,5942060.0)	(30085.8,5942260.0)	0.224	3	1
132 AV NW	WBD	Collector-Residential	(32667.3,5940040.0)	(32013.9,5940040.0)	0.379	3	1
134 AV NW	EBD	Collector-Residential	(32664.1,5940350.0)	(32007.0,5940350.0)	0.348	3	1
134 AV NW	WBD	Collector-Residential	(32664.1,5940350.0)	(32007.0,5940350.0)	0.382	3	1
134A AV NW	EBD	Collector-Residential	(33022.3,5940480.0)	(32828.0,5940360.0)	0.236	3	1
134A AV NW	WBD	Collector-Residential	(33022.3,5940480.0)	(32828.0,5940360.0)	0.203	3	1
134B AV NW	EBD	Collector-Residential	(31110.7,5940340.0)	(30779.2,5940500.0)	0.199	3	1
Total							**20**

Table C-2 Selected Sites by Equally Considering two factors (w=0.5)

Road Name	Direction	Road Type	Start Point	End Point	Δ_{EPDO}	Cvg	#DFS
109 ST [SB-S] NW	SBD	Arterial-Class C (Truck Route Low speeds)	(32583.0,5933660.0)	(32581.6,5933930.0)	3.625	2	1
109 ST [SB-S] NW	SBD	Arterial-Class C (Truck Route Low speeds)	(32581.6,5933930.0)	(32580.3,5934100.0)	2.811	2	1
102 AV NW	EBD	Collector-Residential	(31731.3,5934570.0)	(31099.2,5934560.0)	0.977	3	1
87 AV NW	EBD	Arterial-Class D (Non-Truck Route Low speeds)	(32359.4,5932330.0)	(31977.5,5932330.0)	0.867	3	1
87 AV NW	WBD	Arterial-Class D (Non-Truck Route Low speeds)	(32359.4,5932330.0)	(31977.5,5932330.0)	0.801	3	1
91 ST NW	NBD	Collector-Residential	(35321.8,5931810.0)	(35316.6,5932420.0)	0.645	3	1
102 AV NW	WBD	Collector-Residential	(31731.3,5934570.0)	(31099.2,5934560.0)	0.608	3	1
94 ST NW	SBD	Collector-Residential	(34082.2,5941630.0)	(34063.6,5942110.0)	0.604	3	1
82 AV [EB-S] NW	EBD	Arterial-Class D (Non-Truck Route Low speeds)	(32363.2,5931800.0)	(31786.0,5931780.0)	2.268	2	1
110 ST NW	NBD	Collector-Residential	(32468.4,5933580.0)	(32466.3,5933930.0)	0.528	3	1
91 ST NW	SBD	Collector-Residential	(35321.8,5931810.0)	(35316.6,5932420.0)	0.510	3	1
109 ST [SB-S] NW	SBD	Arterial-Class C (Truck Route Low speeds)	(32580.3,5934110.0)	(32584.7,5934340.0)	2.197	2	1
42 AV NW	EBD	Collector-Residential	(32910.8,5927430.0)	(32492.0,5927460.0)	0.423	3	1
42 AV NW	WBD	Collector-Residential	(32910.8,5927430.0)	(32492.0,5927460.0)	0.423	3	1
135 AV NW	WBD	Collector-Residential	(34081.9,5940570.0)	(33640.1,5940560.0)	0.412	3	1
94 ST NW	NBD	Collector-Residential	(34082.2,5941630.0)	(34063.6,5942110.0)	0.403	3	1
167 ST NW	SBD	Collector-Residential	(25818.2,5933270.0)	(25889.0,5934070.0)	0.396	3	1
RUTHERFORD RD SW	NBD	Collector-Residential	(31568.1,5920310.0)	(31823.8,5920990.0)	0.396	3	1
RUTHERFORD RD SW	SBD	Collector-Residential	(31568.1,5920310.0)	(31823.8,5920990.0)	0.396	3	1
94 ST NW	NBD	Collector-Residential	(34032.4,5941340.0)	(34078.9,5941620.0)	0.383	3	1
Total							**20**

Table C-3 Selected Sites by Considering Collision Reduction Only(w=1)

Road Name	Direction	Road Type	Start Point	End Point	Δ_{EPDO}	Cvg	#DFS
170 ST [SB-S] NW	SBD	Arterial-Class C (Truck Route Low speeds)	(25502.7,5933310.0)	(25509.6,5933710.0)	5.191	0	1
CONNORS RD [NB-S] NW	NBD	Arterial-Class C (Truck Route Low speeds)	(34149.4,5933950.0)	(33983.7,5934200.0)	4.221	0	1

109 ST [SB-S] NW	SBD	Arterial-Class C (Truck Route Low speeds)	(32583.0,5933660.0)	(32581.6,5933930.0)	3.625	2	1
107 AV NW	WBD	Arterial-Class C (Truck Route Low speeds)	(32577.1,5935510.0)	(31723.7,5935500.0)	3.100	1	1
109 ST [SB-S] NW	SBD	Arterial-Class C (Truck Route Low speeds)	(32581.6,5933930.0)	(32580.3,5934100.0)	2.811	2	1
100 AV NW	EBD	Arterial-Class C (Truck Route Low speeds)	(25048.6,5934050.0)	(24695.5,5933960.0)	2.717	1	1
105 ST NW	NBD	Arterial-Class C (Truck Route Low speeds)	(33004.0,5932820.0)	(33080.9,5933180.0)	2.665	0	1
QUEEN ELIZABETH PARK RD NW	NBD	Arterial-Class D (Non-Truck Route Low speeds)	(33579.8,5932500.0)	(32982.1,5932750.0)	2.556	0	1
QUEEN ELIZABETH PARK RD NW	SBD	Arterial-Class D (Non-Truck Route Low speeds)	(33579.8,5932500.0)	(32982.1,5932750.0)	2.556	0	1
107 AV NW	EBD	Arterial-Class C (Truck Route Low speeds)	(32577.1,5935510.0)	(31723.7,5935500.0)	2.459	1	1
34 AV [EB-S] NW	EBD	Arterial-Class C (Truck Route Low speeds)	(34557.4,5926150.0)	(34133.4,5926190.0)	2.448	0	1
127 ST [SB-S] NW	SBD	Arterial-Class C (Truck Route Low speeds)	(30365.1,5940900.0)	(30366.8,5941140.0)	2.413	1	1
111 ST [SB-S] NW	SBD	Arterial-Class C (Truck Route Low speeds)	(32108.7,5924700.0)	(32105.7,5924940.0)	2.325	1	1
82 AV [EB-S] NW	EBD	Arterial-Class D (Non-Truck Route Low speeds)	(32363.2,5931800.0)	(31786.0,5931780.0)	2.268	2	1
107 AV NW	EBD	Arterial-Class C (Truck Route Low speeds)	(33057.1,5935510.0)	(32577.1,5935510.0)	2.251	1	1
82 AV NW	WBD	Arterial-Class C (Truck Route Low speeds)	(33131.4,5931800.0)	(32743.5,5931800.0)	2.199	1	1
109 ST [SB-S] NW	SBD	Arterial-Class C (Truck Route Low speeds)	(32580.3,5934110.0)	(32584.7,5934340.0)	2.197	2	1
87 AV [EB-S] NW	EBD	Arterial-Class D (Non-Truck Route Low speeds)	(24473.0,5932100.0)	(24062.4,5932140.0)	2.195	1	1
FORT RD [SB-S] NW	SBD	Arterial-Class C (Truck Route Low speeds)	(37682.8,5940080.0)	(38261.2,5940840.0)	2.145	1	1
CONNORS RD [SB-S] NW	SBD	Arterial-Class C (Truck Route Low speeds)	(34417.9,5933460.0)	(33939.5,5934060.0)	2.141	0	1
Total							**20**