Developing HOV Lane and Ramp Meter Analysis Frameworks for Alberta Highways

by

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ABSTRACT

The Province of Alberta constructs new highways and widens existing roadways relying responding to demand. Absent from these improvements, however, are other capacity expansion and demand management strategies such as high-occupancy vehicle (HOV) lanes and ramp metering—strategies that exist on other Canadian urban highways. Since HOV lanes and ramp metering have not been implemented and a process for planning and analysis is absent in Alberta Transportation's engineering guidelines, I develop a framework, guiding the planning and engineering process to study the viability and design of these strategies at differing levels of detail.

I develop this framework through first conducting a literature review, providing a background on HOV lanes, ramp metering, and commonly used traffic analysis tools. HOV lanes shift travel to higher-density modes while ramp meters maintain free-flow conditions on a highway. Guidelines are then established for conducting a high-level, mid-level and detailed study in order to test various design scenarios. With these outlined studies, I apply this framework as a case study to Hwy 2 (HOV lanes) and Hwy 216 (ramp metering), to examine the location-specific data needs and study requirements.

Through this thesis, I develop a planning framework which allows analysts to test the operational impacts of various design configurations and travel demand management (TDM) policies such as occupancy restrictions on HOV lanes and signal control systems for ramp meters. This connects the existing literature for design guidelines and operational studies, highlighting how various elements of design may be tested at each level of analysis. I also examine data availability for

conducting these analyses, identifying occupancy data and model calibration data as the most significant needs.

The framework developed by this thesis provides a foundation for engineers and transportation planners, by organizing the steps of analysis and helping identify data needs. Although many highway engineering projects follow a similar process, this framework is specifically applied to Alberta and Alberta Transportation's planning process.

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GLOSSARY OF TERMS

ATIS	Advanced Traveler Information System
AADT	Annual average daily traffic
AASHTO	American Association of State Highway and Transportation Officials
AT	Alberta Transportation
CMF	Crash modification factor
DCM	Discrete choice model
DTA	Dynamic Traffic Assignment
EIA	Edmonton International Airport
FFS	Free-flow speeds
FHWA	Federal Highway Association
GP	General-purpose
HCM	Highway Capacity Manual
HGDG	Highway Geometric Design Guide
HHTS	Household Travel Survey
HOT	High-occupancy toll
HOV	High-occupancy vehicle
ITS	Intelligent transportation system
LOS	Level of service
ML	Managed lanes
MOE	Measure of effectiveness
NAFTA	North American Free Trade Agreement
NCHRP	National Cooperative Highway Research Program
O-D	Origin-destination

P3	Private-public partnership
RCMP	Royal Canadian Mounted Police
RM	Ramp meter
RTDM	Regional travel demand model
SOV	Single-occupant vehicle
SP/RP	Stated preference / revealed preference
TDM	Travel demand management
TOR	Terms of reference
V/C	Volume to capacity ratio
VHD	Vehicle-hours of delay
VMT	Vehicle-miles travelled
VPH, VPHPL	Vehicles per hour, vehicles per hour per lane
VSL	Variable-speed limit

1. INTRODUCTION

1.1 Research motivation and purpose

Alberta builds, expands and operates urban highways with the high-level goals of economic and social growth (Government of Alberta, 2016). These guiding principals have resulted in the building of new highways and widening of existing ones into the 21st century. Absent from these improvements are other capacity expansion and demand management strategies such as high-occupancy vehicle (HOV) lanes and ramp metering –strategies that exist on other Canadian urban highways. Through this thesis, I develop a framework for planning and engineering HOV lanes and ramp metering at differing levels of detail to study the viability and design of these strategies. This document provides a structured framework and a case study application to Alberta Highways that can help agencies like Alberta Transportation in planning congestion management strategies that fulfill Alberta's goals of meeting economic and social needs while considering environmental and fiscal responsibilities.

Historically, transportation investments have followed the premise that infrastructure investments that improve efficiency also improve the economy. This is based on the assumption that efficient movement of people, goods, and services contributes to the economic growth of an urban region while inhibited movement hinders its growth, a concept dating back to the expansion of intercontinental highway and rail that crossed North America (Black W. R., 2001). Consequently, increased travel costs, both directly (monetary costs) and indirectly (in terms of time) are perceived as detrimental. As a region grows, a larger population desires mobility, leading to an increase in travel demand. When demand increases and supply remains constrained, congestion occurs and travelers experience delays. In addition, other consequences of congestion include decreased mobility, accessibility, reduced traffic safety and increased emissions (Meyer M. D., 1997; Falcocchio & Levinson, 2015). Traditional highway planning accounts for population growth by forecasting changes in demand, leading to decisions for highway improvements often in terms of highway twinning and increased number of lanes. While increasing the capacity of highways by physically adding pavement increases the supply and may temporarily reduce congestion, it is widely accepted that this strategy is not always the most viable long-term solution as congestion returns due to induced demand - the shifting of travelers from other facilities and modes to the improved one (Meyer M. D., 1997; Varaiya, 2005). Additionally, roadway agencies will need to balance limited resources for infrastructure improvements, preventative maintenance and reconstruction as the transportation network ages (Meyer M. D., 2007). In response, agencies have shifted to focus on improving operational efficiency of existing infrastructure by using technology, Intelligent Transportation Systems (ITS) and by influencing travel behavior through Travel Demand Management (TDM) (Meyer M. D., 1999). Here, TDM strategies use incentives and disincentives to influence travelers to alter behavior by shifting their mode, time and route of travel. In Alberta, contrary to trends in other urban areas, new highways and roadway widenings are being planned and funded with little evidence of structured TDM program planning. Therefore, the main purpose of this study is to develop a framework for different engineering analyses used to plan HOV lanes and ramp metering as well as applying this framework to specific locations in Alberta. These guidelines contribute to highway planning in Alberta by clearly outlining best practices for planning suitable strategies for these urban highways.

1.2 Background

Alberta does not currently have High-Occupancy Vehicle (HOV) lanes or ramp metering on its highways, however the province is taking steps towards facilitating HOV lane implementation. I chose to focus this thesis on these two strategies as there has been expressed interest in these strategies from policy makers, resulting in changes to legislation and execution of high-level studies. There is also a precedent of these strategies used elsewhere in Canada and in the United States for several decades. Although roadway pricing can serve to manage traffic demand and fund infrastructure in other jurisdictions, I do not include it as part of this thesis since tolling is viewed unfavourably in Alberta and private-public partnerships (P3) contracts forbid pricing on Edmonton and Calgary ring roads (Alberta Transportation, 2012).

In 2013, the legislative assembly debated and passed Bill 32, legislation allowing HOV and other types of managed lanes such as reversible and bus-lanes. The bill restricts “the use of specified traffic lanes to vehicles carrying a prescribed number of passengers” or specific “classes of vehicles” (Province of Alberta, 2013). Since these two aforementioned strategies do not exist in Alberta, two locations are chosen as case studies for applying the planning framework. For this case study, I chose these highway segments as they are of interest to Alberta Transportation and contain some of the highest volumes of daily traffic in Alberta, resulting in present and future peak-hour congestion. Figure 1 presents the study areas for Hwy 2 and 216 in the context of the greater Edmonton region. The boundary for Hwy 2 is between Hwy 216 interchange and the Hwy 2A interchange in Leduc.

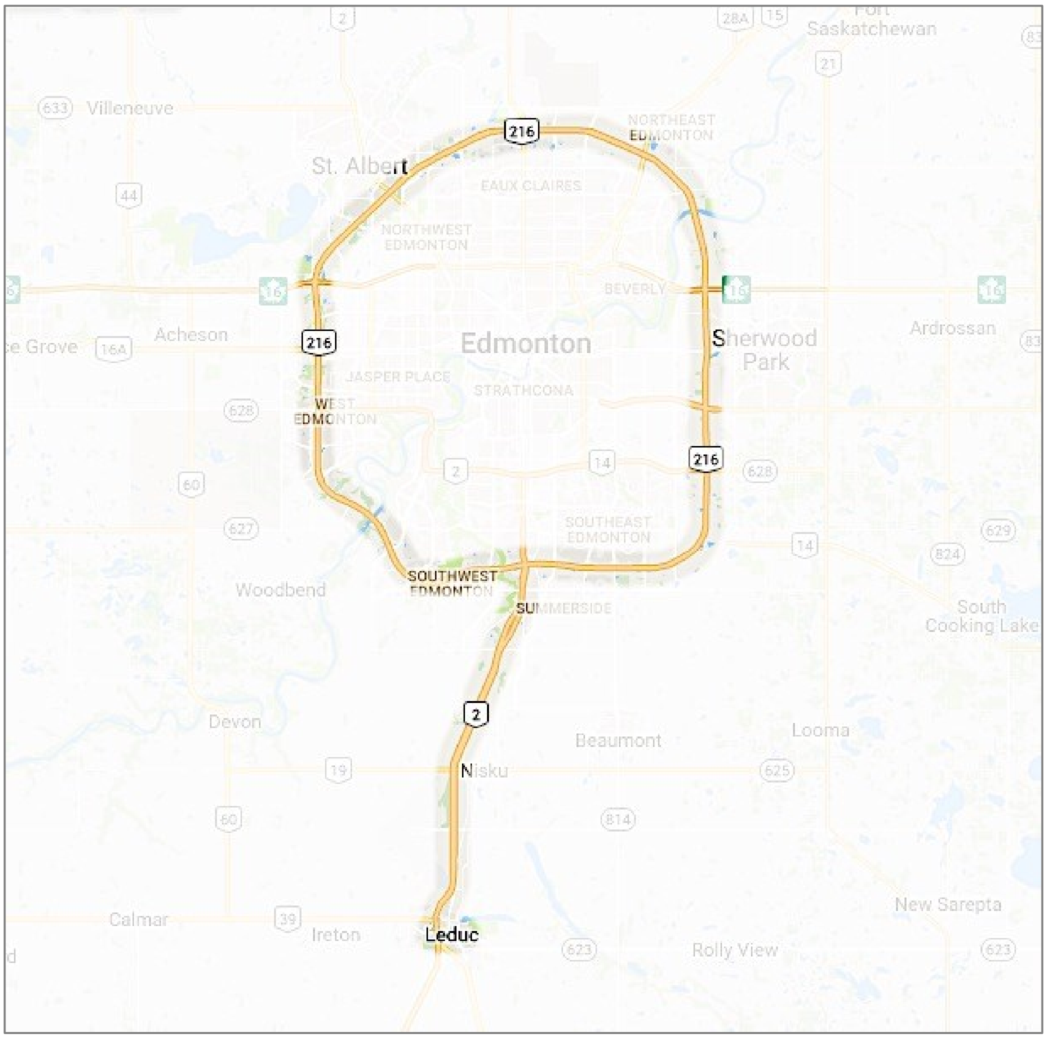


Figure 1 Study Area in the Edmonton Capital Region (Adapted from Google Maps)

Highway 2 is a grade-separated urban highway that serves as the primary north-south route between Edmonton and Calgary. The section of Highway 2 (between Leduc and Edmonton) provides access for those living and working in the City of Edmonton to Edmonton International Airport and the Nisku industrial park. This section of Highway 2 is a divided 6-lane highway with a posted speed limit of 110 km/h and has several partial-clover and diamond interchanges.

They experience some of the highest annual average daily traffic (AADT) counts in the province with an average of 89,360 vehicles/day counted on Hwy 2 north of Leduc (Cornerstone Solutions Inc., 2016).

Highway 216 is a grade-separated urban highway and "ring road" that is located in the Edmonton region and operated by Alberta Transportation. It has a speed limit of 100km/h and the section identified for this study includes divided 4 and 6 lane segments. The portion of Highway 216 named above is the most congested section of the Anthony Henday ring road, largely due to heavy weaving volumes caused by closely-spaced interchanges. The 2016 AADT determined from facility counts taken on Highway 2 South of 216 are 88,110 vehicles/day (Cornerstone Solutions Inc., 2016).

1.3 Objectives and Tasks

The objective of this thesis is to develop and present a framework that guides the planning analyses of HOV lanes and ramp metering, testing their design and viability on existing urban highways in Alberta. I completed several tasks to fulfil this objective, beginning with a comprehensive literature review providing background on these two strategies as well as the technical analysis tools that are used to assess their impacts. In the second task, I outlined the framework for each tool, as well as how and when specific analyses are conducted during the implementation process from concept planning to construction. The final task involved an application of the planning framework for the aforementioned highways in Alberta, which include examining the data needs in addition to the physical properties of the highways and how these properties impact the analysis.

1.4 Findings and Contributions

The resulting framework will contribute to the engineering project planning literature for congestion management strategies on Alberta's highways. Specifically, it will help guide what types of analyses are required at different points in the planning and design process as well as discuss how resource limitations affect the analyses and results. This thesis builds upon existing guidelines by connecting geometric design and operational studies, guiding the modelling of design alternatives. This provides analysts and highway engineers with a framework that shapes the analysis and study of these concepts as specific designs are finalized. This study also assesses the needs for Alberta specifically, identifying data gaps and outlining physical limitations on the candidate facilities.

1.5 Thesis Structure

Chapter 2 provides a literature review of ramp metering and HOV lanes as congestion management strategies used commonly in literature and elsewhere in Canada. It also outlines specific engineering methods and techniques for planning the aforementioned strategies. Chapter 3 organizes a planning framework for HOV lanes and includes a case study applying this analysis to Alberta highways. Chapter 4 presents a planning framework in a similar format but for ramp metering and also includes a case study. Chapter 5 closes with recommendations and conclusions.

2. LITERATURE REVIEW

The following chapter is divided into four sections. Firstly, I provide a background on the highway planning process in Alberta followed by two sections focus on HOV lanes and ramp meters. These describe the operational characteristics, the locations where they are operating and the existing literature. The final section then introduces the tools used to assess aforementioned strategies, categorizing these into demand-based and operational models.

2.1 Highway Planning, Engineering, and Design in Alberta

Highway improvement projects in Alberta follow established guidelines that cover twinning, intersection upgrades, new roadway construction, repaving and other general maintenance (Alberta Transportation, 1999). This section provides a background for Chapters 3 and 4 which then build upon this process by describing where and when the HOV and ramp meter planning studies align with the existing framework. Figure 2 outlines the existing process from Alberta Transportation's Engineering Consulting Guidelines, outlining the progression from long-range concepts to operational plans (Alberta Transportation, 2011).

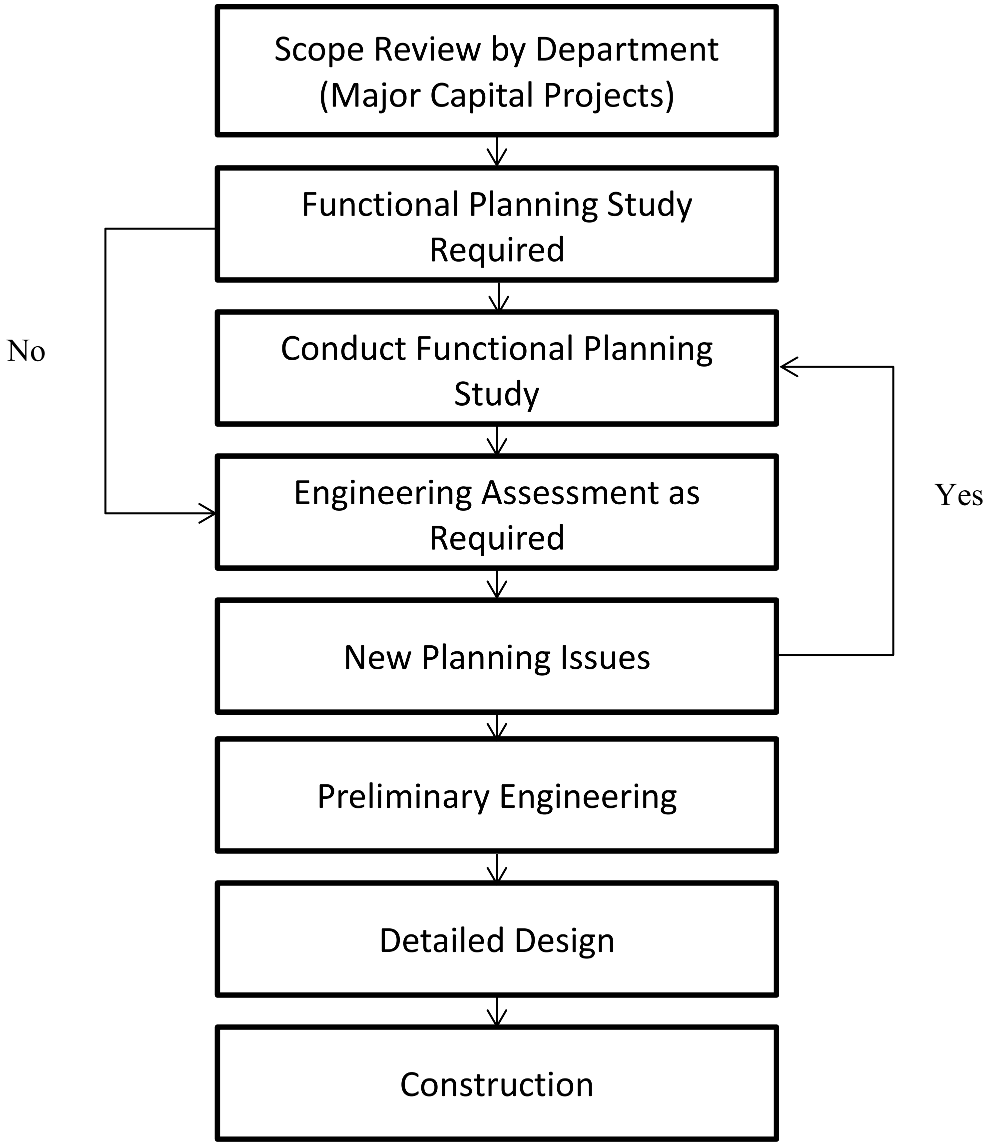


Figure 2 Alberta's Highway Engineering Process (Alberta Transportation, 2011)

Firstly, branches within Alberta Transportation (AT) provide input for scheduling major capital projects. This involves selecting potential corridors and roadways for maintenance or new construction. This 3-year program, containing the proposed projects, is then consolidated and tabled before legislature each year for approval and funding. Once the program is established, AT determines if the studies require a functional planning study and engineering assessments or if these stages may be skipped for simpler projects (Alberta Transportation, 2011). At this phase, sketch planning tools aid the project selection process.

A functional planning study is a detailed and comprehensive investigation into specific issues and design configurations for a target location. These design configurations include present-day and future-case design options. This includes roadway geometric improvements, geotechnical concerns, right-of-way changes, adjustments to utilities, environmental consideration and present and future roadway performance (Alberta Transportation, 2011). Additionally, the functional planning study identifies engineering assessments, such as required geotechnical and environmental studies, along with additional data requirements. Although these assessments also gather geotechnical, structural and hydrological data, this chapter focuses specifically on the transportation studies and data involved in functional planning. Transportation engineering assessments provide guidelines for collecting data which include road safety audits, traffic volume (including turning movement) studies and speed data sampling (Alberta Transportation, 2011). With the collected and existing data, functional planning studies use methods in the Highway Capacity Manual (HCM) for highway Level of Service (LOS) performance analysis as well as Synchro (which is a software implementation of the HCM method) for signalized intersections (ISL, 2005; McElhanney Consulting Services Ltd., 2009).

Once the alternatives are selected, preliminary engineering commences with the objective of gathering data for the design phase. Here, various surveys gather soil, utility, geometric, drainage and existing right-of-way data required for the detailed design. Then, the detailed design process creates plans that fulfil the design and environmental requirements for project construction. Once the detailed designs are finalized, construction commences (Alberta Transportation, 2011).

This previously outlined engineering process guides the planning and design of highway projects in Alberta. Since this process does not contain direct guidance for the planning of HOV lanes and ramp meters, the subsequent sections in this chapter will introduce different levels of analysis and where they can be incorporated into the aforementioned process.

Currently, analysts use the process presented in Figure 2 to choose and finalize design alternatives once a decision is made to proceed with a project (often when funding has been allocated to upgrade an intersection or twin a highway). This process focuses on determining the design elements since the need for these projects are justified according to AT's existing planning guidelines – for instance, where increased traffic volumes warrant highway twinning and intersection upgrades. For more complex projects such as ramp metering and HOV lanes, the changes in operational characteristics may not be known until analysts conduct a detailed study with traffic analysis tools that forecast demands and simulate resulting operating conditions. Therefore, the framework that I propose is similar to Alberta Transportation's as studies are broken down into high-level conceptual to detailed design studies, but differs as the results may indicate that a no-build scenario may be most appropriate. In other words, the process shown in Figure 2 is one that is carried out once a strategy or project has been chosen; my work focuses on the analysis that takes place to actually choose a strategy or project. The resulting outputs from these analyses help capture the full extent of the impacts, the changes in roadway operations and travel habits, that occur due to the implementation of these strategies so that these decision-makers may justify their decisions.

2.2 High Occupancy Vehicle (HOV) Lanes

High-Occupancy Vehicle (HOV) lanes are differentiated from general purpose (GP) lanes by vehicle eligibility restrictions and access controls, requiring minimum passenger occupancies (FHWA, 2015). They may be implemented with time-of-day restrictions (increased occupancies during peak hours), as traffic demands are highly temporal (Carson, 2005). These lanes are often implemented with the objective of increasing the person-throughput of a roadway, by providing the incentive of more reliable and shorter travel times to specific vehicles (Texas Transportation Institute, 1998). More specifically, the purpose of managed lanes is to increase the overall average number of persons per vehicle on a corridor or facility, and maximize person-throughput while reducing the number of vehicles on the facility. The potential benefits of HOV lanes are most critical during peak periods, and HOV lanes were found to be most effective when GP lanes were heavily congested (Kwon & Varaiya, 2008). Another objective of HOV lanes is to provide more reliable bus transit operations, as use of restricted lanes allow transit vehicles to have shorter travel times and improved schedule adherence (Texas Transportation Institute, 1998). There are many types of managed lanes that have been developed over the years, with the general categories and their intended benefits and impacts listed in Table 1.

Table 1 Common Types of Managed Lanes

Lane Type & Description	Intended Benefits and Overall Impacts
HOV lanes Lanes restricted to vehicles with a minimum occupancy of 2+, 3+ or 4+. Lanes restricted	· Maximize person-throughput while reducing number of vehicles during peak periods (Texas

to 2+ passengers are most common in Canada (Transport Canada, 2010). Eligible vehicles also include emergency vehicles, vanpools, and transit.	Transportation Institute, 1998) · Higher travel time reliability and better service for eligible vehicles (Falcocchio & Levinson, 2015) · Less vehicles on the road lead to improved air quality through reduced GHG emissions

In reality, the intended benefits and impacts may be not as simple to quantify or evaluate. For example, HOV lanes have received heavy criticism for being underused or overused; overuse has led to conditions on the HOV lane that are just as bad, if not worse, than the GP lanes (Dachis, 2011; Poole & Orski, 2000).

The two most common configurations of HOV lanes are concurrent lane and separated lanes. Concurrent lanes have no physical separation from GP lanes, and are relatively less expensive (Texas Transportation Institute, 1998). Separated lanes have a physical separation from GP lanes with either concrete barriers or painted buffer zones with limited access points for vehicles to enter or exit (Carson, 2005).

HOV lanes were first introduced in 1969 in New Jersey, with the purpose of maintaining and/or encouraging transit ridership (Fuhs & Obenberger, 2002; FHWA, 2017). It began as a dedicated bus-way until 1981, when the lane was opened to vehicles with 4+ occupancies due to chronic underutilization (Safirova, Gillingham, Harrington, & Nelson, 2003). Currently, there are over 150 lane kilometres of HOV highway facilities in Canada, specifically on urban highways in British Columbia, Ontario and Quebec (Transport Canada, 2010). In the United States, there were currently over 300 operating HOV facilities as of 2008 (Chang, Wiegmann, & Bilotto, 2008).

The effectiveness of HOV lanes in reducing congestion has been a subject of debate (Dachis, 2011; Dahlgren, 1998; Daganzo & Cassidy, 2008; Kwon & Varaiya, 2008). HOV lanes are argued to be underutilized during peak periods and over-utilized and congested at other times (Dachis, 2011). Thus, extensive research has gone into assessing the performance of HOV lanes.

Dahlgren (1998) argued that adding an HOV lane is only more effective than adding a general-purpose lane when the initial maximum delay is 35 minutes or more and that the proportion of HOVs is at least 20%. Kwon and Varaiya (2008) analyzed the effectiveness of the 1171 mile HOV system in California. They found that the benefits of HOV lanes were underwhelming;

81% of HOV lanes are underutilized during the afternoon peak hours (categorized by flow below 1400 vehicles per hour per lane). HOV lanes were found to reduce congestion only slightly when the general-purpose lanes were congested. However, it is important to note that this study looked at vehicle throughput instead of person throughput (Kwon & Varaiya, 2008).

An empirical study of HOV lanes in the San Francisco Bay Area in 2005 argued that "HOV lanes increase overall congestion." The authors then suggested this may be caused by merging and safety concerns due to the speed disparity between the GP and HOV lanes (Chen, Varaiya, & Kwon, 2005). A reassessment conducted in 2006 instead found no evidence indicating that HOV lanes worsened congestion, and on the other hand, were able to increase throughput at bottlenecks (Cassidy, Daganzo, Jang, & Chung, 2006). Further, Daganzo and Cassidy found that HOV lanes added less than 2% to vehicular delay and reduced person delay by 10% (Daganzo & Cassidy, 2008). Therefore, because not all HOV lane implementations may result in improved operating conditions, engineers and highway planners should carefully analyze the potential impacts of these changes.

HOV lanes may be a potential strategy for highways in Alberta since they have been established and operate in other Canadian and American jurisdictions; however studies are needed for analyzing their operational feasibility. I determine this through planning studies which follow the framework outlined in this thesis.

2.2.1 HOV Lane Planning Guidelines

HOV lanes have existed since 1969. There have been several State and National guidelines published pertaining to their operation and planning (Fuhs & Obenberger, 2002). These include general guidelines such as NCHRP 835 (National Cooperative Highway Research Program) (Fitzpatrick K. , et al., 2016), NCHRP 404 (Texas Transportation Institute, 1998), Freeway Management and Operations Handbook (FHWA, 2011), and the Guide for High-Occupancy Vehicle (HOV) Facilities (AASHTO, 2004). These guidelines are broad in scope, describing all elements related to HOV lane planning, design, and operations. For example, NCHRP 835 covers topics such as traffic control design, environmental impact studies, public involvements in planning and project financing (Fitzpatrick K. , et al., 2016). NCHRP 404 outlines methods for estimating demand and describes traffic analysis tools used for planning however the guidelines are 20 years old (Texas Transportation Institute, 1998).

Other region-specific guidelines have been created by California (Caltrans, 2003), Nevada (Jacobs Engineering, 2013), and Washington State (WSDOT, 2016). These guidelines include some of the topics introduced by the general guidelines as well as specific design properties such as lane widths and traffic control standards which conform to the State's existing design standards. These guidelines provide a foundation for HOV planning however they do not focus specifically on the modelling process. Although there are other guidelines dedicated to traffic analysis tools such as FHWA's traffic analysis toolbox, detailed guidelines specifically tailored for HOV lane planning were not found(Dowling, Holland, & Huang, 2002).

2.3 Ramp Metering

Ramp metering is a strategy that regulates vehicle rates entering a highway mainline facility from an on-ramp through use of a traffic signal on a ramp (FHWA, 2014). Vehicles can only proceed onto the highway mainline if they have a green light. The vehicle volumes entering the highway can be adjusted using different signal control strategies (FHWA, 2014). Since ramps facilitate additional vehicle demand entering a highway facility, these merging vehicles lead to traffic flow issues when vehicles cannot safely merge. This is caused by vehicles on a ramp travelling in a tight platoon from signalized intersections or when high ramp demand leads to the breakdown of traffic conditions from a facility operating near capacity (FHWA, 2014). Ramp metering improves highway performance by addressing these two issues through breaking up platoons, improving merging conditions, and through limiting ramp flows so that downstream volumes remain below capacity (Papageorgiou & Kotsialos, 2002).

Ramp metering has been implemented in various physical forms and by multiple control methods. Examples of these include a commonly used single-lane, and dual lane where one lane is for high-occupancy vehicles (passenger vehicles, and buses; motorcycles are also included) (FHWA, 2014). Ramp signals have been installed under different timing-control schemes ranging from pre-programmed timings to system-wide adaptive control that alters timings based on live traffic conditions. Fixed timing systems permit vehicles to enter at a specific rate for different times of day and are developed from historic highway demands (Papageorgiou & Kotsialos, 2002). Although this method is the simplest and most cost effective, it is not able to adapt to variable conditions and changing demands due to weather or incidents (Papageorgiou & Kotsialos, 2002). Traffic responsive ramp metering involves the use of sensors located on ramps and on highways in order to set an appropriate ramp frequency to maintain downstream traffic demands below capacity (Papageorgiou & Kotsialos, 2002). These may be isolated where a single ramp is timed independently of others or coordinated where multiple ramps are managed as a system (Zhang, et al., 2001).

Since the first manually controlled ramp metering signals were introduced in 1963 on the Eisenhower Expressway (Piotrowicz & Robinson, 1995), there have been numerous installations, control designs and studies examining the impacts of ramp metering on highway performance and safety (Meyer M. D., 1997; Arnold, 1998). These studies have found increases in average speeds, decreases in travel times and decreases in collisions on highways across The United States. The following study in particular demonstrates the impacts of ramp metering because of its unconventional study design (Cambridge Systematics, 2001). In this case, Minnesota legislature requested a shutdown of existing ramp metering signals, in order to investigate their performance and effectiveness. They were specifically interested in evaluating the impacts of ramp metering for a cost-benefit analysis. This was achieved by examining selected metrics before and after the ramp meters were turned off including travel times, travel time reliability, traffic volumes, number of crashes and transit vehicle performance. The resulting analysis revealed an overall 9% reduction in traffic volumes along the four selected interstate highways with a 14% decrease during specifically peak periods (Cambridge Systematics, 2001). It also found no changes in volumes on parallel arterials and an increase in peak period crashes by 26% (Cambridge Systematics, 2001). In total, the ramp-meters were calculated to provide a total of 25,121 hours of travel-time savings (Cambridge Systematics, 2001). The study design is quite unique as most other studies involve assessing conditions before ramp metering is installed.

Additionally, ramp metering may have other system-wide impacts that should be considered. Although the total person-delay of travellers on a roadway network may decrease with improvements on the main highway, ramps may face increased delays with excessive queues spilling back onto arterial streets (Kang & Gillen, 1999). These ramp delays may also contribute to travellers choosing to take parallel routes, diverting demand to other roadways or facilities (Papageorgiou & Kotsialos, 2002).

Ramp metering has been used extensively on urban highways in the United States and the province of Ontario while reporting improvements in traffic flow and safety. As guidelines for ramp meter planning and modelling are absent in Alberta, the subsequent chapters in this thesis outline the methodology for analyzing their potential operation.

2.3.1 Ramp Meter Planning Guidelines

There are many existing guidelines that cover the ramp metering planning process, some of which include Washington (WSDOT, 2016), Texas (Chaudhary & Messer, 2000), Nevada (Jacobs Engineering, 2013), Arizona (Simpson, Riley, Yasmin, Paul, & Warnick, 2013), and California (Caltrans, 2016). These guidelines include geometric requirements such as calculating lane lengths, detector and signal requirements, and signage design (Caltrans, 2016). However, many merely provide design standards and lack a guided process for modelling and designing ramp meter signal timings. The Federal Highway Administration (FHWA) has also produced comprehensive national guidelines for ramp meter planning that describes the decisions of the planning process in detail (Jacobson, Stribiak, Nelson, & Sallman, 2006; Mizuta, Roberts, Jacobsen, & Thompson, 2014).

2.4 Traffic Analysis Tools

This section outlines the different tools and methods that are used to plan, design and operate the congestion management strategies introduced in Section 2.3, on urban highway facilities. These tools require data collected from existing facilities to simulate and model traffic conditions at different levels of detail in order to assess how these strategies can impact facility performance measured using a variety of metrics important to the analyst and facility managers such as Alberta Transportation. This section categorizes analysis tools into four categories; sketch planning tools, discrete choice models, Highway Capacity Manual (HCM)-based tools, and traffic models. For each analysis tool group, this section discusses how they work, the data required to apply the tool, examples of how they assess congestion strategies, and their strengths and weaknesses.

Sketch planning tools provide high-level, order-of-magnitude estimates of the impacts of specific strategies. Often in the form of worksheets or spreadsheets, they are used early in the concept planning stages to prioritize specific strategies over others without the time and cost investment of more detailed analysis. Discrete choice models are developed from travel behaviour data, specifically mode choice surveys, in order to assess the probability of travellers choosing one mode (or other travel option) over another. Analytic and HCM tools rely on analytically and/or empirically-derived relationships between volume and roadway capacity to evaluate the impacts of geometric changes and other strategy implementations (such as ramp metering). Traffic models of highway corridors and networks rely on empirically or analytically-derived equations describing aggregate traffic flow to perform macroscopic segment-based analyses, and equations describing individual vehicle behaviours and interactions in microscopic analyses.

In order to assess the potential benefits of a given strategy or set of candidate strategies, these tools always involve establishing a baseline scenario to which strategies may be compared. This baseline scenario involves characterizing existing traffic conditions or travel patterns in the present and future if no strategies are applied to the facility (i.e. the infrastructure and controls remain "as is") (AASHTO, 2003). Strategies applied to a facility, corridor or network are assessed by how they impact performance metrics chosen to measure congestion: delays, speed reductions, travel times, LOS (level of service), environmental impacts and generalized costs and many more (Omrani & Salek, 2016).

There are several factors to consider when determining which tool group to use, as several different analysis tools may be appropriate for assessing a given strategy. Often, tools are chosen based on data availability and resources available to perform the analysis. When data required for a more detailed analysis is not available, planners may consider a less data-intensive analysis tool; however, they may also need to consider the limitations of the results from a more generalized (or high-level) approach (Alexiadis, Jeannotte, & Chandra, 2004). Detailed analyses tools such as microsimulation models involve skilled analysts, costly programs, and detailed data in order to develop, calibrate, validate, and obtain results from such models.

2.4.1 Sketch Planning Tools

Sketch planning tools play an important role in the selection and prioritization of strategies. These tools rely on results from previous studies to estimate the potential impacts of newly-considered strategies; therefore, results will not be as accurate or applicable as a model built specifically for a given facility. However, they require a significantly smaller time and cost investment. The benefit of these tools is that they require the least amount of training, time and data to assess the impacts of specific strategies. This allows decision makers to assess the benefits and costs early on in the planning process, which may lead to studies that are more detailed or the rejection of a strategy (Alexiadis, Jeannotte, & Chandra, 2004). These tools are in the format of visual basic excel worksheets (TRIMMS, TOPS-BC, etc.) and modules that operate as post-processing units to travel demand models (FITSEVAL, IDAS).

Some sketch planning tools use demand model output files such as network and transit links as well as origin-destination (OD) matrix files to calculate the impacts of different congestion management strategies (Xenelis, 2005). These programs estimate changes to the performance of a base case by applying factors gathered from national studies (FHWA, 2016). A benefit-cost analysis can also be performed based on approximated costs based on other examples of ITS strategies implemented. The outputs from the tool can then assess the impacts of specific strategies and how they affect delays, emissions and operational costs (FHWA, 2016).

Other sketch planning tools estimate the benefits and costs of TDM programs by calculating the impacts of strategies such as telecommuting, alternative work schedules and roadway pricing on travel times, emissions, noise and fuel consumption (Concas, 2012). These models use changes in commuting mode shares based on changes in transit fares, roadway pricing, travel times and parking prices. The amount to which these changes impact demand – reflected by the demand elasticities (of mode) with respect to different variables – is based on values gathered from existing literature (Concas & Winters, 2010), typically from studies of other facilities. This is called a meta-analysis as the approach is to apply evidence from other situations to the one at hand. An example includes a study estimating mode shifts due to TDM strategies in Washington State (Winters, Hillsman, Lee, & Georggi, 2010). This study ran the output mode split percentages through the sketch-planning tool, TRIMMS, to assess how these splits changed when different TDM programs were applied.

Sketch planning tools provide a relatively simple method of developing ball-park estimates of how strategies affect roadway performance and travel behaviour. They provide a platform to estimate impacts from many different strategies such as advanced traveller information systems (ATIS), HOV lanes, high-occupancy toll lanes (HOT), variable speed limits and ramp metering, while providing a relatively cost-effective method of assessing strategies with existing data. Due to their lower data requirements, they are comparatively simpler to run when considering other more complex tools and may be part of a preliminary assessment or high-level feasibility planning. However, the clear downside to sketch planning tools – and in particular, metaanalyses – is that the transferability of transportation models and analyses from one locale to another is often in question. Also, analysts should be aware of the limitations of forecasting tools, recognizing the uncertainty that accompanies the estimates produced (Flyvbjerg, Holm, & Buhl, 2005).

2.4.2 Demand-Side Models

These models are used to obtain estimates of demands under new strategies, which can be input to the operational models introduced in Section 2.4.3.

Traveller Surveys and Discrete Choice Models

Discrete choice models are used to model decisions that users make when faced with a set of choices (Train, 2009). These choices sets are mutually exclusive and finite. For example, two alternatives in a choice set may be commuting by transit or personal vehicle. The main principle is that each user (or decision maker) will make the choice that is most beneficial to them, thus maximizing their utility. A deterministic utility function is created for each alternative, containing variables (for example travel time, cost, comfort), an estimated coefficient for each variable, and estimated constants. Although these utility functions are meant to include all the most important factors that impact a user's utility for a given alternative, there inherently will be other factors or attributes unseen to the researcher. Thus, for each user the full utility of each choice is comprised of the deterministic utility plus a random utility term that accounts for this uncertainty. The most commonly used model specifications in transportation applications include logit, nested logit, and mixed logit models (Train, 2009). The utility for each choice is relative to those of the other alternatives in the choice set, and therefore do not have absolute values. This provides the advantage of estimating the elasticities of demand for different variables (travel time, travel cost, etc.), alternatively, how sensitive the probability of an alternative is for unit changes in each variable (Train, 2009).

Analysts require travel survey data in order to statistically estimate the parameters in a discrete choice model of travel choice (in other words, what factors should be included, the degree of their "effect" on the user's choice, and whether this effect is significant or not). This travel survey data will contain user characteristics (such as gender, age, and income), users' commuting characteristics, and sometimes, their choices in hypothetical scenarios designed by the analysts to answer specific research questions (Train, 2009). A survey asking for hypothetical choices is known as stated preference data (SP); for example, if TDM strategies were put in place, would their travel behaviour change? If respondents are asked about behaviours already done or choices already made, this is what is known as a revealed preference (RP) survey dataset (Bradley, Daly, Stopher, & Lee-Gosselin, 1997). A limitation of SP data is that users may not actually do what they say, but the obvious strength is that it can be used to estimate the potential outcomes of implementing a new strategy that does not currently exist (Patil, Burris, & Shaw, 2011). Model parameters are estimated using optimization methods such as the maximum likelihood (Train, 2009).

A study on California's State Route 91 used a mixed logit model with both SP and RP survey data to assess whether drivers would choose express toll lanes or GP lanes (Small, Winston, & Yan, 2005). One of the findings revealed that users highly value travel time and predictability. Studies also utilized a random parameter logit model on users' stated choices for a future HOV to HOT lane conversion on the Katy Freeway in Houston, Texas, finding that the survey design significantly affected the estimates of a user's value of time travel savings (Patil, Burris, & Shaw, 2011).

In Edmonton, an investigation of commuter behaviors was conducted by Zaman & Habib in response to proposed TDM measures (2010). This study used City of Edmonton workplace commuter survey data from 2007, which consisted of both RP and SP data, to assess mode choice behaviours and the potential impacts of workplace TDM programs. The data was used to estimate a nested logit mode choice model using the BIOGEME program (Bierlaire, 2003). The model results (demand elasticities) suggest that flexible work times and a compressed work-week schedule would have a significant impact on mode choices. The study also concluded that an increase in the drive-alone cost of commuting would not significantly impact drive-alone car use, suggesting that the respondents of the survey are not likely to change travel modes if the costs of driving alone increase.

Given the applications in Alberta and in other locations, discrete choice models are a viable option for Alberta Transportation to evaluate TDM strategies. This, however, would require obtaining a survey dataset that provides an adequate and unbiased sample of the region's travellers, with questions (and responses) specifically tailored to the congestion management strategy under consideration (SP), and also covering travellers' current behavioural responses (RP).

Regional Travel Demand Models

Regional travel demand models (RTDMs) are macroscopic tools used to forecast travel behavior, specifically the number of trips, as well as route, mode and destination choices. They incorporate behavioral data from aggregated household travel surveys and model travel demand changes due to policy changes. Due to their macroscopic nature, they are often used in conjunction with simulation models. Alberta Transportation currently runs 3 RTDMs (for Edmonton, Calgary and Fort McMurray) and is developing a province-wide model.

2.4.3 Operational Models

These tools are used to model the operational outcomes of demand and capacity-enhancement (i.e. congestion management strategy application) interactions.

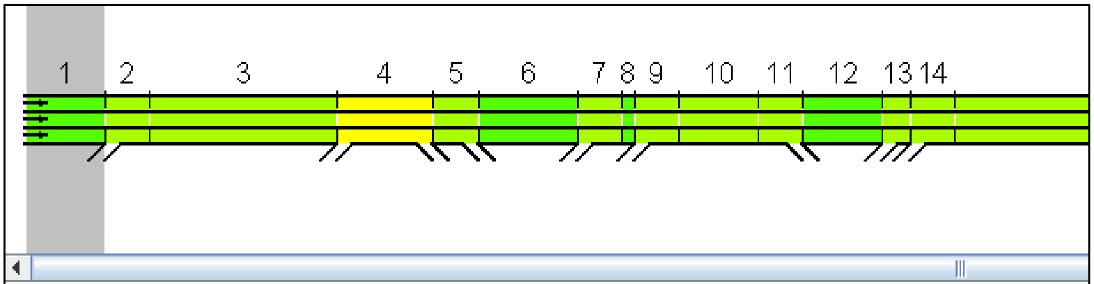
Analytical Models

Analytical models determine operational characteristics and performance based on close-form equations developed from real-world observations and studies. The most prevalent of these tools is the Highway Capacity Manual (HCM) methodology developed by the Transportation Research Board (TRB), which provides methods by which to determine the capacities and performances of various transportation facilities (Transportation Research Board, 2010). There are also computer applications such as HCS and FREEVAL that apply the HCM methodology (Trask, Aghdashi, Schroeder, & Rouphail, 2015). HCM is a highly macroscopic application, calculating LOS, delays and speeds on a segment-by-segment basis in 15-minute and 1-hour analysis periods (Jeannotte, Chandra, Alexiadis, & Skabardonis, 2004). Since these methods evaluate average conditions within a given time period (using inputs that reflect averages of that time period in question), they are not able to assess the impacts of operational changes to a roadway dynamically. Due to this limitation, this strategy cannot quantify the formation or dissipation of congestion. In addition, since HCM calculates conditions on a segment-by-segment basis for a roadway, it is not appropriate for calculating network impacts of roadway changes (Jeannotte, Chandra, Alexiadis, & Skabardonis, 2004).

Of the strategies that are introduced, HCM-based tools can assess ramp metering, operational characteristics of managed lanes, traveller information systems and to a very limited extent, TDM strategies (Transportation Research Board, 2010; Rouphail, Schroeder, & Eads, 2011). Managed lanes facilities are analyzed as a separate lane group from GP lanes that interact with each other (Transportation Research Board, 2010). Here, two separate analyses are conducted with data from each segment of the managed lanes and the GP lanes groups. This requires managed-lane and GP lane demands, and geometric characteristics such as lane widths, segment lengths, and the buffer type separating the facilities. The impacts of ramp metering are assessed by limiting the on-ramp capacity below a target flow rate, which is representative of a fixed-time control strategy. The impacts of other control strategies cannot be tested with HCM but with simulation software. Such analytical tools can also be used to assess TDM strategies; however, these methods will simply apply a “demand adjustment factor” to represent the demand effects of TDM strategies and in turn, the general segment-level operational characteristics (Trask, Aghdashi, Schroeder, & Rouphail, 2015). From the HCM 2010 edition to the HCM Sixth Edition (2016), several section were updated based on research since 2010, chapters 35-38 outlining TDM, travel time reliability and managed lanes (Wisconsin Section ITE, 2016). The HCM-based FREEVAL software was also updated based on these chapters.

The data is used to calculate the capacities and the demand-to-capacity ratios per segment and analysis period. Then, space mean speeds are calculated as a service measure. Lastly, Level-of-Service (LOS) values are assigned by analysis period and segment and may be calculated over the length of the facility by a weighted average, reflecting the average performance of the entire facility (Transportation Research Board, 2010). This tool is useful due to its ease of use and implementation, allowing for an efficient and relatively quick analysis to be performed if data is available and analysis criteria are met.

FREEVAL has been used to assess the impacts of ramp metering along the I-80 in Nebraska and I-235 in Iowa (Sharma, Wang, & Khattak, 2016; HRGreen; Cambridge Systematics, 2014). The Java-based spreadsheet software accepts the same inputs as a traditional HCM analysis as seen in Figure 3.



Segment	Seg. 1	Seg. 2	Seg. 3	Seg. 4	Seg. 5
General Purpose Segment D...	*	*	*	*	*
General Purpose Segment N...	50th Ave	50th Av...		Sparro...	Airport ...
General Purpose Segment T...	Basic	On Ramp	Basic	Weaving	Off Ramp
Segment Length (ft)	2,640	1,500	6,266	3,216	1,540
Terrain	Level	Level	Level	Level	Level
Truck-PC Equivalent (ET)	2.00	2.00	2.00	2.00	2.00
# of Lanes: Mainline	3	3	3	3	3
Free Flow Speed (mph)	68	68	68	68	68
Mainline Dem. (vph)	2,237	3456	3456	4107	3669
Mainline Single Unit Truck a...	4.34	4.31	4.31	4.55	5.01
Mainline Tractor Trailer (%)	15.40	10.55	10.55	9.58	10.57
Seed Capacity Adj. Fac.	1.00	1.00	1.00	1.00	1.00
Seed Entering Dem. Adj. Fac.	1.00	1.00	1.00	1.00	1.00
Seed Exit Dem. Adj. Fac.	1.00	1.00	1.00	1.00	1.00
Seed Free Flow Speed Adj. ...	1.00	1.00	1.00	1.00	1.00
Seed Driver Pop. Capacity ...	1.00	1.00	1.00	1.00	1.00
Seed Driver Pop. Free Flow ...	1.00	1.00	1.00	1.00	1.00

Figure 3 FREEVAL data entry screen (Source FREEVAL).

The HCM 2010 analysis method has limitations in its usefulness for assessing managed lane treatments. Firstly, this analysis provides only a high-level operational analysis. It does not estimate the influence of TDM and traveller information systems strategies on travel behaviour and the resulting demand for the lane groups; rather, these are required inputs (that must be obtained from other sources external to the tool) (Transportation Research Board, 2010; Trask, Aghdashi, Schroeder, & Rouphail, 2015). This allows for existing conditions and facilities to be assessed if managed-lane demands can be estimated from vehicle occupancy studies or as outputs from a regional demand model. Secondly, this method does not assess how different managed lane entrance and exit configurations impact highway performance, which are left to simulation tools (Transportation Research Board, 2010). Lastly, research has found the FREEVAL software limited for evaluating oversaturated weaving conditions, recommending the use of simulation software instead due to the lack of detail and representation of endogenous parameters (Jolovic & Stevanovic, 2013).

Traffic Simulation Models

Traffic simulation models represent the movement of vehicles at varying levels of detail. They are generally classified by the detail of analysis and data requirements, from macroscopic models to mesoscopic and microscopic simulation models. Macroscopic models represent roadway performance on an aggregated segment-by-segment level while relying on analytic and deterministic relationships between traffic flow, speed and density (Jeannotte, Chandra, Alexiadis, & Skabardonis, 2004). Microscopic models analyze the movement of individual vehicles based on equations governing vehicle interactions and behaviours: car following, lane changing, and gap acceptance (Stirzaker & Dia, 2007). These principals allow detailed operational analyses of how physical changes to the roadway network affect the formation, duration and dissipation of vehicle queues. Mesoscopic models (Hoogendoorn & Bovy, 2001) lie somewhere between macroscopic and microscopic models. Through model development, many of the commercially available simulation tools are able to represent simple isolated strategies such as ramp metering, managed lanes and traveller information systems natively without requiring additional programming. Complex strategies that coordinate multiple ITS systems have been modelled but they require significantly more coding and data to collectively optimize a performance metric, such as minimizing travel times along a corridor while operating variable speed limits and ramp meters in unison.

Macroscopic Traffic Simulation Models

Macroscopic models assess traffic conditions at an aggregate level by representing average vehicles densities and speeds for each link, in small time increments. These links represent roadway segments of uniform characteristics, which are demarcated by interchanges, ramps, or other changes in geometry. The aggregate flows of vehicles are similar to the flow of a fluid that is continuous and uniform. This simplification allows for the characteristics of flow to be represented by partial differential equations (Hoogendoorn & Bovy, 2001). These models are able to test how some of the aforementioned operational strategies such as variable speed limits, ramp metering, lane closures, and traveller information systems affect performance criteria such as travel times, queue lengths, fuel consumed and distances travelled (Papageourgiou, Papamichail, Messmer, & Wang, 2010).

Macroscopic models require less detailed data compared to microscopic simulations and do not need as much computational power to run, since individual vehicle movements (such as lane-changing and car-following) are not represented (Papageourgiou, Papamichail, Messmer, & Wang, 2010). This allows a larger scale of analysis to be conducted on a regional or network level. This is useful in assessing the feasibility of a strategy, on a network where roadway geometric changes are not the dominant source of congestion.

These models have been used to assess the impacts of ITS and managed lane strategies on traffic flow performance. They rely on basic variables such as travel time and cost to model driver choice. Simultaneously implemented strategies, such as ramp metering and variable speed limits, have been modelled to optimize algorithms based on highway and ramp demands. These models test control systems that assign speed limits or ramp metering rates, in order to optimize performance criteria such as minimizing travel times or maximizing vehicle-throughput. (Alessandri, Di Febbraro, Ferrara, & Punta, 1998; Hegyi, De Schutter, & Hellendoorn, 2005)Some control strategies such as ALINEA and other well-established ramp metering algorithms are included in macroscopic modelling software (Papageourgiou, Papamichail, Messmer, & Wang, 2010). Researchers have also represented managed lanes by coding the lanes as parallel links between nodes. Different access types were also modelled, representing managed lanes that have continuous access and those with access at specific entrance and exit points (Wright, Horowitz, & Kurzhanskiy, 2016).

Microscopic traffic models can provide detailed analyses of traffic conditions as they model individual vehicle behaviour. These models are dynamic in that roadway conditions can change continuously throughout a simulation, and stochastic in that vehicles are randomly generated and randomly assigned driver behaviour characteristics (distributed randomly) (Dowling, Holland, & Huang, 2002). Vehicle movements are then calculated based on vehicle characteristics and dimensions, the physics of motion for individual vehicles, and driver behaviours and interactions. The level of detail required to build, calibrate and validate a high-quality microscopic model requires significant computing resources, data, and time. This allows for highly customized models, with heterogeneous driver characteristics, unique roadway geometry, and custom ITS strategies (usually implemented through APIs – advanced programming interfaces). There are many commercially available microsimulation software packages, including AIMSUN, CORSIM, Paramics, Simtraffic, Transmodeler, VISSIM, WATSIM, and more (Dowling, Holland, & Huang, 2002).

Microscopic Traffic Simulation Models

Microscopic models, since they can evaluate detailed queue formation and dissipation, are able to assess many types of complex configurations and operational strategies, as well as multiple strategies in tandem. These include coordinated ramp metering systems, managed lanes, variable speed limits and other ITS installations. The impacts of the different strategies are measured using operational performance metrics, including total vehicle-hours travelled, travel times, delays, and speeds on highways, ramps and managed lanes (Chu, Liu, Recker, & Zhang, 2004).

The I-680 in California was modelled in PARAMICS to assess the impacts of ramp metering, an additional HOV lane and an additional mixed-use lane (Gardes, May, Dahlgren, & Skarbardonis, 2002; Gardes, Kim, & May, 2003). After developing the corridor model, ramp metering was tested with and without queue detectors. A mixed-use lane was tested in addition to an HOV lane with varying HOV demand. Against a base-case of doing nothing, the study was able to compare the average mainline highway speeds that resulted from the different strategies implemented. The authors found that ramp metering without queue detectors provided a greater improvement in average speeds compared to an HOV lane and demand of 20%. PARAMICS software was also used to test different ramp-metering algorithms and how they affected ramp and mainline performance (Chu, Liu, Recker, & Zhang, 2004). In order to simulate the hardware, a ramp-metering controller and loop data aggregator were programmed using an API. Algorithms ALINEA, BOTTLENECK and ZONE, all of which control ramp meter timings, were each evaluated based on how they impacted the total VHT (Vehicle-Hours Travelled), AMTT (Average Mainline Travel Time) and TOD (Total On-ramp Delay). Another study using both FREQ (a macroscopic model) and VISSIM investigated the impacts of HOV and transit priority on passenger-hours of delay on the I-290 corridor in Illinois (Rodriquez, Kawamura, & Samimi, 2008). The authors tested a base case of no ramp metering against ramp metering, metering with HOV priority, and metering with HOV/Bus priority. When compared to a projected 2030 base case of no ramp metering, passenger-hours of travel was found to be reduced by 2-15%.

The combination of managed lanes with truck restrictions on the I-95 in South Florida has been simulated to observe the impacts of each individual strategy and both in unison (Siuhi, 2006).

The study found that HOV lanes provided improved travel times for vehicles able to use those lanes, due to the restriction on lane usage. The study also found that truck restrictions led to delays at merging areas due to limited gaps in the traffic flow. This study required the use of microsimulation since the strategy changed restrictions for various lanes, which would not be able to be modelled by a more aggregate tool.

Detailed guidelines for how to use traffic microsimulation software in transportation analyses can be found in the FHWA report: Guidelines for Applying Traffic Microsimulation Software (Dowling, Skabardonis, & Alexiadis, 2004).

2.4.4 Conclusions

Through this chapter, I provide a background on analysis tools used to plan highway improvement strategies, setting a foundation for Chapters 3 and 4. The various elements of the planning framework are presented, providing a background on ramp metering and HOV lanes, as well as the tools commonly employed to assess their impacts on a transportation system. Through this review of guidelines and studies, I find that the planning literature was generally broad in scope, with insufficient detail for assessing data needs and planning individual projects. Studies of individual facilities on the other hand, are narrowly focused and specific. Since there is a lack of available studies that chronicle the development of a project from conception to construction, this thesis aims to develop this framework for highways in Alberta.

3. PLANNING FOR HOV LANES: CASE STUDY OF HWY 2

The following section outlines an HOV lane planning framework that incorporates travel demand and simulation models into the highway planning process in Alberta. Since there are no HOV facilities in Alberta and HOV lane planning is absent from Alberta's highway engineering guidelines, this chapter presents a framework guiding how and when technical studies with differing levels of detail may be conducted. In the early stages of the planning process, studies focus on examining the feasibility of prospective corridors, often using minimal resources and data. As the location is finalized and implementation is imminent, detailed studies assess opening-day and future-design operational performance, aiding the geometric design and vehicle restrictions for the facility. In addition to applying these studies to the planning process, this chapter outlines how they may be applied to Hwy 2 south of Edmonton, focusing on data needs and specific issues pertaining to this corridor.

Section 3.1 first provides background on the HOV lanes in Alberta and the location or the case study, Highway 2. A table summarizes the main stages of HOV-lane planning, which are largely distinguished by level of analysis detail in Section 3.2. The subsequent three sections explain the table, and a closing discussion examines the issues that arose through the analysis.

3.1 Hwy 2 Background and HOV Planning in Alberta

Highway 2 is a divided and grade-separated facility connecting the Edmonton and Calgary regions, under management and jurisdiction of Alberta Transportation. It is part of the CANAMEX trade corridor, which was established under North American Free Trade Agreement (NAFTA) and is important to the international transportation of goods (Alberta Transportation, 2016). This specific segment is a grade-separated urban highway that serves as the primary north-south route between Edmonton and Leduc, providing access for those living and working in the City of Edmonton to Edmonton International Airport and the Nisku industrial park. This section of Hwy 2 is a divided 6-lane highway with a posted speed limit of 110 km/h and includes several partial-clover and diamond interchanges. This segment experiences some of the highest annual average daily traffic (AADT) counts in the province with an average of 89,360 vehicles/day (Cornerstone Solutions Inc., 2016); it also carries a substantial proportion of commercial trucks (Alberta Transportation, 2016). Given the high traffic volumes, high-level area studies have examined congestion management strategies along this corridor; however, no substantial analysis on HOV-lanes has been conducted to our knowledge (AEDA, 2013).

Currently, Alberta does not have High-Occupancy Vehicle (HOV) lanes on its highways, however, the province is moving towards allowing their implementation. In 2013, Bill 32 was passed by the legislature, allowing HOV and other types of managed lanes such as reversible lanes and bus-lanes. This bill restricts "the use of specified traffic lanes to vehicles carrying a prescribed number of passengers" or specific "classes of vehicles" (Province of Alberta, 2013). The discussion surrounding the bill was generally supportive however several issues were identified. Firstly, members were concerned that HOV lanes should not take away existing lanes, and that most of the provincial highways would not be eligible without adding additional lanes (Province of Alberta, November 18, 2013). Secondly, members questioned the safety of these lanes and if drivers are able to learn and adapt to the new system (Province of Alberta, November 18, 2013). They also questioned the operational efficiency, requesting studies to assess if the lanes would be sufficiently utilized (Province of Alberta, November 26, 2013). The steps taken in Bill 32 towards allowing these lanes reveal Alberta's stance on HOV lanes, providing a background for this chapter which delves into the planning process.

Recent reports reflect an interest and a political will for further study and planning. In 2013, a report by the Alberta Economic Development Authority (AEDA) recommended HOV lanes as a solution to rising congestion in economic hubs (AEDA, 2013). The Capital Region Board, representing the City of Edmonton and surrounding municipalities and counties, then commissioned a report to explore the potential of HOV lanes (AECOM, 2016). This report, conducted by AECOM, included interviews with stakeholders, an extensive review of HOV lane geometries used worldwide, and a qualitative assessment of Highways around the capital region. In measuring congestion, the report observed segments from Google Maps during peak-hour commutes which coloured congestion orange or red based on severity (AECOM, 2016). These resources reflect a political willingness to proceed with HOV planning, however there has been little technical study as modelling of HOV vehicles or commuter decisions are absent.

3.2 HOV Analysis Table

The following section contains the three aforementioned analysis levels in a table structure. The main purpose of presenting this information in a table is to clearly and distinctly present the details of each analysis level while also showing how each level compares with the other two. A table also provides the ability to compare and contrast elements of an analysis along its columns (Maier, 2017). Readers can understand a specific aspect of the process without reading through the entire description. For example, this allows an analyst to compare data required by the different analysis levels or allows an analyst to identify commonly used simulation programs at a specific analysis level. Through this format, this document can aid transportation engineers and planners in the development of project terms of reference (TOR) as well as providing a reference to data needs and analysis components.

The table was constructed from examining the various design and planning references cited in this thesis, as well as project reports from HOV studies which were introduced in the literature review. The table also identifies the data available to Alberta Transportation; it also highlights data gaps, which are discussed at each level of analysis.

The table includes the following column headers:

- **Level of Analysis:** Rows include: High-level (sketch planning), Mid-level (analytic models and macrosimulation), and Detailed operational analyses (microsimulation)
- **Details:** Short description of the tools at the subject level of analysis.
- **Tools Included:** listing of a sample of the more predominant tools identified in the literature.
- **Application [to candidate facility]:** this column provides a description of the general purpose of the analysis, and its use, on the particular urban highway facility in question. Provides some further details on about the strategy itself as applied to the subject facility.
- **Model Inputs:** These columns list the data required to perform the analysis at the candidate level of analysis, categorized as **Base Case (Current Conditions)**, **Future Case (Forecasted/Design Year) Do Nothing**, and **Future Case (Forecasted/Design Year) with Strategy**. These columns list the geometric and operational data required, in addition to the source of demand estimates (simple growth factor applications, targeted traveller survey and models, and/or RTDM output results)
- **Sample Outputs / MOEs (Measures of Effectiveness):** Common results/outputs used for analysis. The outputs from the different scenarios listed above (Base Case, Future Do Nothing,

Future Design Year) should be compared against one another. It is to be noted that when using stochastic tools (i.e. microsimulation), results should be obtained for many model runs, and descriptive statistics should be generated. In addition, statistical differences tests should be applied to evaluate whether changes between scenarios are statistically significant.

- **Evaluating:** More details on how results may be used by analysts.
- **Previous Applications:** Brief listing of examples of other analyses found in the literature.

Table 2 HOV Lane Assessment for Hwy 2 (QEII, between Edmonton and Leduc)

Level of Analysis	Details	Tools Include	Application	Model Inputs*			Sample Outputs, MOEs**	Evaluation	Previous Applications
				Base Case (Current Conditions)	Future Case (Design Year) Do Nothing	Future Case (Design Year) with Strategy			
High-Level	· A high-level HOV-lane study examines whether sufficient HOV volumes currently exist on a facility, by gathering vehicle occupancy counts and vehicle classification counts · This study also examines existing highway performance in addition to a preliminary screening of geometric requirements	N/A	· This study would examine vehicle occupancy and classification counts for vehicles travelling on Hwy 2 · This assessment does not include modelling and only examines if existing conditions meet recommended thresholds	· *Traffic counts/volumes on mainline and ramps (peak periods and others) from turning count surveys (with vehicle classifications) collected during a similar time period* · *Vehicle occupancy counts; vehicle classification counts* · Geometric data including right-of-way and pavement widths	· *Projected (peak-period) counts, including vehicle classifications and occupancies, estimated from simple growth factors (set as some % of current volumes)*	· *Projected (peak-period) counts, including vehicle classifications and occupancies, estimated from simple growth factors (set as some % of current volumes)* · The above would provide an estimate of volumes that would be eligible for HOV lane use	· Counts of HOV vehicles and preliminary estimates of design-year demands	· This study examines if HOV lanes have sufficient volumes for an opening-day scenario, and therefore, what type of HOV lane (i.e. usage restrictions) may be warranted (if any at all).	· Guidelines for Implementing Managed Lanes (Fitzpatrick K. , et al., 2016) · HOV Systems Manual (Texas Transportation Institute, 1998) · Predicting HOV Lane Demand (Dowling, Billheimer, Alexiadis, & May, 1996)

Mid-Level	· These tools assess operational performance using empirically-derived equations
	· Tools are macroscopic; they calculate LOS, delays & speeds on segment level
	· Operations analyses of facilities with managed/HOV lanes are based on HCM 6e methodology; HOV lanes are treated as a lane-group
		FREEVAL 2015e, HCM, HCS	· Studies on Hwy 2 should examine operational performance of an HOV lane compared to GP lanes, at differing HOV lane and GP lane demand levels, as well as where lanes should start and end (in each direction)
			· Travel behaviour surveys (by residents and employees) would be helpful to understand demand characteristics
			· Assess different lane usage policies (i.e. eligibility)
				· *Traffic counts/volumes on mainline and ramps (peak periods and others) from turning count surveys (with vehicle classifications) collected during a similar time period*
				· *Vehicle occupancy counts; vehicle classification counts*
				· Detailed geometric data (including link lengths, no. of lanes (ramp, mainline), lane widths, lateral clearance, ramp accel/decel lengths, etc. (everything required for HCM))
				
				· *Additional data and parameters*
					· *Projected (peak & other periods) counts, from one or more of:*
					  · *Outputs from RTDM (demand volumes)*
					  · *Using simple growth factors on current demand volumes (taken from RTDM or counts)*
					
					· Geometric & control data (same as base case)
						· *Projected (peak & other periods) counts, from one or more of:*
						  · *Outputs from RTDM (demand volumes) where HOVs are included in the RTDM as a link restricted to HOVs*
						  · *Using simple growth factors on current demand volumes (taken from RTDM or counts)*
						· The above would provide an estimate of volumes that would be eligible for HOV lane use
						
						· Geometric & control data for strategy implementation scenarios
							· Speeds
							· Densities
							· V/C ratio
							· LOS
							· Travel times
							· VHT
							VHD
							· Passenger throughput
							· PHT (passenger-hours travelled)
							· PHD (passenger-hours of delay)
								· Change in outputs / MOEs between future do nothing case and various future HOV cases
								· Comparisons of performance for vehicles in GP lanes versus HOV lane
									· Developing the HOV Lanes Analysis Method in HCM (Schroeder, Aghdashi, Rouphail, Liu, & Wang, 2012) (Kittelson & Associates, Inc./Dowling, 2012) (Wilson & Morris, 2012)

Table 2 Cont'd

Level of Analysis	Details	Tools Include	Application	Model Inputs*			Sample Outputs, MOEs**	Evaluation	Previous Applications
				Base Case (Current Conditions)	Future Case (Design Year) Do Nothing	Future Case (Design Year) with Strategy			
Detailed Analysis	· Microsimulation models represent individual vehicles; they can model lane-changing operations between HOV and GP lanes, and potential performance impacts · Any combinations of strategies may be studied, including ramp meter HOV/transit bypass lanes and dedicated facilities directly into HOV lanes · At this level of modelling detail, good demand estimates are important, and may come from updated RTDM runs and travel surveys (and subsequent models)	Discrete Choice Models, AIMSUN, CORSIM, Paramics, Simtraffic, Transmodeler, VISSIM, WATSIM and others	· Should examine specific design elements such as HOV-lane entrance/exit points, HOV-bypass lanes on ramps, HOV-lane separation treatments, etc. Travel behaviour surveys (by residents and employees) would be helpful to understand demand characteristics · This may include residences in Leduc and workplaces in Nisku · Assess different lane usage policies (i.e. eligibility) · The operational outcomes of many different configurations and demand scenarios can be explored, e.g. · HOV/Transit bypass lanes on ramps with metering control, different HOV-lane alignments (concurrent lanes, physically separated lanes, lane access/egress details, lane beginning & end locations, etc.)	· *<u>Traffic counts/volumes on mainline and ramps (peak periods and others) from turning count surveys (with vehicle classifications) collected during a similar time period</u>* · *<u>Vehicle occupancy counts; vehicle classification counts</u>* · Detailed geometric data (including link lengths, no. of lanes (ramp, mainline), lane widths, lateral clearance, ramp accel/decel lengths, etc. (everything required for HCM)) · *<u>Travel time data from floating car runs</u>* *<u>Point speed data from radar or loop detectors</u>* · *<u>Additional data and parameters such as location-specific model calibration values</u>*	· *<u>Projected (peak & other periods) counts, from one or more of:</u>* · *<u>Outputs from RTDM (demand volumes)</u>* · *<u>Using simple growth factors on current demand volumes (taken from RTDM or counts)</u>* · Geometric & control data (same as base case)	· *<u>Projected (peak & other periods) counts, from one or more of:</u>* · *<u>Outputs from RTDM (demand volumes) where HOVs are included in the RTDM as a link restricted to HOVs</u>* · *<u>Using simple growth factors on current demand volumes (taken from RTDM or counts)</u>* · *<u>Information from travel surveys & subsequent discrete choice modelling efforts</u>* · The above would provide an estimate of volumes that would be eligible for HOV lane use · Geometric & control data for strategy implementation scenarios	· Animations from simulation · Various operational characteristics, including all those listed previously, in addition to more detailed results such as creation of weaving sections (due to placement of HOV lane access/egress, whether access to the lane will be controlled or open, etc.), bottleneck locations, etc.) · Performance measures for GP lanes versus HOV lanes; e.g. travel time, average operating speeds · Temporally-based operational outputs · Distributions and histograms of all outputs (because these tools are inherently stochastic) · Many highly detailed and vehicle-level outputs	· Change in outputs / MOEs between future do nothing case and various future HOV cases · Comparisons of performance for vehicles in GP lanes versus HOV lane · Objective at this level of analysis is to investigate the detailed operational outcomes of different HOV lane configurations (listed in previous columns) and usage restrictions, and how to mitigate any unfavourable conditions that may arise · Public perceptions (through opinion surveys, which are warranted at this level of analysis detail; may be gathered in conjunction with travel behaviour survey) · Animations from simulation runs are helpful for non-technical policy makers and the general public for visualizing operations · Due to stochastic nature of these tools, all results can be described and analyzed using statistical methods	· Florida I95 (VISSIM) (Siuhi, 2006) · California I680 (with 1st-order macroscopic network model) (Wright, Horowitz, & Kurzhanskiy, 2016) · California I-405 (Paramics) (Zhang, et al., 2001) · California I-210 (VISSIM) (Gomes, May, & Horowitz, 2004)

* Data/Inputs required but not currently available, shown in *<u>italic and underlined</u>*
** For each segment and time period analyzed

In Sections 3.3, 3.4 and 3.5, I describe the key components of studies that examine the operational feasibility of managed lanes at each of the levels of analysis (each represented by a row of the table. Each section also presents a case-study application of HOV-lanes for Hwy 2 which was introduced in Section 3.1. This section focuses specifically on the analyses tools, the methods introduced in Chapter 2, which include operational and travel behavior/demand analysis tools, in order to estimate the performance of the facility on opening day and on future dates. For HOV lane planning and design, these traffic analyses estimate the potential impacts of HOV lanes using performance measures such as average travel times, person and vehicle throughput, and person and vehicle delays. These performance measures are generated from modeling analysis, and are used to compare future strategy scenarios (2+ HOV lanes, 3+ HOV lanes, etc.) against a do-nothing case. These measures can then be input into benefit-cost analyses to compare costs of the alternatives.

3.3 High-level Studies

Using a high-level study, engineers and planners can (relatively) quickly determine whether further analyses are warranted, using existing or easily obtained data. Also known as introductory or sketch-level analyses, the objective of a high-level study is to make high level choices between project alternatives, and often takes one to two months to complete (Fitzpatrick K. , et al., 2016). In Alberta Transportation's Highway Engineering Process, this would occur during the long-range planning phase for inclusion in the 3-year program (which was introduced in section 2.1) (Alberta Transportation, 2011).

In Table 2, the high-level study parameters described in the first row focuses on determining the operational feasibility of HOV lanes. This involves comparing existing and projected HOV-lane demands to various established thresholds and warrants. Operational feasibility focuses on how an HOV lane impacts traffic flow; this is distinct from other aspects of HOV planning that may also be examined at this stage, including public acceptance and institutional feasibility. High-level operational feasibility analysis may require counts of various vehicle classifications including commercial vehicles, single-occupant vehicles (SOVs), double occupant vehicles (HOV2), vehicles with 3 or more occupants (HOV3+), taxis, electric vehicles and transit (including ridership). Turning count surveys, which involve collecting traffic volumes from the field, provide this data and growth factors are applied to predict future case volumes. As this is a high-level analysis, growth factors applied to historical counts to estimate future volumes may be highly speculative in estimating HOV demand, as it does not account for potential shifts in demand that can be estimated with additional data and more complex models.

Error! Reference source not found.3 presents the performance criteria and demand thresholds which indicate that consideration of managed lanes is warranted, minimum performance thresholds expected from a managed lane installation, and geometric design requirements, as found in the existing literature (Fitzpatrick K. , et al., 2016; WSDOT, 2016; PB Americas, Inc., 2010; CALTRANS, 2009; Sisiopiku & Alnazer, 2012). The Alberta Highway Geometric Design Guide currently does not contain any criteria regarding managed lanes (Alberta Transportation, 1999; Alberta Transportation, 2003).

Table 3 Various Criteria for HOV Lanes

Criteria	Thresholds
Performance thresholds*	· LOS D or worse "for a significant period" (Fitzpatrick K. , et al., 2016) · LOS E or worse for 2 consecutive hours in the peak direction of travel (1700-2000 vphpl) or average speeds <30mph (WSDOT, 2016) · V/C Ratio of >1.0 and average speeds <30 mph at present and for 20-year design forecast (PB Americas, Inc., 2010) · LOS E or F for 2 consecutive hours in the peak direction, AM and PM peak periods existing in >60% of the eligible corridor (Sisiopiku & Alnazer, 2012)
Vehicle demand thresholds*	· 400-500 vphpl on concurrent lanes and 600-800 vphpl on separated facilities (WSDOT, 2016) · 400-800 vphpl on concurrent facilities (Sisiopiku & Alnazer, 2012; Texas Transportation Institute, 1998) · 800-1000 vphpl (Texas Transportation Institute, 1998) · 600 pce/hour (PB Americas, Inc., 2010) · Greater person-movement capacity than adjacent GP lanes (person/ln/hr) - from regional model forecasts (PB Americas, Inc., 2010)
Minimum expected performance	· Travel time benefit of 5 minutes or more during peak periods (WSDOT, 2016) · Trip distances 5 miles or more (Fitzpatrick K. , et al., 2016) · Operate at LOS C or better for HOT lanes (CALTRANS, 2009) · Time savings of 0.5 min/mile during peak (Fitzpatrick K. , et al., 2016) · A "minimum average operating speed of 45mph (72km/h) for 90 percent of the time over a 180-day monitoring period during morning and evening weekday peak hours" when speed limits are >50mph (80km/h) for HOV lanes desiring to expand vehicle eligibility to HOT lanes (FHWA, 2016)
Physical	· Median width – 26ft and lane width per direction 12ft (Sisiopiku & Alnazer,

requirements	2012) · Adding a lane on the shoulder – 16ft per direction (PB Americas, Inc., 2010)

* *Warranting consideration of strategy*

3.3.1 Performance Thresholds

Table 2 summarizes thresholds gathered from HOV and managed lane guidelines and studies. These include performance thresholds, vehicle demand thresholds, minimum expected performance, and physical requirements that the guidelines highlight as criteria that should be identified early in an HOV sketch planning study. The first row, performance thresholds, refers to the performance of the existing facility during peak hour conditions. With LOS values, average speeds, and V/C ratios, these performance thresholds reflect a recurrent level of congestion on the roadway that may warrant HOV lanes (Texas Transportation Institute, 1998). These values may be obtained from existing operational studies. Should they be absent, Chapter 12 of the Highway Capacity Manual (HCM) outlines a methodology for determining LOS, estimating free-flow speeds (FFS), and estimating lane density (Transportation Research Board, 2016). Guidelines identify recurrent congestion as a prerequisite for HOV lanes in order to justify a highway improvement project as well as to provide an incentive for HOV lane use (Fitzpatrick K. , et al., 2016).

3.3.2 Vehicle Demand Thresholds

Minimum recommended demands for HOV-lane operations exist as a lack of demand leads to negative public perception, or “empty-lane syndrome” (Chang, Wiegmann, Smith, & Bilotto, 2008). The range of minimum recommended vehicles per hour per lane (vphpl) varies significantly and there is little consensus on what this minimum demand should be. These recommendations also do not specify whether this demand should be measured only during peak hours or should be a daily average. Therefore, HOV demand projections that are near the adopted/benchmark minimum demand thresholds warrant further examination while those that fall below may still grow beyond minimums to warrant HOV lanes.

3.3.3 Minimum Expected Performance

There also exist criteria for the minimum travel-time benefit that should be experienced by HOV lane users. Insufficient HOV lane travel-time benefits may result from HOV lanes with demands high enough to result in poor Level of Service (LOS), potentially providing little benefit when compared with travel in the GP lanes, or from HOV facilities which are too short to provide adequate travel-time benefits. Since estimating travel time benefits requires some level of modelling, the measures are more applicable in mid-level and detailed analyses. For a high-level study, the analysis should simply identify the potential length of the proposed HOV-lane.

3.3.4 Geometric Requirements

A brief geometric assessment of the existing right-of-way at this level of study evaluates the physical requirements for an additional lane. This includes examining the corridor dimensions and determining if land acquisitions are necessary. If there is insufficient space for constructing a lane, further studies may examine the possibility of converting a GP lane to an HOV lane, although various agencies have either advised against it or required a detailed study examining the impacts to a corridor's person-moving capacity (California DOT, 2016; WSDOT, 2016).

3.3.5 Discussion

Therefore, a high-level study considers the previously discussed four elements: existing low Level of Service, projected HOV-lane demand, travel-time savings as a benefit, and geometric availability. At this point in the planning framework, these criteria may assist in prioritizing a specific location over other eligible facilities. If one of the criteria is unmet, further examination into the conditions in which it might be met may be warranted. For example, an assessment can identify the demand required to warrant an HOV lane implementation if there is insufficient projected demand for a specific opening date. Also, if additional land is required, right-of-way costs may be estimated.

3.3.6 Case Study: High-level HOV-Lane Study on Hwy 2

The following section examines how a high-level HOV-lane study may be conducted in Alberta on Hwy 2 on the segment between the Hwy 216 and Hwy 2a interchanges. The study applies the previously introduced performance measures to this specific facility by following the assessment guidelines in Table 2. Through this process, the data that is available to Alberta is highlighted and data gaps are identified.

Part of the assessment involves identifying existing congestion on Hwy 2. There are numerous resources that present methods to quantify congestion; commonly used metrics include travel times, delays, speeds, travel time variability and others (Omrani & Salek, 2016). V/C ratios or LOS values from such sources as the Regional Travel Demand Models (RTDMs) would be adequate for this high-level assessment.

It does not appear that Alberta Transportation has an ongoing vehicle occupancy data collection program. Currently, Alberta Transportation hosts turning count survey data, turning movement volumes from RTDMs with breakdowns by car, truck, and recreational vehicle. For even a sketch planning study, some estimate of vehicle occupancy is required. With a general growth rate applied, which may be approximated from historic increases in traffic volumes, a rough “guess” of opening day HOV demand may be estimated. With future projected vehicle volumes from existing models (RTDMs), projections may reveal if sufficient demand exists and if demands are below the thresholds, the yearly growth rate may be used to calculate when sufficient demand would exist. At this stage in the assessment, satellite images and cross sections of the ROW reveal that sufficient physical space exists for future lane construction in the study area presented in Figure 1.

3.4 Mid-Level HOV-Lane Studies

A mid-level HOV-lane study focuses on assessing future operational performance and involves multiple modelling tools and data sources to compare various build scenarios. When compared to a sketch planning study which helps select potential projects and assess feasibility, a mid-level study focuses on a single corridor in greater detail, taking steps to assess operational conditions at opening day and at the design horizon. This study would likely be categorized as a “functional planning study” according to Alberta Transportation’s established engineering process in Figure 2 (Alberta Transportation, 2011). Typically, this would involve generating various design alternatives while examining how each alternative impacts the overall local and area network traffic flow. The outcomes of this study would include recommended geometric designs, forecasted demands, minimum occupancy requirements as well as measures of effectiveness (MOEs) comparing person-throughput, travel times, speeds and other metrics for each alternative.

3.4.1 Model Design and Scenarios

First, different design scenarios are established, identifying potential alignments. Possible start and end locations for the lane are selected (which can be represented by HOV-only links in a travel demand model). Smaller geometric details such as lanes on the left or right and lane separation techniques are covered in more detailed models. The modelling should also include build and no-build scenarios at opening day in order to compare performance under different lane-restrictions. Depending on the capabilities of the travel demand model, a forecast to a horizon year can be conducted; however, capturing the HOV and SOV demand in forecast years may require additional steps that are covered in the Detailed level study. In order to simplify the modelling process, some assessments include only opening day scenarios (Cambridge Systematics, Inc., 2010) while others include forecasted HOV-lane demand (Wilson & Morris, 2012). The time of opening day and the design horizon are defined in the build contract (Alberta Transportation, 2012).

Once the build scenarios are developed and programmed, the model is run and the outputs may be compared. The results aid the decision-making process for determining start and end locations as HOV that enter the facility vary between interchanges. Modelling of the design horizon at this level of detail follows a similar process but includes future planned upgrades to the corridor. Here, assumptions are made when forecasting HOV vehicle volumes as detailed demand-shift modelling is covered in detailed assessments.

3.4.2 HOV Lane Modelling

Once the opening day and future year scenarios are established, a travel demand model can be updated for modelling the HOV-lane links. Although it is out of the scope of this chapter to describe travel demand modelling as a whole, there are several updates that may be made to an existing model to accommodate the modelling of HOV lanes. At a minimum, a network should be updated to include HOV-links between interchange nodes along a highway running parallel to GP lanes (SCAG, 2012). This updated network allows HOVs, which are determined through the mode-choice step, to be assigned to the restricted lanes. Unless captured in the model already, other changes in behaviour resulting from the new facility, such as departure-time and mode shifts are unable to be represented by this level of modelling. This level of modelling therefore strikes a balance between using the existing resources (model and data) and upgrading the model to represent the various ways HOVs influence travel choices. The resulting outputs from the travel demand model are forecasted demands, often in the form of O-D matrices and link V/C ratios which are seen in Table 2, above.

Although travel demand models report V/C ratios, these are macroscopic models that do not include detailed operational modelling. In a mid-level study, analytical and macroscopic simulation tools, which were introduced in the literature review (Section 2.4.2) are used to provide a rough estimate of operational performance while requiring less data than a microsimulation model. Newer versions of HCM and FREEVAL (a HCM based software) contain methods that provide general measures of traffic conditions - calculating the weaving between GP and HOV lanes as well as the friction-effects from different physical lane-separations (Wang , et al., 2012). Once models are developed, outputs for the selected scenarios may be compared. These may include speeds, traffic flow densities, V/C ratios, LOS values, travel times, delays, and other metrics presented in Table 2.

3.4.3 Case Study: Mid-Level HOV-Lane Study on Hwy 2

The following section examines how a mid-level HOV-lane study should be conducted for Hwy 2. The study applies the previously introduced performance measures to this specific facility by following the assessment guidelines in Table 2 and the previous section.

At this point in the analysis, design alternatives (build scenarios) are chosen which guide the subsequent modelling. For Hwy 2, within the boundaries of our study between the Hwy 216 and 2A interchanges, this involves identifying potential start and end locations of an HOV lane. Along this corridor, the major origins of trips include the Edmonton International Airport (EIA), 50^{th} and 65^{th} Avenue interchanges in Leduc, and the Ellerslie Road and 41^{st} Avenue interchanges accessing the southern communities in Edmonton. Major origins and destinations along this route include EIA and the Nisku industrial area accessed by Hwy 625 and Airport Rd. interchanges. Currently, the publicly available volume data for this corridor differentiates between 5 vehicle types: passenger vehicles, recreational vehicles, busses, single-unit trucks and tractor trailer units (Alberta Transportation, 2017). The data includes yearly estimates, outputs from the Edmonton RTDM as well as turning count surveys every few years. From our investigation, it appears the RTDM is capable of modelling future improvements to this specific corridor however I could not find evidence of data needed to model HOV-lane performance on this facility (Castleglenn Consultants, 2016). Necessary data would include vehicle occupancies gathered from various survey techniques that will be discussed in the subsequent section and discussion. With the HOV count data added to the RTDM, the model may be used to estimate future demands HOV-lane demands for each of the build/non-build scenarios at the opening day and at the design horizon (Kittelson & Associates, Inc./Dowling, 2012).

With the outputs from the RTDM, an operational model may be populated to assess the performance of ramps and segments. For modelling future scenarios, anticipated infrastructure improvements should be included in the model since infrastructure improvements occur regardless if HOV lanes are added or not. For this corridor, this includes potentially adding express lanes, lanes that bypass lower-volume interchanges, as well as expanding the GP lanes to 5 lanes in each direction (Castleglenn Consultants, 2016). As highlighted in Table 2, the data required to conduct an operational study, in addition to the RTDM outputs, would require geometric data, including link lengths, no. of lanes (ramp, mainline), lane widths, lateral clearance, and ramp acceleration/deceleration lengths. This data is available readily from as-built design drawings (Alberta Transportation, 2011). With this model, changes in performance between the alternatives (various starting and ending positions) can be compared.

For a mid-level study, there is a trade-off between a study that is accurate enough to compare build alternatives, yet cost-efficient and time-sensitive. This leads to the tension between increasing the accuracy and precision of the modelling process which comes at the cost of additional resources, modelling expertise and data. In this scenario, without updating a RTDM model to model HOV demand shifts (specifically, discrete-choice models based on stated preference/revealed preference (SP/RP) data which are outlined in Section 3.5), there are assumptions made about the inelastic nature of HOV demand. Namely, the model would not capture the travel time savings for HOVs in exclusive lanes and the resulting behavioural response. These limitations are also evident in the operational modelling as analytical and macroscopic models are not able to model detailed traffic phenomena such as the formation and dissipation of queues. Therefore, due to limitations in time and cost in assessing multiple build scenarios, an analyst should be aware and clearly state the assumptions made in forecasting and modelling that may limit the accuracy of the model at this stage of analysis.

3.5 Detailed HOV-Lane Studies

A detailed HOV-lane study focuses on modelling the demand and operation of HOV lanes at a detailed level, requiring large amounts of data and resources as outlined by the last row in Table 2. When compared to a mid-level planning study, which helps select operational design alternatives, a detailed study focuses on modelling the representation of changes in demand due changes in facility supply (i.e. the new HOV lane as well as other new geometric and operational characteristics). The detailed nature of these objectives requires complex models in order to test and replicate these phenomena. This study would likely be categorized as a "preliminary engineering study" according to Alberta Transportation's established engineering process in Figure 2 (Alberta Transportation, 2011). The following section is divided into the demand and operational modelling categories with the demand section examining how discrete choice modelling as well as tour/activity based travel demand models account for a wider variety of responses and behaviours influenced by HOV-lanes. The operational section outlines how microsimulation and dynamic traffic assignment model the formation and dissipation of congestion formed by and around HOV lanes for detailed design decisions.

3.5.1 Detailed HOV-Lane Studies: Demand Modelling

Detailed modelling of demand shifts caused by HOV lanes involves representing the travel behaviour and decisions of travellers through tools such as discrete choice models and travel demand models. Some of these changes in travel decisions due to HOV lane implementation include lane choice as not all HOVs choose to travel in HOV lanes, route choice as HOVs from other parallel routes may choose to shift to a facility with HOV lanes, and mode choice as travellers may be willing to form carpools (Noland & Polak, 2001)

Although this thesis does not delve into the details of discrete choice modelling applications, a brief introduction is provided in Section 2.4.1. For the purposes of developing a model in Alberta, I outline the data required to estimate these models. This data includes stated preference (SP) and revealed preference (RP) data, acquired from travel behaviour surveys (Kittelson & Associates, Inc., 2006). With these surveys, analysts have modelled travel behaviour choices with nested logit models with complex structures (San Diego Association of Governments, 2013). The explanatory variables based on survey results include travel times and travel time variability which allow researchers to estimate mode and lane choices (Goodin, et al., 2013).

These SP and RP surveys, as outlined by Table 2 also reveal public opinion to various build configurations and preferences.

These discrete choice models are then incorporated in regional travel demand models (RTDMs). In conventional 4-step modelling, several deficiencies are identified due to the oversimplification of the process of modelling behaviour. One such issue involves calculating mean estimates in discrete choice models (DCMs) for time and cost coefficients (Kittelson & Associates, Inc., 2006). In reality, the time and costs coefficients follow a distribution of varying values of time (VOT) of various travellers and are not accurately represented by a point estimate or mean. Also, through modelling HOV as simply a choice of mode, the process of coordinating travel between household members for the same time and to a similar destination is overlooked, possibly overestimating HOV demand. This same issue arises when searching for available rideshares outside the household (Davidson, et al., 2007). With these limitations, the aforementioned reports recommend the use of activity and tour based travel demand models which estimate the various activities that are taken by each individual, thus overcoming the identified limitations.

3.5.2 Detailed HOV-Lane Studies: Operational Modelling

Detailed modelling of traffic operations on facilities with HOV lanes involves microsimulation – simulating individual vehicles in order to assess the traffic dynamics resulting from new geometric designs and control strategies. At this level of detail, outlined in the last row of Table 2, microsimulation software can be used to model the operational outcomes of design alternatives such as weaving segments, ramps, ramp signals, and managed lanes such as HOV lanes. As outlined in the literature review Section 2.4.2, modelling at this level of detail requires significant time and data, and includes many steps to calibrate and validate the model in the development phase. The models are able to output various metrics that describe the formation and dissipation of congestion through changes in speeds, queueing, and signal timings (Nikolic & Pringle, 2008).

Because detailed operational models of future design alternatives are built with outputs from demand modelling tools, allowing for some representation of supply-and-demand feedback is necessary to capture any demand changes due to Level of Service (Noland & Polak, 2001). Including feedback involves re-calculating the mode-choice, lane-choice, route-choice and trip generation as congestion forms since changes in travel-time directly influence traveller's decisions and here, a dampening factor may be applied to help achieve convergence (Nikolic & Pringle, 2008). These feedback loops in essence capture the elasticity of demand to supply (i.e. congested conditions) and require a significant amount of time to implement.

In the past ten years, recent publications and U.S. federal guidance recommended dynamic traffic assignment tools (DTA) (Szeto & Wong, 2012; FHWA, 2017). Because DTA incorporates changing conditions over time, these models can capture the relationship between traffic flow and travel choices, specifically how mode, lane, route choices are impacted by changes in travel time due to the volume of vehicles on a link (Szeto & Wong, 2012). Studies conclude that DTA is able to produce model results closer to real-world characteristics when compared to static traffic assignment models (Shabanian, 2014). Additionally, these models are able to replicate how mode choice is influenced by existing travel times, or if a trip is avoided.

These models result in many outputs and parameters which help illustrate the traffic flow and demand shifting properties of HOV-lanes. Some of the outputs include traffic performance measures, which include travel times, speeds, speed contour maps, histograms and other specific traffic parameters. From the mode choice modelling, metrics include the % diversions by mode, lane or route, representing the quantities of travellers changing behaviours due to congestion (Shabanian, 2014). Also, direct performance comparing the HOV and GP lanes in person-throughput and emissions/person allows comparison between various HOV build alternatives. Lastly, optimal traffic control timings for ramp meters and traffic signals are also outputs, however, these will be further examined in the subsequent chapter on ramp meters.

3.5.3 Case Study: Detailed HOV-Lane Study on Hwy 2

The following section examines how a detailed HOV-lane study should be conducted in Alberta on Hwy 2. Building on the mid-level study, which uses analytical tools to assess build alternatives such as lane start and end locations, a detailed study examines the operational impacts of minute design choices as well as projections for long-term HOV demand.

In the previous section outlining a mid-level study for planning HOV lanes on Hwy 2, Section 1.4.1, I describe how observed occupancy data inputted into existing or slightly modified RTDM models can produce forecasts of HOV demand, thus treating HOVs as simply another classification of vehicles similar to busses and trucks. I also identify the limitations of this modelling, as well as how detailed demand forecasting may account for these demand shifts with activity and tour-based models. Here, Alberta Transportation may build a detailed forecasting model including pre-existing data in order to more accurately model the demand-shifts brought by HOV-lanes. It is not within the scope of this document to recommend a specific program or form of detailed model; therefore, the focus of this explanation remains on the required data.

In addition to the occupancy data mentioned in Section 1.4.1, which represents existing HOV demand, data on travellers' potential behaviors is required for modelling future scenarios. For the Hwy 2 corridor, the peak-hour commuters live within the greater Edmonton region, an area captured by the Edmonton Household Travel Survey (HHTS) where the most recent survey gathered responses from 22,400 households and 54,000 residents (Toop, 2016). The data included household data, personal information, and a travel diary for each resident from Edmonton and the surrounding regions such as Leduc and Leduc County (City of Edmonton, 2015). Currently, this data contains patterns of trip characteristics along the Hwy 2 corridor, which records if a traveller is a passenger in a vehicle or takes transit, and could be used to contribute to existing counts of travel modes based on revealed travel behavior. Other methods by which stated and revealed preference data could be obtained may include travel surveys distributed to major origin and destinations along the Hwy 2 corridor including EIA, Nisku business park and Leduc. Such surveys may present factual questions which are similar to Edmonton's existing HHTS, which request commuters' experiences, attitudinal and opinion questions, or stated response questions (Richardson, Ampt, & Meyburg, 1995). This data would aid analysts with understanding the existing HOV mode share, commuters' opinions towards HOV lanes, and their willingness to form carpools in order to use the lane. With this data, the models outlined in 1.5.1 could be built to more accurately represent the decisions made by travellers.

On Hwy 2, a detailed operational study of HOV-lanes involves using microsimulation tools to examine specific design alternatives. For this specific case study, since there are no existing HOV or managed lanes on urban highways in Alberta, this implementation would set a precedent for future HOV-lanes. Since uniformity in geometric design is crucial for highway safety, as drivers would be familiar with specific lane entrance and exits, the first installation of signs and lane demarcations would require careful assessment.

For Hwy 2, there are several operational characteristics to be considered. Firstly, access control varies as some HOV-lane designs include a continuous-access, while others include a barrier-separated design. For non-continuous-access HOV-lanes, weave zone locations and lengths at on and off-ramps need to be determined as well. Since Hwy 2 is a commercial corridor and this section contains 3-5 lanes in each direction, this may add difficulty to HOVs accessing the leftmost lane as they would need to merge through the GP lanes. Additionally, due to the snowfall, snow-storage and clearing should be considered if the lane is barrier-separated.

3.6 Discussion

In the following discussion, I expand upon the HOV-lane planning process presented in this chapter. Here, I cover an application to the highway engineering process in Alberta, data availability, study scoping which explores the depth of each stage of study, guidelines for consistency and future modelling, and local context.

3.6.1 Application to Alberta's Highway Engineering Process

The framework outlined in Sections 3.3-3.5 contains similarities to the existing Highway Engineering Process introduced in Figure 2 in Chapter 2. This provides analysts with guidelines that align the levels of detail to existing studies. Here, the high-level analyses which use sketch planning tools and thresholds to screen locations may be used during the development of the 3-year plans. The medium level analyses then align with functional planning studies, modelling the performance of HOV lanes given various levels of forecasted demand. The engineering assessments that follow might include detailed analyses of HOV demand while collecting survey data and updating the RTDM. Lastly, detailed studies align with the detailed design phase, outlining an investigation that allows analysts to test the various scenarios of HOV lane policies. Once specific scenarios are chosen, the designs then proceed to construction sequencing. The developed framework differs from the existing Highway Engineering Process as HOV lanes do not currently exist on Alberta's highways. Therefore, this framework guides the decision-making process that determines not only the appropriate design, similar to the existing Highway Engineering Process, but also aids decision makers determine if HOV lanes are appropriate at all.

3.6.2 Data

By breaking down the HOV-lane planning process into successive studies, I reveal how data requirements increase as models require more detailed data to produce disaggregate operational and demand models. In an ideal world, all the data required for the modelling steps would be available or easily obtained by the analyst. This, however, is not the case as data is often missing, inconsistent, or repurposed from another application. Collecting the data also leads to another issue, namely, prioritization and selection. Given limited budgets and resources for data collection, analysts are tasked with choosing between data that is required, and data that is "nice to have." In the analysis provided in the previous sections, I identify occupancy data as the most crucial data since none of the assessments can be conducted without it. This data would be required for assessing present-day HOV-demand as well as for populating the RTDM models for forecasting. In addition to household travel surveys which were introduced in Section 2.4.1, occupancy data is collected from roadside surveys examining the occupants in vehicles. Additionally, data may be available from crash data from the RCMP or other enforcement agencies that reveal the number of occupants in vehicles involved in collisions. These records would include the locations and times, however may be biased and over-represent certain road users (Heidtman, Skarpness, & Tornow, 1997).

3.6.3 Study Scoping

Another issue that arises when developing HOV studies is defining the scope with respect to depth and breadth. There is a natural progression in the highway planning process for studies to narrow in focus and increase in detail as designs are confirmed and selected in the high, mid-level and detailed studies. In the three levels of studies that I outline, the depths of study correlate with the detail of data inputs and outputs into the modelling tools. Though the depth of study, defined by the resolution of data as well as the extent to which the modelling is discrete, is clearly demarked by the three major stages, I do not clearly define the breadth of each study. The breadth of study involves establishing a scope that defines the extent to which design alternatives are modelled and examined. For example, in modelling the network effects of HOV lanes on HOV travel, boundaries around the study area need to be defined. Also, the future design horizon year should be established. Since there are no set defined limits to these studies, engineering judgement is required to define the spatial and temporal limits of studies for the efficient use of resources as the additional analysis would provide information, but would be diminishing in value and accuracy.

Another complex issue that arises involves allocating available funds for the planning process. Given limited resources to improve the accuracy and capabilities of the demand and operational modelling, a specific scenario may include choosing between improving the RTDM model, and building a more detailed microsimulation model. The decision would likely warrant a trade-off analysis as each investment would result in very different benefits. Improving the RTDM model perhaps to an activity or tour-based model from a 4-step model would benefit other regional projects and long-term forecasting. Alternatively, building a detailed microsimulation model of the Hwy 2 corridor would in turn result in a more accurate understanding of the formation and dissipation of congestion along the corridor. These decisions are not trivial and are often influenced by political decisions that guide investments. Given these difficult decisions, hopefully this document provides background for these modelling tools, describing the benefits of increased detail at different places along the planning process.

3.6.4 Analysis Guidelines

Through researching the various studies assessing current and future HOV-lanes, I discovered a lack of standardization for planning HOV-lanes. This is highlighted in NCHRP 15-49 where the authors state that "no single issue represented more frustration among practitioners than the need to have a clearly defined method for evaluating such operational changes in this context when developing the managed lanes guidelines" (pp.19) (Fitzpatrick K. , et al., 2016). The quote is written in reference to the operational modelling of lane conversions from a GP to HOV lane and highlights the lack of guidance on the level of study required for such operational changes. The authors further state that lane-conversions may not receive the same funding and operational scrutiny as newly-constructed HOV-lanes since there is significantly less capital costs for construction. Fitzpatrick et al. then presents Caltrans as the lone agency to define the requirements for operational studies pertaining to managed (and HOV) lanes (Fitzpatrick K. , et al., 2016). This operational policy directive requires an operational and safety traffic analysis for "all managed lane projects." Specifically, the policy directs analysts to assess "the entire freeway facility, including both the managed lane(s) and general-purpose lanes" as well as merge/diverge locations (CALTRANS, 2009). The document also goes on to set the design horizon at 20 years from the opening day of the facility. Similar to the Caltrans policy directive, this thesis fills the gap between the design guidelines and operational studies, outlining the objectives and design alternatives that may be examined at each level of modelling detail. This document also highlights several gaps for future HOV-lane planning in Alberta, namely due to the absence of HOV lanes. In order to develop an HOV-lane network, standardized designs would be needed in the HGDG where lane geometries are appropriate for the Albertan context.

3.6.5 Hwy 2/Local Context Application

Throughout the analysis I outline how each of the assessments may be applied to HOV-lane planning for Hwy 2 between Hwy 216 and Leduc. The applications to Hwy 2 highlight the need for occupancy data and user preference data for the demand modelling process. Additionally, facility improvements for no-build scenarios also need to be identified for the operational analysis of future cases. Given the fact that studies (Castleglenn Consultants, 2016) along this corridor do not mention HOV lanes, ramp metering, or any type of congestion management strategy other than constructing new lanes to facilitate vehicle demand from future growth, initiating an HOV lane study may present difficulties. This reflects how existing corridor plans do not include congestion management strategies. Several reasons that might explain this is the lack of precedent (as no HOV lanes exist) and the lack of clarity (given the lack of knowledge as to how to specifically implement these lanes). This chapter addresses the latter of the two issues, presenting a framework for planners and engineers to follow while integrated into Alberta Transportation's existing highway engineering process.

3.7 Summary

In this section, I incorporate the HOV-lane planning framework including travel demand and simulation models into the highway planning process in Alberta. Through the analysis, the HOV-lane planning process was presented in 3-levels of detail, highlighting the objectives and data needs at each step. This process also included applying each level of detail to Hwy 2 as a case study, discussing location-specific issues. Through the discussion, I identify several needs going forward for HOV-lane planning in Alberta which are listed below. Firstly, occupancy data is identified as the most crucial data required for proceeding with demand analysis. This data may be collected through roadside surveys or household travel surveys. Secondly, Alberta Transportation would need to update their Highway Geometric Design Guide (HGDG) to reflect standardized HOV-lane designs as well as identifying a standardized modelling procedure. Lastly, with the occupancy data, updates may be required to the RTDM models to capture the demand-shifts due to HOV-lanes.

4. Planning for Ramp Metering: Case Study of Hwy 216

In the following section I present a planning and analysis framework for ramp metering in Alberta, that incorporates travel demand and simulation models. As there are no ramp metering facilities in Alberta and technical details for planning such facilities are absent from Alberta's highway engineering guidelines, this chapter presents a framework guiding how and when technical studies at differing levels of detail may be conducted. In the early stages of the planning process, studies focus on examining the general possibility of ramp meters at specific locations, often using minimal resources and data. At this point, the complexity of ramp control is determined as the modelling for multiple coordinated adaptive ramps requires significantly more detail when compared to an isolated pre-timed signal. Detailed studies assess different location and control alternatives for opening-day and future-design operational performance, aiding the geometric design and control algorithms for the meters. This chapter outlines how a study of ramp metering may be conducted for Hwy 216 (Anthony Henday Drive) in Edmonton, focusing on data needs and specific issues pertaining to this corridor.

Required tools and operational data remain similar to those required for HOV lane planning. In HOV lane planning, congestion formation and dissipation are central for determining HOV lane performance. Ramp metering also requires similar operational modelling requirements, however there is less of a focus on demand-shifting when compared to HOV lanes as there is a greater focus on optimizing signal timing. Although ramp meters may lead to altering route choices, these shifts are often perceived as a negative by-product (Jacobson, Stribiak, Nelson, & Sallman, 2006).

The following chapter firstly provides the background on highway planning in Alberta as context for introducing ramp metering. This is followed by a table outlining the major levels of detail of ramp meter planning. The subsequent three sections explain the table, and lastly, I discuss the issues that arose in the analysis.

4.1 Hwy 216 Background and Ramp Metering Planning in Alberta

Ramp metering is a strategy that regulates vehicle rates entering a highway mainline facility from an on-ramp through use of a traffic signal on a ramp, leading to improvements in safety and traffic flow (FHWA, 2014). In order to assess the efficacy of ramp meters on highway operations and safety, a decision-making process is needed to guide the development of the ramp metering from conceptual idea to design and finally implementation. In general, this involves first identifying safety and operational problems in the vicinity of an on-ramp. A high-level analysis examines these issues early in the planning process through comparing existing collision statistics, ramp volumes, and geometric requirements with pre-established thresholds and warrants (Jacobson, Stribiak, Nelson, & Sallman, 2006). Once the strategy is justified, macroscopic analytic modelling tools such as HCM and FREEVAL model the operational impacts of simple ramp meters. These tools fall under the mid-level studies that will be introduced later in this chapter. Although limited in their abilities to represent complex ITS strategies such as adaptive and connected ramp meters, these tools quantify the operational changes on both the ramp and mainline (ML) when comparing a metered to no-build scenario (Trask, Aghdashi, Schroeder, & Rouphail, 2015). At the same time as these high and mid-level studies, roadway authorities should also determine the level of technical complexity for ramp signal control. Agencies face a difficult decision as studies demonstrate that adaptive ramp control performs better when compared to those with a fixed timing pattern, requiring greater modelling detail and operational resources (Chu, Liu, Recker, & Zhang, 2004). This decision is not only technical but also financial, as adaptive and connected ramp meters may be a part of larger ITS systems, presenting significantly higher costs for operations and maintenance. Lastly, analysts conduct a detailed study using microsimulation software, modelling the traffic and safety impacts on the ML, ramp and surrounding arterials resulting from the ramp control scheme. This process will be presented and further discussed in Table 4.

Highway 216, also known as Anthony Henday Drive, was selected as a candidate facility for ramp meter planning. Hwy 216 is a divided and grade-separated facility under the management and jurisdiction of Alberta Transportation and fully encompasses the city of Edmonton as presented in Figure 1. As part of the CANAMEX trade corridor, established under North American Free Trade Agreement (NAFTA), it holds economic value to the transportation of goods in the region (Alberta Transportation, 2016). Currently, tolls are not allowed on the facility due to the public-private partnership (P3) model used to build and operate the roadway (Alberta Transportation, 2012). In Alberta, delays resulting from increasing traffic volumes have historically lead to roadway infrastructure expansions, with urban highways designed with space for future pavement expansions. This is evident as the southwest portion of Hwy 216 (Anthony Henday Drive), is already listed for bridge expansion and lane widening, although funding has not yet been allocated (Alberta, 2016). Given the need for additional capacity, this chapter presents a planning framework applied to Hwy 216 for possible ramp meter implementation.

Since there is no regulation or guidelines for planning ramp meters specifically, this document seeks to build upon and add to existing documents that support the modelling and design of signalized intersections at highway interchanges. These include existing signal and loop detector designs, outlined parameters for traffic modelling, a pervious discussion paper on ramp metering on Alberta highways, and values for signal timing (Alberta Transportation, 2003; Alberta, 2016; MacDonald , 2012).

4.2 Ramp Meter Analysis Table

The following section contains the three aforementioned analysis levels in a table structure with a similar structure to the table presented in the HOV lane chapter. It was constructed from examining various design and planning manuals as well as project reports from ramp meter studies (ADOT, 2013; Caltrans, 2016; Crash Modification Factors Clearinghouse, 2014; FHWA, 2014; WSDOT, 2016; Jacobson, Stribiak, Nelson, & Sallman, 2006; Jacobs Engineering, 2013). The table also identifies the data available to Alberta Transportation as well as identified data gaps which are also discussed in a subsequent section.

Table 4 Ramp Metering Assessment for Hwy 216

Level of Analysis	Details	Tools Include	Application	Model Inputs*			Sample Outputs, MOEs**	Evaluation	Previous Applications
				Base Case (Current Conditions)	Future Case (Design Year) Do Nothing	Future Case (Design Year) with Strategy			
High-Level	· Some tools accept RTDM outputs & shape files, others are spreadsheets that only require volumes · Estimate general impacts of ramp metering using parameters developed in other studies · Not able to represent coordination or advanced control algorithms; analysis too aggregate · Results are order-of-magnitude	TOPS-BC, FITSEVAL, IDAS	· Different ramp metering strategies (isolated, coordinated, etc.) cannot be represented/differentiated due to very aggregate level of analysis · Can help narrow down candidate strategies to be taken forward for further (more detailed) analysis · Method can very roughly estimate general operational characteristics of different strategies	· Traffic counts/volumes on mainline and ramps (peak periods and others) from estimates and turning count surveys (with vehicle classification) ^^ · Geometric data (including link lengths, no. of lanes (ramp, mainline), etc.) · Mainline & ramp capacities · Mainline & ramp free flow speeds	· *Projected (peak-period) counts, estimated from simple growth factors (set as some % of current volumes)* · Geometric data (same as base case)	· *Projected (peak-period) counts, estimated from simple growth factors (set as some % of current volumes) as an estimated response to the control* · Geometric & control data for strategy implementation scenarios	For mainline & ramps: · Speeds · VMT · V/C ratios · VHT · Ramp speeds	· Change in outputs / MOEs between future do nothing case and various future metering cases · Can be used as rough operational inputs to a benefit-cost analysis for comparing potential strategies · Results are rough, and should only be used to justify further study and analysis	· Warrants for application (Minnesota DOT, 2012; Jacobson, Stribiak, Nelson, & Sallman, 2006; California DOT Division of Traffic Operations, 2016)

Mid-Level	· These tools assess operational performance using empirically-derived equations
	· Tools are macroscopic; they calculate LOS, delays & speeds on segment level
	· Represents fixed-time ramp metering by limiting on-ramp capacities (to below target flow rates)
	· Different cases tested by changing ramp capacities, representing different timing patterns, applying signals for different combinations of ramps on a corridor
	· Not able to represent coordination or advanced control algorithms; analysis too aggregate
		FREEVAL 2015e, HCM, HCS	· Different ramp metering strategies (isolated, fixed time coordinated, dynamic coordinated, etc.) cannot be represented/differentiated due to very aggregate level of analysis
			· Studies should examine operational impacts of installing signals at different ramps on corridor, and impacts of different metering rates.
			  · Including 111 St, Rabbit Hill Road, and Terwillegar Drive, particularly in PM peak period.
				· Traffic counts/volumes on mainline and ramps (peak periods and others) from estimates and turning count surveys (with vehicle classifications)+
				· Detailed geometric data (including link lengths, no. of lanes (ramp, mainline), lane widths, lateral clearance, ramp accel/decel lengths, etc. (everything required for HCM))
				· Ramp metering rates (used to set ramp capacities in programs)
					· *Projected (peak & other periods) counts, from one or more of:*
					  · *Outputs from RTDM (demand volumes)*
					  · *Using simple growth factors on current demand volumes (taken from RTDM or counts)*
					
					· Geometric & control data (same as base case)
						· *Projected (peak & other periods) counts, from one or more of:*
						  · *Outputs from RTDM (demand volumes) where ramp metering is represented in the RTDM as a capacity restriction*
						  · *Using simple growth factors on current demand volumes (taken from RTDM or counts)*
						
						· Geometric & control data for strategy implementation scenarios
							For mainline & ramps:
							· Speeds
							· Link densities
							· V/C ratios
							· LOS
							· Travel times
							· VMT
							· VHT
							· VHD (vehicle-hours of delay)
								· Change in outputs / MOEs between future do nothing case and various future metering cases. For example: change in average peak-period mainline vehicle speeds
								· Can be used as rough operational inputs to a benefit-cost analysis for comparing potential strategies
									· Nebraska I-80 (FREEVAL) (Sharma, Wang, & Khattak, 2016)
									· Iowa I-235 (FREEVAL) (HRGreen; Cambridge Systematics, 2014)

Table 4 Cont'd

Level of Analysis	Details	Tools Include	Application	Model Inputs*			Sample Outputs, MOEs**	Evaluation	Previous Applications
				Base Case (Current Conditions)	Future Case (Design Year) Do Nothing	Future Case (Design Year) with Strategy			
Detailed Operational Analysis	· Microscopic simulation models individual vehicle behaviours and interactions · Certain control schemes and algorithms used in actuated and coordinated ramp metering may require external code (through plugins) · Because microsimulation is stochastic (random drawing of several vehicle characteristics in simulating individual vehicles), models must be run many times (usually in the range of 20-100 times) ·	AIMSUN, CORSIM, Paramics, Simtraffic, Transmodeler, VISSIM, WATSIM, and others	· Should examine the operational impacts of detailed design elements such as ramp configurations, meter placement, and metering controls (isolated, coordinated, demand responsive, etc.) · May include modelling two closely-spaced interchanges on Hwy 216 (such as 62 Ave & Lessard Rd) for isolated and coordinated ramp control to improve mainline traffic flow · Can model: isolated/pretimed metering, actuated metering, coordinated meters (pretimed or demand responsive algorithms), HOV/transit bus bypass lanes	· Traffic counts/volumes on mainline and ramps (peak periods and others) from estimates and turning count surveys (with vehicle classifications) + · Detailed geometric data (including link lengths, no. of lanes (ramp, mainline), lane widths, lateral clearance, ramp accel/decel lengths, etc.). Sources such as GIS shape files and liDAR are excellent. · Ramp metering details: ramp locations, no. of lanes controlled, metering rates and other signal timing and coordination characteristics and control programs / algorithms · *For calibration (and otherwise):* · *Travel time data from floating car runs* · *Point speed data from radar or loop detectors* · *Other data, parameters such as location-specific model calibration values*	· *Projected (peak & other periods) counts, from one or more of:* · *Outputs from RTDM (demand volumes)* · *Using simple growth factors on current demand volumes (taken from RTDM or counts)* · Geometric & control data (same as base case)	· *Projected (peak & other periods) counts, from one or more of:* · *Outputs from RTDM (demand volumes) where ramp metering is represented in the RTDM as a capacity restriction* · *Using simple growth factors on current demand volumes (taken from RTDM or counts)* · *Information from travel surveys & subsequent discrete choice modelling efforts*+ · Geometric & control data for strategy implementation scenarios	· Animations from simulation · Various operational characteristics, including all those listed previously, in addition to more detailed results such as queue lengths and spillback, bottleneck locations, etc.) · Temporally-based operational outputs · Distributions and histograms of all outputs (because these tools are inherently stochastic) · Many highly detailed and vehicle-level outputs	· Change in outputs / MOEs between future do nothing case and various future metering cases. · Objective at this level of analysis is to investigate the detailed operational outcomes of different ramp metering schemes (locations of meters, metering plans including coordinated systems, adaptive controls, etc., discussed in previous columns) and how to mitigate any unfavourable conditions that may arise · Public perceptions (through any opinion surveys, which are warranted at this level of analysis detail) · Animations from simulation runs are helpful for non-technical policy makers and the general public for visualizing operations · Due to stochastic nature of these tools, all results can be described and analyzed using statistical methods	· California I-680 (Paramics) (Gardes, May, Dahlgren, & Skarbardonis, 2002; Gardes, Kim, & May, 2003) · California I-405 (Paramics) (Chu, Liu, Recker, & Zhang, 2004; Zhang, et al., 2001) · Houston Hwy 290 (VISSIM) (Chaudhary, Tian, Messer, & Chu, 2004) · California I-210 (VISSIM) (Gomes, May, & Horowitz, 2004) · Wisconsin US 45 (Paramics) (Horowitz, Wu, & Duarte, 2004)

* Data/Inputs required but not currently available, shown *italicized and underlined*
** For each segment and time period analyzed
^^ Turning counts are available within a similar time period in 2015 for this location with the exception of Hwy 2-Hwy216 interchange on the Alberta Transportation Website.
+ A traveller survey may be used to understand route choice behaviour with ramp metering

In Sections 4.3-4.5 I discuss each of the table rows, the levels of analysis. Each of the sections also presents a case-study application of ramp metering on Hwy 216 which was introduced in section 2.1.1.

4.3 High-Level Ramp Meter Studies

High-level ramp-meter studies determine if further analyses are warranted using sketch-planning tools and established thresholds. The objective of these studies is to determine if ramp metering would be suitable for target locations along a highway in a cost-efficient and timely manner. In Alberta Transportation's Highway Engineering Process, this occurs during the long-range planning phase for inclusion in the 3-year programs (Alberta Transportation, 2011).

Planning for ramp metering from a high-level includes applying thresholds and warrants, as well as using sketch planning tools to approximate operational changes. Table 4, above, outlines how sketch planning tools such as TOPS-BC, FITSEVAL, and IDAS approximate operational improvements for high-level planning (FHWA, 2017). These tools use RTDM outputs such as network and transit links as well as origin-destination (OD) matrix files to calculate the impact of ramp metering on existing link performance (Xenelis, 2005). The purpose of quantifying these benefits is to develop ballpark estimates for project financing (AASHTO, 2003).

In addition to these tools, thresholds for performance, demand and safety have been identified as prerequisites for ramp meter implementation. Table 5 shows the performance, demand, and safety thresholds found in the existing literature which indicate when ramp metering warrants consideration. The Alberta Highway Geometric Design Guide (Alberta Transportation, 1999; Alberta Transportation, 2003) currently does not contain any criteria regarding ramp metering installations.

Table 5 Ramp Metering: Operational and Design Elements to Consider

Criteria	Existing Thresholds
Performance thresholds*	· "The freeway operates at speeds less than 50 mph for a duration of at least 30 minutes for 200 or more calendar days per year." (Minnesota DOT, 2012) · A performance of LOS D or worse (Jacobson, Stribiak, Nelson, & Sallman, 2006)
Vehicle demand thresholds*	· Combined ramp and freeway volumes: · Combined flow rate of entrance ramp and shoulder freeway lane >2050 vph AND entrance ramp flow >400 vph (Simpson, Riley, Yasmin, Paul,

Criteria	Existing Thresholds
	& Warnick, Ramp Metering Design Guide, 2013) · Combined flow rate of entrance ramp and shoulder freeway lane >2100 vph in design hour (Minnesota DOT, 2012) · Ramp volumes alone: · 240-900 vphpl during peak periods (Minnesota DOT, 2012) · One ramp meter per 900 vph on ramp (California DOT Division of Traffic Operations, 2016)
Safety issues*	· "…high frequency of crashes (collision rate along the freeway exceeds mean collision rate in the subject metro area) near the freeway entrances because of inadequate merge area or congestion" (Minnesota DOT, 2012) · An increase in rear-end collisions near ramp merges onto a highway (Jacobson, Stribiak, Nelson, & Sallman, 2006)
Physical Requirements	· Sufficient storage for 10% peak hour volume at 25ft per vehicle (Jacobson, Stribiak, Nelson, & Sallman, 2006) · Sufficient storage for 7% peak hour volume at 29ft per vehicle (California DOT Division of Traffic Operations, 2016) · Minimum queue distance 400ft (Simpson, Riley, Yasmin, Paul, & Warnick, Ramp Metering Design Guide, 2013)

** Warranting consideration of strategy*

4.3.1 Performance Thresholds

Table 5 summarizes thresholds gathered from various ramp meter planning guidelines and studies published over approximately the last decade. The four major categories of thresholds/requirements pertain to are traffic performance, vehicle demand, safety and physical requirements. The guidelines highlight that these criteria should be identified early in ramp meter planning studies. Performance thresholds refer to the operational performance of the mainline in the vicinity of the on-ramp merge. Here, LOS values and other metrics such as free-flow speeds and lane densities which quantify congestion are available from operational studies or may be calculated from the Highway Capacity Manual (Transportation Research Board, 2016). As some ramp meters may vary signal timings based on real-time traffic performance, they respond to both recurrent and non-recurrent congestion.

4.3.2 Vehicle Demand Thresholds

Vehicle demand thresholds detail the minimum recommended demands for ramp-meter operation. These values are established from existing models and ramp meter implementations and provide a basis for comparing existing and projected ramp volumes (Jacobson, Stribiak, Nelson, & Sallman, 2006). The thresholds outlined in Table 5 vary considerably, highlighting the difficulty of presenting a definitive cut-off level where ramp meters are effective. This is because ramp meters aim to restrict on-ramp volumes to prevent down-stream volumes on the mainline from exceeding capacity, leading to a traffic flow breakdown. In order to determine if ramp meters would provide a significant benefit, further analysis using tools within the mid and detailed-level studies are needed. Until then, the thresholds in Table 4 provide a rough guideline for warranting further planning.

4.3.3 Ramp Safety Issues

Safety issues are identified through an analysis examining historic crashes at various locations. The accepted method of safety analysis follows the Roadway Safety Management Process outlined in the Highway Safety Manual, providing a framework for identifying and addressing various highway safety issues which include on-ramps (AASHTO, 2014). This process requires crash severity and location data to calculate crash frequencies and applies a crash modification factor (CMF) to estimate the impacts of ramp meters on reducing crashes (Crash Modification Factors Clearinghouse, 2014). The results of this analysis lead to an economic appraisal which quantify the improvements in safety in a monetary value which can be combined with the monetized travel time savings calculated from the sketch planning tools.

4.3.4 Ramp Geometric Requirements

Lastly, the high-level analysis should include a geometric assessment of existing ramp dimensions that examines ramp length for potential vehicle queue storage and signal location. The included thresholds in Table 4 calculate the required storage for queued vehicles from a percentage of the peak hour volume (California DOT Division of Traffic Operations, 2016). Required storage length, in addition to the required length for acceleration (which is available in the Alberta HGDG), results in the minimum ramp length required for ramp metering implementation (Alberta Transportation, 1999). When compared to existing ramp geometries, analysts may simply determine if existing ramps may be retrofit or if geometric changes are required to accommodate the acceleration distance and queue storage. Through this relatively quick screening, planners may determine whether ramp meters may be retrofit onto existing ramps.

4.3.5 Discussion

In conclusion, a high-level study examines the feasibility of ramp meters through high-level sketch planning tools in addition to operational thresholds. At this point in the assessment these criteria may be used to prioritize a specific ramp over other locations. Also, patterns may help identify if the issues are a safety issue. Lastly, the steps of estimating safety and operational improvements as well as the costs of implementation aid in the quantifying the costs and benefits for an economic analysis.

4.3.6 Case Study: High-level Ramp Meter Study on Hwy 216

The following section examines how a high-level ramp metering study may be conducted on Hwy 216 in Alberta. The study applies the previously introduced performance measures to this specific facility by following the assessment guidelines in Table 4, highlighting the available data for analysis.

For the sketch planning tools, ramp volumes and LOS values (output from RTDMs) are required to determine whether current volumes and traffic conditions warrant ramp metering. For Alberta, these would include present-day and projected future-year volumes on ramps and on the mainline. Turning count studies are essential for determining ramp volume thresholds. Currently, contractors conduct surveys periodically collecting ramp and ML volumes which are published online (Alberta Transportation, 2017). Additionally, historic collision data was made available through personal correspondence which identified collision severity, location and time. This data is sufficient for identifying hotspots, or locations where there is a high frequency of collisions. The data is limited in detail as the locations do not identify if a collision occurred on a ramp or on the adjacent ML facility, but merely on roadway segment. This may lead to difficulties when determining if collisions are due to vehicles merging from the ramp or vehicles merging between lanes on the ML. Further detail may be obtained from collision records which I was unable to access.

4.4 Mid-Level Ramp Meter Studies

Mid-level ramp-meter planning studies focus on assessing the present and future operational performance of various metering strategies on ramps and mainline traffic flow. These studies, described in row 2 in Table 4, build upon the high-level sketch planning process and results by modelling traffic flow and ramp operation using macroscopic and analytic operational models. Additionally, if authorities only deem isolated pre-timed signals necessary or feasible, ramp timing plans may be developed from this level of analysis.

First, analysts conducting a mid-level ramp metering study should develop a model of existing and future conditions on the target corridor. These macroscopic models, introduced in Section 2.4.2, require geometric data such as link and ramp lengths, lane widths, as well as mainline and ramp demand data, focusing on the accuracy of demand at the peak hours when ramp meters would likely be operational. Models such as FREEVAL contain demand inputs in 15-minute bins which should guide data collection formats (Sharma, Wang, & Khattak, 2016). In addition to opening-day scenarios, future conditions may also be modelled with the purpose of assessing future operational conditions and determining the impacts of ramp meters. This assessment may help determine when meters are suitable at each ramp, helping the staging of future ramp implementation.

Once the model of existing and forecasted operations on the corridor is developed, various scenarios of ramp control may be tested which include simulating ramp metering on various ramps along the corridor. Selective operation involves modelling a corridor with simulated ramp meters in different combinations in order to determine the impact of isolated ramp meters on corridor travel times and average speeds. Additionally, these analytic models allow for a sensitivity analyses in order to determine appropriate ramp metering rates (Trask, Aghdashi, Schroeder, & Rouphail, 2015). Such analysis would vary the signal timing for a modelled isolated ramp meter by limiting the on-ramp demand. Through changing this value, changes in other operational MOEs, such as queue lengths, travel times and average speeds may be recorded. Although these studies model the operation and performance of ramp meters, they are limited in their modelling ability. Firstly, they model isolated installations which are appropriate if ramps are spaced far away or if congestion is isolated. Even if numerous ramps along a corridor are modelled, the benefits from any connected or adaptive signal timings are not realized due to limitations in the modelling resolution. Additionally, integration with interchange signals on adjacent arterials as well as queue dispersion and detection are not available as well (HRGreen; Cambridge Systematics, 2014). Also, any behavioral choices resulting from operational choices such as changes in route or departure choices cannot be captured by these models (except very roughly, using tools like sensitivity analysis). For these, further analysis in a detailed study is required.

The resulting outputs of this study, which include changes in operative MOEs before and after RM installation (travel times, average speeds) and more complex congestion metrics (travel time reliability), aid in quantifying the most appropriate signal timing plans for the corridor (Omrani & Salek, 2016; Cambridge Systematics, Inc., Texas Transportation Institute, 2005). First, signal timing may be calculated from the ramp-volume limitations used in the models (HRGreen; Cambridge Systematics, 2014). This involves taking the volumes and calculating the number of green phases per time period (often 15-minute) assuming one vehicle per green-light. Secondly, the total corridor improvements represent overall benefits. These in conjunction with the installation and operational costs of ramp meters are inputs into benefit-cost analyses. Through this analysis, various ramp meter installation plans may be compared for funding decisions.

4.4.1 Case Study: Mid-Level Ramp Meter Study on Hwy 216

I examine how a mid-level ramp meter planning study should be conducted for Hwy 216. The study applies the previously introduced modelling steps to this specific facility by following the assessment guidelines in Table 4.

At this point in the analysis, design alternatives (location and number of metered ramps) are chosen through established models which further guide the subsequent detailed modelling. For Hwy 216, this involves systematically modelling the ramp operations during peak-hour flows on opening-day and design horizon timeframes. The data for developing these models is available from Alberta Transportation as both field turning counts and RTDM projections (Alberta Transportation, 2017). For developing a FREEVAL model, I determine that there is sufficient data for a mid-level operational study. For this corridor, locations of interest may include ramps with high volumes and ramps that are closely spaced which include 111st, 119st, and Hwy 2 ramps.

4.5 Detailed Studies

A detailed ramp meter planning study focuses on modelling the operation of ramp meters with microsimulation software, requiring large amounts of data and resources which are outlined by the last row in Table 4. These studies build upon the results of analytic and macroscopic models used in mid-level studies to model with greater detail the operational impacts of ramp meters. Several of the objectives, which are explained in the following paragraphs, include developing a signal control system, assessing the route diversion due to metering and the quantifying the safety impacts of platoon dispersion. The detailed nature of these objectives requires complex models in order to test and replicate these ramp control algorithms.

Detailed modelling of ramp metering operations involves using microsimulation tools to capture discrete vehicle behaviours for modelling control algorithms, vehicle merging behaviour and high-volume vehicle throughput close to traffic breakdown (Papamichail, Kotsialos, Margonis, & Papageorgiou, 2010). These tools, which are introduced in the literature review, explain how and when they have been applicable in operational highway studies. The data required includes that which is listed in Table 4 under model inputs, including roadway geometric data, existing and predicted ramp and mainline demands, a ramp control system and historic safety/collision data (Horowitz, Wu, & Duarte, 2004). Additionally, these models require data which may be gathered from floating car runs and delays from signalized intersections (Dowling, Skabardonis, & Alexiadis, 2004). This is for calibration of the model's constants as well as validation, where model outputs such as travel times and speeds are compared with real-world conditions. Once a model is calibrated and validated for local conditions, the testing of alternative control scenarios follows.

With simulation tools, adaptive ramp and coordinated ramp control systems may be modelled. These systems involve simulating a feedback control system which modifies the permitted ramp volumes based on volumes and speeds detected on the mainline (Hegyi, De Schutter, & Hellendoorn, 2005). Here, the complexity of modelling and operations governs the modelling detail. Coordinated ramp control systems build upon adaptive systems by adjusting signal timing based on traffic flow data gathered along the entire corridor, continuously modelling corridor conditions to prescribe optimal signal timings to individual ramps (Papamichail, Kotsialos, Margonis, & Papageorgiou, 2010). Both of these control schemes build upon systems of control loops which measure the occupancy of loops on the mainstream as well as measure ramp queues for overflow (Papageorgiou & Papamichail, 2011). At this point in a detailed study, analysts should identify the infrastructure (hardware including signals, control systems and loop detectors, and control software) for both adaptive and coordinated ramp control systems as well as their implementation and operational costs. Though coordinated systems have resulted in improved traffic speeds and flows, their operational costs and technical complexity may be prohibitive (Papageorgiou & Papamichail, 2011).

With these detailed simulation tools, a diversion analysis may be conducted to estimate the re-routing behaviour of vehicles when facing delays on a ramp. Here, commuters choose alternative routes to their destination with less overall delay, often entering the mainline from less-used ramps (Horowitz, Wu, & Duarte, 2004). The re-routing of travellers is an example of how ramp meters are a TDM (travel demand management) tool, encouraging ramp demand spreading amongst multiple entry points along a corridor. In determining the willingness of drivers to take alternative routes based on perceived ramp queues, analysts have conducted diversion propensity surveys, a form of stated preference survey, that examines route choice behaviour (Horowitz, Wu, & Duarte, 2004). The outputs from the RTDM models would include the % change in ramp volumes due to re-routing in addition to the locations that experience re-routed demands (Kittleson & Associates, Inc., 2013).

A detailed study also allows the quantification of safety improvements due to the operation of ramp meters. These models have been used to assess the reduction in on-ramp crash potential, the likelihood of collisions at specific locations (Lee, Hellinga, & Ozbay, 2006). Studies have also quantified corridor-wide safety changes due to changing the number of ramps as well as the cycle lengths (Abdel-Aty, Dhindsa, & Gayah, 2007). With the change in safety quantified, the changes in crash potential may be inputted into an economic analysis following HSM guidelines (AASHTO, 2014).

A detailed-level ramp-metering study achieves several objectives by modelling ramp metering operations on a highway. This includes quantifying the operational and safety changes before and after ramp metering implementation in addition to determining best signal control timings. The changes in operational MOEs, outputs from the model, may then be input to economic models for monetizing the benefits of ramp meters.

4.5.1 Case Study: Detailed Ramp Meter Study on Hwy 216

The following section examines how a detailed ramp meter planning study should be conducted on Hwy 216 in Alberta. Building on the mid-level study, which uses analytic tools to model isolated ramp operations, a detailed ramp meter study on Hwy 216 models the entire corridor, resulting in a signal timing plan and detailed operational impacts of ramp meter implementation.

A model of the entire corridor, Hwy 216, is necessary in a detailed study as this captures potential shifts in demand from one interchange to another.

Here, evaluating ramp metering on Hwy 216 would require Alberta Transportation to build several macroscopic and microscopic models of the Hwy 216 corridor. This includes an RTDM that including parallel arterials in order to more accurately model the demand-shifts brought by route diversions, as well as detailed microsimulation models which simulate the behaviors of individual vehicles in response to various ramp controls.

The data available to Alberta is listed in Table 2 with data gaps bolded and underlined. Future projections of highway mainline and ramp demands may be obtained from the RTDM model, however, consideration should be taken as these models are macroscopic in nature and do not model the detailed operations of ramp meters, limiting their ability to replicate controls such as loop detection and coordinated metering. Existing data includes roadway geometries, turning count surveys and vehicle counts from in-road loop detectors which are all required for developing the aforementioned models (Alberta Transportation, 2017). At this point, both the RTDM and microscopic models are developed while their outputs feed into each other. The changes in ramp volumes due to the various ramp control algorithms is modelled by the microsimulation which then may be input into the RTDM to output the shifts in demand. In order to calibrate the microsimulation models, field data from vehicles travelling along the mainline and ramps is required, which includes travel times, delays and average speeds.

Driver behavioural response data may be needed for understanding potential route diversion behaviour by travellers. This data, in the form of a stated-preference survey, would outline hypothetical scenarios for commuters, and would gauge their willingness to change to an alternative route when faced with ramp queues causing delays. For the Edmonton region, an opportunity to gather this data would be future household travel surveys or in the communities and industrial areas immediately adjacent to Hwy 216 (Toop, 2016). Additionally, an analysis should identify viable alternatives that commuters may use as a diversion, though for Hwy 216 there are few parallel routes available.

4.6 Discussion

The following discussion expands upon the ramp metering planning process presented in this chapter. This discussion covers the application of the planning framework to Alberta, ramp meter system complexity, location screening and local context.

4.6.1 Ramp Metering and Alberta Highway Engineering Process

The outlined planning ramp metering planning framework contains similarities to the Highway Engineering Process currently used in Alberta presented in Figure 2. Here, the high-level analyses may be conducted during the development of the 3-year plans when concepts are proposed for potential funding. Following this, the medium level studies align with the functional planning studies, applying analytical and HCM-based analysis methods to quantify the changes in highway MOEs. The engineering assessments that follow include observing the geometric requirements for ramp metering queues and acceleration. If changes are required to the existing pavement cross-section, geotechnical and environmental studies are required. Lastly, detailed studies align with the detailed design phase, presenting a study that allows analysts to test the various elements of ramp meter operation such as optimizing signal timings as well as quantifying safety impacts of various geometric changes. Once specific scenarios are chosen, the designs then proceed to construction sequencing. The developed framework builds upon the existing Highway Engineering Process, describing the analysis process that can determine the most appropriate RM control and geometric guidelines for a location. This involves not only choosing an appropriate control system, but also assessing if ramp metering is appropriate for Hwy 216 when compared to a no-build future scenario.

4.6.2 Data

I reveal the data requirements for each level of analysis as models require more detailed data to produce disaggregate operational and demand models. The resources that provide funding for modelling and data collection are constrained, requiring the identification of crucial data. At each level of analysis, I identify present and future traffic volumes on the mainline and the on-ramp as the modelling at each stage hinges upon this data. This would be required for assessing opening-day ramp operation as well as for populating the RTDM models for forecasting. This data is collected from count surveys which record the number of vehicles passing a designated point on a facility. Currently, Alberta Transportation conducts surveys to collect these volumes at interchanges along Hwy 216 which are available online (Alberta Transportation, 2017). For the purposes of detailed modelling, I would recommend the data collection to occur simultaneously at each interchange in order to balance traffic volumes while modelling. I would also recommend concurrently gathering travel-time and speed data from probe vehicles which would then provide operational data for detailed modelling.

4.6.3 Study Scoping - Ramp Meter System Control Complexity

One of the issues faced by planners early in the modelling process involves determining the technical and spatial limits of study. Determining the level of technical complexity is difficult as the decision is influenced by many factors which include existing ITS infrastructure, available capital for maintenance and operations, the predictability of traffic volumes, the experiences of transportation professionals and other external influences. The aforementioned framework of three planning studies does not take into account these factors as these should be examined concurrently to the technical modelling. However, the results from the planning studies influence the choice of ramp meter complexity and vice versa. Here, if an analysis reveals that the corridor contains closely-spaced ramps and traffic flow breakdowns, a detailed study is further justified. This also may influence subsequent studies to further expand their spatial extent of analysis in order to include the interchanges with observed high volumes. On the other hand, if analysts conclude that only a single isolated ramp meter is required, due to predictable and isolated congestion, planning may forego a detailed microsimulation.

The difficulty of determining the technical limits of a ramp meter study lies in the difficulty of comparing the different control systems. This presents a chicken-and-egg situation where transportation analysts may not know the relative effectiveness of a coordinated system when compared to a pre-timed signal without actually modelling the corridor with a detailed study capable of simulating this system. Therefore, analysts should be mindful of the modelling limitations of the tools at each level of analysis. Hypothetically, if unlimited resources were available, a planning study could begin with all available data and an expensive microsimulation model, comparing pre-timed, adaptive and coordinated meters. This is unrealistic, and if this analysis reveals that merely a pre-timed signal is effective, a resource-intensive study may not be required. Therefore, this reinforces the outlined framework of conducting studies with successively increasing levels of detail as conclusions may be reached through simpler analyses. Also, outlining the levels of detail aids analysis in determining the trade-offs from continuing with further detailed modelling.

4.6.4 Ramp Meter Analysis Guidelines

Currently, ramp meter planning guidelines exist from FHWA and other state-level jurisdictions in the United States (FHWA, 2014). The Federal Highway Administration has also published documents guiding generic highway modelling (Dowling, Skabardonis, & Alexiadis, 2004). Through the research in this thesis, I have found minimal guidance for planning ramp metering on highways in Canada and specifically in Alberta (Transportation Association of Canada, 1999). This chapter therefore provides a framework that guides the data collection, modelling and decision-making process from a project's concept to construction phases. Since ramp meters are absent on Alberta's highways, there is no uniform design standard pertaining to ramp metering, requiring analysts to test various signal designs and geometric configurations that are suitable for highways in Alberta. This leads to uniform design standards that are included in the analysis process, outlined in the consultant engineering guidelines, as well as ramp geometric design in the HGDG (Alberta Transportation, 2011; Alberta Transportation, 1999).

4.6.5 Ramp Meter Local Context: Hwy 216

The decision-making process for ramp meters on Hwy 216 should take into account several location-specific issues. First, since there are no existing ramp meters in Alberta and ramp meter guidelines are absent from Alberta's HGDG, it is reasonable to assume that Hwy 216 ramps were not initially designed for ramp meters (Alberta Transportation, 1999). Since ramp meters require room for acceleration after the signal head and room for queued vehicles before the stop-line, an additional geometric assessment would be required prior to ramp modelling to identify any ramps requiring geometric modifications. The new ramp lengths may then be used as part of the modelling so as to represent the modified ramp geometry on opening day.

Additionally, since Alberta Transportation controls Hwy 216 and the City of Edmonton controls the arterials intersecting the highway, data is required from both agencies to facilitate coordination of signals. This is particularly of importance for modelling coordinated systems at a detailed level where ramp control is ideally coordinated not only with other ramps, but also with adjoining arterials. Failure to consider the intersection timings may lead to queue overflows due to mistimed signals.

Since Ramp meters operate in Ontario and Quebec, their implementation serves as an example for Alberta. In the Canadian literature, I found a brief outline from TAC as well as a more detailed outline from Ontario Ministry of Transportation (Transportation Association of Canada, 1999; Ontario, 2007). Though these documents do not contain the level of detail as those published by some American agencies, they may be used in conjunction with those published by the FHWA and CALTRANS (FHWA, 2014; Caltrans, 2016).

4.7 Summary

In this section I incorporate the ramp meter planning framework into the highway planning process in Alberta. Through this analysis, the ramp meter planning process was presented in 3-levels of detail, highlighting the objectives and data needs at each step. This process also included applying each level of detail to Hwy 216 as a case study, discussing location-specific issues. Through the discussion, several considerations were identified going forward for ramp meter planning in Alberta which are listed below. Firstly, system complexity relies upon multiple factors such as operational costs, technical expertise, and the ability of the system to manage traffic flow. I outline in this chapter how the different levels of analysis assess varying levels of system complexity. Secondly, Alberta Transportation would need to determine an appropriate configuration of ramp meters along the Hwy 216 corridor. This would include coordinating signal timing with Edmonton, St. Albert and Sherwood park whose roads adjoin Hwy 216. Lastly, floating car and commuter stated preference survey data may be required to populate detailed models that capture the demand-shifts due to ramp meter installations.

5. CONCLUSIONS

This chapter contains an overview of the research tasks and findings of this thesis, and also discusses applications and limitations of the research.

5.1 Research Overview

In this thesis, I have developed a guiding framework for planning HOV lanes and ramp meters that builds upon Alberta Transportation's existing highway engineering framework. Currently, Alberta expands their highway capacity by constructing new highway facilities or widening existing ones. Other jurisdictions in North America have long turned to alternative methods for improving the efficiency of their highway networks. HOV (high occupancy vehicle) lanes facilitate shifts in travel behaviour towards more efficient modes of travel such as car-pools and transit, leading to an increase in the person-throughput of a facility while reducing the number of vehicles. Ramp metering regulates vehicle volumes entering a highway facility, with the goal of improving safety and reducing delays due to traffic flow breakdowns. Currently, HOV lanes and ramp meters do not exist on Alberta highways. Therefore, this research establishes a framework for modelling these two strategies. By examining existing guidelines and studies, the planning process is broken into three successive study levels, each with increasing complexity and detail, namely high-level, mid-level and detailed studies. This research also includes applying these as case studies for Hwy 2 and Hwy 216 in Alberta, and identifying the data needs and context-specific issues.

5.2 Research Findings

Through the literature review, I organized the process of planning these strategies from a long-ranged concept to engineering design and construction. In Chapters 3 and 4, I develop guidelines, organizing the analysis and modelling tools for planning HOV lanes and ramp metering while also identifying data needs. This research is applied to two urban highways in Alberta, specifically examining data availability and data gaps. For HOV lane planning studies, vehicle occupancy data is often not readily available and should be obtained through field surveys. Other (passive) data, including geometric properties of segments, turning count surveys and vehicle volume counts are available from Alberta Transportation. With these datasets, high and mid-level planning assessments for ramp meters may be conducted but HOV lane studies remain contingent on vehicle occupancy demand data. Detailed studies require additional data for modelling traveller behaviour in response to these strategies. Here, data gathered from commuter surveys is required for behavioural modelling of commuter choices for estimating changes in mode and route choices in response to HOV lanes and ramp meters. Additionally, these detailed studies rely on microsimulation to model the operation of these strategies, requiring data for calibration and validation of models. This includes travel time and speed data, gathered probe vehicle runs and speed-detecting radar and loop detectors. With these identified sources of data, the planning studies outlined in this thesis may then be conducted.

Lastly, this research clarifies the objectives at each level of analysis, identifying how the data and models aid the planning process through the testing of design alternatives. This involves describing the capabilities of each model to replicate real-world operations as well as highlighting major assumptions and limitations.

5.3 Research Contributions

This research contributes to highway planning in Alberta by developing a structured framework that organizes the modelling tools for planning HOV lanes and ramp meters. This bridges the gap between design guidelines, which contain geometric and operational requirements, and operational studies. Also, data requirements and data gaps were identified, which may be included in future data collection programs. This research is relevant as Alberta recently updated roadway regulations that allow for HOV lanes (Province of Alberta, 2013). Additionally, since the presented strategies neither exist on Alberta highways nor exist in the guiding literature (Highway Geometric Design Guide(Alberta Transportation, 1999), Consulting Guidelines (Alberta Transportation, 2011)), this research provides a novel application of existing highway strategies. This research is also novel in the format of three successive studies as many existing guidelines focus on presenting individual traffic analysis tools, or guidelines for ramp meters or HOV lanes.

Therefore, this research contains several applications for transportation professionals responsible for Alberta's highways. Breaking down the required analyses aids in developing specific project terms of conditions (TOCs). Identifying data requirements and modelling requirements in a tabular format, can help establish project timelines and cost estimates for modelling and acquiring data. Also, this research may be applied to the development of long-term guidelines and manuals. This may include specific guidelines pertaining to HOV lane and ramp meters in local manuals, but also, the method or organizing an analysis into three levels of increasing detail may also be applied to other highway engineering projects.

5.4 Research Limitations and Future Work

The major limitations of this research stem from the limited access to Alberta Transportation's data and planning methodologies. Although this thesis presents the data that is available for planning studies, it is limited to that which is publicly available, such as traffic counts on Alberta Transportation's websites, and data revealed through personal correspondence. Other relevant sources of data may exist; but remain outside the purview of this thesis. Also, because access to Alberta Transportation's travel demand modelling processes is limited, and the few details I have are from existing manuals and model outputs in reports, I am unable to provide specific modelling guidance.

With this research, Alberta Transportation may apply the planning framework to other highway management strategies which might include roadway pricing or variable speed limit (VSL) systems. The structure may also be expanded upon to include cost estimates for the data and modelling, as well as including estimates to construction and operational costs.

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