An Integrated Modelling Approach for LRT Projects
A Case Study of Edmonton's Valley Line LRT

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Abstract

Various Light Rail Transit (LRT) projects are currently being constructed or planned in several jurisdictions across Canada. With many projects now in the planning stages, agencies are defining how LRT operations are governed, modelled, and evaluated. Different jurisdictions, agencies, and consultants tackle operations differently which can affect the final outputs from a technical perspective. Typically, each LRT line varies in design and operation— from street running with basic Transit Signal Priority to lines with gated operation—requiring modeling unique situations. There are innovations in modelling processes resulting in better outcomes in the planning stage by garnering more confidence in outputs such as the LRT and traffic operational models. The significance of improving outputs reliability, such as LRT run time, traffic Measures of Effectiveness (MOEs) including those for active modes, is that they set the expectation for opening day operations. Depending on the project's funding and procurement method, the outputs can become part of Project Agreements (PAs) which govern penalties and relief events for operations during the concession period. Jurisdictions, agencies, and practitioners may develop guidelines, tools, and processes to control the quality of traffic forecasts and micro-simulation models. This would help achieve consistency between different models, such as LRT models and traffic models.

The Valley Line West is a proposed extension of the Valley Line LRT project currently under construction in Edmonton. The Valley Line West is planned to be a low floor urban integrated LRT concept with many in-street running segments. The planning process involves modelling the interactions between the LRT, vehicular traffic and pedestrians to achieve a balanced approach between all modes. An extensive modelling exercise is currently underway and involves the integration of the following models:

- Edmonton Region Travel Model (RTM) – An EMME based macroscopic model for travel demand forecasting
- City of Edmonton Dynamic Traffic Assignment (DTA) Model – A Dynameq based mesoscopic sub area model for network-wide traffic diversion impact analysis
- Valley West LRT VISSIM Model – A microsimulation traffic model for detailed operational analysis
- OpenTrack Model – An LRT operational modelling tool

The modelling team has developed an integrated and iterative approach whereby the various models feed into each other. This paper highlights and details of modelling approach undertaken towards meeting the goals of the project. This paper focuses on processes rather than the results. This will include an innovative in-house developed program that integrates VISSIM and OpenTrack to achieve better results for both traffic and LRT modelling.

INTRODUCTION

Light Rail Transit (LRT) Systems are currently a popular mode of transport in developed countries and cities around the world. There has been an increasing trend in LRT projects' construction since the 70's within Europe and North America [1]. In 2015, the modal split of metro (subway), LRT, and suburban rail transport constituted 37% of the global public transport journey splits [2]. According to LRT statistics in 2015, 36 North American cities have developed 1,525 km of LRT networks with 106 lines covering 1,647 stops, which comes in fourth place compared to Europe, Russia, and Asia [3]. The report estimated that North American LRT systems serve approximately 710 million passengers per year.

Rail Transit is one of the most preferred modes of public transport by planners and public due to its: capacity, speed, reliability, low environmental impacts, passenger comfort, effects on land use planning, and low operating costs [4] [5] [6]. Generally, LRT capital infrastructure cost is higher compared to Bus Rapid Transit (BRT); however, LRT systems can carry significantly higher capacity and have a lower operational cost [7] [8]. LRT infrastructure exhibits more voters' support, higher impacts on land-use planning and land value, higher ridership, better service quality, and better community image around stations in comparison to BRT [8]. Typically, planning LRT is resource extensive [8] [9] [10].

Modern LRT systems have been implemented in various North American cities since the late 1970's with the first modern LRT line operating in the City of Edmonton since 1978 [11]. Various cities implemented similar systems in later years including City of Calgary, San Diego, Portland, Los Angeles, Denver, Salt Lake City, etc [11].

Many North American cities are currently aiming towards achieving a sustainable mode of transportation and are heavily investing in public transport infrastructure. One of the most popular investment is constructing new or upgrading existing LRT infrastructure. For example, in Minneapolis, Minnesota, the Metropolitan Council is planning (currently at engineering phase) two major LRT projects: the METRO Blue Line Extension and the Southwest Light Rail Transit. The projects consist of 13.5 and 14.5 miles of newly added tracks with 11 and 15 stations, respectively [12] [13]. The City of Durham, North Carolina, is planning 17.8 miles of added tracks with 18 stations; the project is expected to increase ridership by 71% by 2035 [14]. Other smaller scale LRT extensions are currently ongoing in Portland, Dallas, Tacoma, Phoenix, San Francisco, and others; a list of ongoing projects in the United States can be found in the Federal Transit Administration website [15].

In Canada, various cities and jurisdictions are currently planning and constructing major LRT infrastructure projects. The current leading examples are Calgary, Edmonton, Hamilton, Ottawa, Waterloo, Surrey, and Toronto. Some of these systems are planned to have a segregated Right-of-Way (ROW); but many of these systems are planned to be at-grade low-floor systems. Ottawa's Stages 1 and 2 LRT is planned to have its own ROW with over 52.5 km of track and 36 stations; Stage 1 will be operational in 2018 while stage 2 is expected to operate in 2023 [16].

Various at-grade integrated LRT systems other modes of transport are currently under study and in the planning stages in Canada. Such systems are becoming popular as officials envision urban-integrated and user-friendly systems. For example, City of Surrey's future LRT is planned to be an at-grade street oriented system envisioned to be integrated with livable communities. The project is pending funding confirmation and is expected to be completed over 2 phases and will add 27 km of tracks with 19 stations; service is expected to begin by 2024 [17].

In Calgary, there are multiple lines being planned (Green line, Blue line, and Red line extension). The Green Line (GL) Stage 1 was approved for funding and is planned to be 20 km of track with 14 stations serving communities directly north of downtown to communities in the southeast portion of Calgary [18]. Most of the alignment is either grade separated from traffic or operating at full LRT preemption at selected intersections. Stage 2 is anticipated to operate at-grade for most of the alignment and LRT will interact with traffic signals at different sets of LRT intersection priorities. Stage 2 will be approximately 26 km long serving riders at 14 stations in communities north of downtown of the City [19].

The City of Edmonton is currently constructing the first stage of Valley Line LRT (southeast) while planning for the second stage (west and most of downtown). Valley Line LRT is planned to be a 27 km low floor urban line operating at-grade for most of the alignment and will serve communities in the southeast and west of Edmonton via 27 stations [20]. Similar to Calgary's Green Line Stage 2, Valley Line LRT will interact with traffic signals at grade for most of the alignment at different levels of LRT priority.

Many of these projects in Canada are under development using a Public-Private Partnership (P3) funding module. In urban at-grade LRT systems, traffic and train modelling is typically used by the owner's engineer team (usually the Transit Agency, City or its consultants) to: evaluate impacts on the roadway network, develop run times for the LRT corridor, and optimize or improve future network geometry and operations. The traffic model can produce different MOEs at an intersection or corridor level. Typically, they would be used to evaluate the LRT impacts on the network from an operational perspective in addition to evaluating LRT operations. A harmonized balance between at-grade LRT and traffic operations can be challenging during the project development.

Unlike LRT systems with a segregated alignment, that focus solely on operations from a rail perspective, urban LRT systems such as those planned in Surrey, Calgary and Edmonton require full operational analysis, evaluations, and modelling from both the rail and traffic perspectives. Such systems interact at grade with other modes of transport such as car and heavy vehicular traffic, bus feeder systems, and active modes such as pedestrian and cyclist traffic. Giving the LRT absolute priority in this type of system can deteriorate traffic operations. While car and truck operations may not be critical from a system's perspective, busses and active transport are essential and complementary to the planned LRT project.

Urban at-grade LRT systems are generally modelled at the planning stage from by traffic forecasting, LRT modelling, and traffic modelling teams. From the railways perspective, the alignment would generally be modelled by a rail modelling software such as TrainOps, EnerGplan, Etab, or OpenTrack. From a traffic perspective, the network is typically first modelled at a macro level using regional planning software packages such as EMME, AimSun, or VISUM. Then, a micro-simulation model is developed to examine LRT, and traffic (cars, heavy vehicles, pedestrians, etc) operations. Such models are developed using software packages such as VISSIM, AimSun, Paramics, etc. The three planning stages in many cases lack intercommunication and input/output compatibility.

For example, the macro transportation forecasting models generally provide a onetime input into micro transport models, which may result in a misleading operational micro-simulation model. Furthermore, rail modelling generally receives a small amount of input data from micro traffic simulation modelling exercise and vice versa. In theory, micro traffic modelling can be the link between forecasting outputs and rail operations/modelling. Through proper integration and input/output transferability, the modelling effort can be performed efficiently and would result in higher confidence at the planning stage.

Continuous information exchange between the three modelling groups: rail, transportation forecasting, and traffic is essential for detailed operational models and analysis as every group analyze/evaluate the network from different aspects. Planning outputs are essential as they set users' expectations for opening day and may be part of the project construction agreements especially for P3 projects. For example, rail modelling software excels in modelling traction power and headway sensitivity. However, without sufficient input from traffic micro-simulation software regarding LRT delays curves, statistics, and/or distribution, rail modelling headway sensitivity outputs can be inaccurate and meaningless. Similarly, transportation forecasting models do not accurately capture the LRT priority impacts along major corridors. Therefore, an iterative approach between the Regional Transport Model (RTM) and the traffic micro-simulation model, may be necessary to reap higher confidence in the alternative traffic rerouting options and operational MOEs.

Traffic micro-simulation is a multi-themed investigation tool and there is a lack of guidance on many aspects specifically for specialized modelling (LRT, evacuation, ports, etc.). Current guidelines such as Washington's Protocol for VISSIM Simulation (WSDOT), the Federal Highway Administration (FHWA), and others provide excellent guidance on general network building, calibration, simulation procedure, and level of confidence statistics [21] [22] [23] [24]. While these provide an excellent start, additional parameters and techniques for building a network are diverse and are subject to the modeler's experience and preference. An advanced level of statistical knowledge is beneficial for LRT corridors modelling. In addition, knowledge and understanding of the capabilities, inputs, and outputs of the modelling software package used is essential. Most of these are challenges faced during the traffic modelling exercise that may lead to inappropriate conclusions at the end of the project.

This research is intended to guide processes and procedure for LRT projects with respect to modelling and operations, and to highlight technical challenges, misconceptions, and recommended practices. In addition, this paper introduces innovative modelling techniques, tools, and processes that were used for LRT projects.

SCOPE AND STUDY OBJECTIVE

The scope of this study is limited towards the processes and interaction between the different planning and operational models used in LRT planning projects. Different procedures, tools, and innovations in data transferability between the different models will be explored. Furthermore, this paper will focus on traffic micro-simulation modelling misconceptions, challenges and best practices from a technical perspective. The research will refer to PTV's VISSIM and OpenTrack rail modelling software packages as examples and tools for LRT modelling applications. In addition, Trafficware's Synchro software package will be used as an example of preliminary traffic capacity evaluation tools. It should be noted that there are other software packages can be used in practice to model and evaluate LRT projects, VISSIM, OpenTrack, and Synchro are only used due to their popularity in the Canadian context.

TRAFFIC MODELLING: METHODOLOGY AND CHALLENGES

Operational LRT/traffic micro-models can usually be challenged in terms of modelling inputs, development, and outputs. Practitioners usually perform multiple layers of assumptions wherever there is lack of data. Such assumptions should be performed with caution, should be defendable and should reflect the expected operations of at project's opening day or ultimate horizon analysis year(s). In terms of modelling outputs, the models should represent reasonable operations and calibration. In addition, signalized LRT/traffic operations should reflect the operations and capabilities of the signal controllers the city or jurisdiction (referred to as "the City" in the rest of the paper) is planning to install in the field.

Modelling Inputs

Modelling inputs can be categorized into horizon based levels, which are typically existing/base, opening day, and an ultimate horizon year.

<u>Existing/Base Models:</u>

Typically, a base or existing network is modelled first to calibrate driver behavior on the network based on actual conditions. As the objective of a base network is to model the current network operations to the best degree possible, the modelling team requires the following data: recent traffic and pedestrian counts, signal timing plans, roadway speeds, existing transit routes and schedules, truck routes, and vehicle fleet related data, travel time surveys/data, and queue measurements.

The developed base models go through a calibration process by adjusting driver behavior parameters. Guidance through calibration can be found in relevant guidelines developed in the United States. The main challenge with modelling existing network is budgeting time and resources for proper data collection and calibration. The main objective of developing driver behavior parameters (calibrating) is to carry them forward to the future horizon models with LRT in place. The models can be used later by the City to evaluate improvements to existing conditions if needed. According to a 2010 study, data collection and model development costs may reach up to 70% of the overall modelling project's budget, depending on the complexity [25].

<u>Future Horizon Models (Opening Day and Ultimate Horizon Year):</u>

City's transportation forecasting group feed future micro-simulation with inputs such as: traffic volumes, traffic splits and shares (passenger cars, heavy vehicle, public transport, and active modes) in addition to future transit routes and headways, if available. These inputs may also include forecasts for active modes of transport (pedestrians and bikes).

Forecasting data is essential in any model development; however, due to the introduction of LRT along a corridor, macro models may underestimate the impacts of the LRT on traffic operations. Also, traffic demand models do automatically restrict capacity based on LRT priorities and in many cases the demand at the macro level can exceed the capacity at the micro level. The result is an overestimation of traffic using intersections along the LRT corridor. If the forecast traffic volumes cannot be processed through the microsimulation model, this can result in unserved demand which remains queued outside the network. This can also result in bottlenecks which may limit traffic reaching downstream parts of the network. Often, if the forecast demand traffic volumes are deemed too high to be processed through the network, high-level estimates are performed and traffic is re-routed manually to use other corridors and intersections. It is important that the traffic modelling team and the City's forecasting team communicate such issues so that realistic assumptions can be made to develop traffic volumes that will be used as input into the microsimulation models.

In cases where future bus routes are not available, any assumptions should be developed in coordination with the City's transit authority. In many cases, on-street bus stops or bus stops along a one-lane per direction roadway on the alignment can cause significant impacts on vehicle traffic. In some cases, LRT service would replace/re-align most bus routes along or adjacent to the corridor.

Many jurisdictions do not have forecasting data for active modes. When there is lack of data, practitioners may classify intersections and crossings along the alignment based on surrounding land uses and expected pedestrian activity. Pedestrian activity can be compared to existing LRT alignment crossings at similar locations. If there is lack of data, factors such as: future LRT stations proximity, surrounding land use plans, future bus service connectivity, and boarding and alighting forecasts at platforms can aid with generating future intersection pedestrian activity levels. An example of pedestrian assumptions is shown in **Table 1**.

Table 1: Pedestrian Volume Assumptions

Pedestrian Activity	Assumed Flow	Description
Low	10 ped per direction /hr	• Pedestrian Mid-Block crossings and intersections in suburban areas and away from LRT platforms. • Existing pedestrian counts (if available) very low. Typically, 5-10 pedestrians during peak hour.
Medium	20 ped per direction /hr	• Pedestrian Mid-Block crossings and intersections in suburban areas and within close proximity to LRT platforms. • Existing pedestrian counts (if available) very low. Typically, 5-15 pedestrians during peak hour.
High	35 ped per direction /hr	• Intersections nearby Transit Oriented Developments (TOD), Platforms, and mixed land uses. • Existing pedestrian counts (if available) is typically 15-30 pedestrians during peak hour.
Very High	50 ped per direction /hr	• Mainly downtown areas where there is more priority for maintaining active modes connectivity.

Based on **Table 1**, an intersection with a low pedestrian activity would be modelled to serve a total of 80 pedestrians during the peak at all crossings. On the other hand, a very high pedestrian activity intersection would be modelled and designed to serve 400 pedestrians at all approaches during the peak. **Table 1** shows an example of pedestrian assumptions that can be applied towards future micro-simulation models. The project's traffic team can develop model specific assumptions based on the alignment characteristics and the project's expected future ridership forecast for each horizon year.

Model development

Developing a micro-simulation model can be done in several coding styles, depending mostly on the experience and preference of the traffic modeler. Although some jurisdictions may limit the flexibility of how the models can be coded, modelers would still have a wide range of methodologies and inputs that can be built differently. Practitioners should reference the City's modelling guidelines and other relevant guidelines for suggested practices. It is essential that all operational assumptions be discussed with the City and that the models are peer reviewed before proceeding with conclusions from the outputs.

Modelling guidelines: strengths and weaknesses

There are no published comprehensive Canadian guidelines for traffic microsimulation simulation. However, a few studies and reports were published discussing some aspects related to traffic microsimulation within Canadian context [26] [27] [28]. Most Canadian publications lack technical details on model development using different software packages. The City of Edmonton is one of the few jurisdictions that has a technical draft guideline on building a micro-simulation network using PTV-VISSIM. However, the guideline was developed in 2009 based on an old version of the software and are currently under revision. Such lack of guidelines in Canada may be attributed to the infrequency of using micro-simulation compared to the United States or Europe.

Many practitioners working on micro-simulation projects tend to follow guidelines from different jurisdictions in the United States. Many States developed detailed guidance for micro traffic simulation. Such examples include:

- Traffic Analysis Toolbox published by the Federal Highway Administration [22] [29];
- Traffic Analysis Handbook published by Florida Department of Transportation [24]; and
- VISSIM Protocol published by Washington State Department of Transport [21].

These guidelines provide excellent reference for base model development and calibration; however, most guidance is related solely to roadway and highway operations. There is lack of guidance for modelling many network aspects such as toll roads and toll booths, LRT and transit operations, border crossings, statistical modelling outputs, future modelling assumptions, evacuation modelling, dynamic assignment modelling, and others. Such lack of guidance initiates the need for research and collaboration between the modelling team and the City where the project is taking place.

LRT Operations

As mentioned earlier, traffic operations can differ depending on how the models are coded. Issues related to existing traffic operations can mostly be addressed by the modelers' experience, familiarity with the network, and collaboration with the City through the modelling exercise.

Future network modelling typically has additional challenges, especially, with the addition of a new element in the network such as an LRT corridor. One example is how traffic signals are expected to operate in the future and handle LRT priority events. Different operational assumptions require discussion with the City before implementation in the traffic models such as:

- Can the future controller alternate between different barrier groups and allow only phases that can work with LRT?
- How are pedestrian phases going to operate during a priority event (TSP or preempt)?
- What are the different levels of LRT priorities in the network? Can future controllers set conditional priorities depending on schedule or traffic operations?

- Can priority events truncate the minimum green times for conflicting movements?
- When can protected versus permissive phasing be used?
- Can the traffic controllers alternate between lead/lag left turns after a priority event?
- How does the City operate coordination and transitions between coordinated and non-coordinated phases and how does priority affect coordination?
- What are the LRT station dwell time variability and distribution?
- What is the variability in LRT and transit headways entering the network?
- How are LRT vehicles be operating at the block level (fixed versus moving blocks)? Are trains following line of sight operations?

Many of these questions are left until the detailed design stage, which is not practical for many projects. The operational assumptions will impact the model results which in turn could impact design decisions. It is recommended that questions related to signaling system be addressed with the City to avoid delays and additional costs at later stages of the project.

Another example that feeds into signal operations is LRT block operations. Is the LRT expected to follow fixed block or moving block operations? Block systems define LRT operations when there are near bunching events (i.e. trains at getting closer). A fixed block system means that if a train is in the preceding block (one or two signals ahead), the following train will not proceed until the tail of the downstream train clears the block. A moving block system means that the block is dynamic and moves based on the prior and subsequent trains' locations. i.e. train can enter the intersection if the preceding train is clearing the following intersection or station as long as the dynamic distance (block) is not violated. If train operations are not defined in the micro-simulation models, trains will operate in a similar fashion to passenger cars which can affect queueing, interaction with signals, and ultimately the reported LRT run time in an unrealistic manner.

Additionally, LRT headway variability or entry to the network requires discussion with the City. Although a proposed LRT system may have a target headway, it is likely that the actual headway will have some variability. It is important to develop some reasonable assumptions for this variability. For example, if the City has a target headway of 5 minutes with a variability of 1 minute, such assumptions need to be implemented in the micro-simulation models as they can affect bunching and signals coordination for the LRT. Similarly, LRT dwell times may have variability which depend on boarding, alighting, and minimum doors cycle time, which can have an impact on LRT's detection time at platforms.

Understanding inputs and outputs

As mentioned earlier, one of the weaknesses of modelling guidelines is that they do not provide guidance related to special modelling needs such as LRT networks. Modelling specialists need to have familiarity with the modelled network to assist in using proper modelling inputs. Sufficient knowledge in statistics is needed to understand the impacts of different inputs and the meaning of the modelling outputs. Examples of misinterpreted inputs and outputs are summarized below for projects performed using PTV VISSIM:

Modelling Inputs:

Traffic volume: with the introduction of an LRT system, the corridor's roadway classification may change from arterial roadway to a lower class of mobility roadway (such as an urban boulevard). LRT corridor's traffic nature changes from being a vehicle based mobility corridor to an active modes and public transit friendly corridor. This change is coupled with changes in the adjacent land uses. Often, the future corridor will show signs of congestion and platooning which is highly influenced by LRT operations. Therefore, the assumption that existing peak hour traffic distributions will match future conditions may be misleading as peak spreading will change. Furthermore, for a seeded and congested network, there will be little value added in matching future traffic input distributions to existing conditions. In such cases, it may be necessary to investigate the peak hour 10-15 minutes traffic distributions in existing LRT corridors with similar characteristics to the planned LRT corridor. If no such data is available, it may be preferable to have the traffic inputs coded as flat hourly distributions with no sub-hourly variations. This will leave vehicle arrival rates as random, discrete, and independent events that follow a Poisson distribution, which is widely accepted in literature to model vehicle arrivals [30] [31]. Other inputs that require verification and proper understanding include, but not limited to:

- Vehicle fleet sizes, performance and compositions,
- Traffic conflicts coding via conflict areas versus priority rules,
- Lane Change Behavior and modelling closely spaced intersections,
- Vehicle inputs exact versus stochastic inputs, and
- Effect of modelling grades in the network.

Modelling Outputs:

Typical, modelling outputs are typically focused on queueing, delays, travel times, and processed traffic. However, there are many other outputs that can be extracted and are relevant to the project needs. Such outputs may be extracted easily using the available output options, or by defining a new custom attribute that can be read by the software. Some outputs need to be extracted from the log files of the simulation runs. Such outputs include percentile based travel time calculations or LRT delay statistics.

Level of Confidence: To report on a level of confidence of 95%, a student t-test should be performed based on outputs from preliminary simulation runs (for example 10 runs). Depending on the variability of select Measures of Effectiveness (MoEs), a number of runs is calculated. Guidance on this calculation can be found in relevant guidelines [21] [22] [24].

95th Percentiles: Reporting on 95th queues is not a straight-forward process and may require postprocessing intersection raw data, guidance through the process can be found in relevant guidelines. However, caution should be used for intersections with highly variable cycle lengths due to the impacts of LRT priority. In such cases, practitioner may prefer to report on the average, and maximum values, of queues.

Interpretation of Node Evaluations: Minimum, maximum, average, and standard deviation values of queues and delays for multiple network model runs can be wrongfully interpreted by practitioners. For example, the maximum queue length or delay of 14 VISSIM runs is the average of the maximum values of 14 runs. Many practitioners interpret this value as the absolute maximum queue or delay. This can be misleading when dealing with mitigation measures for traffic performance at closely spaced intersections and LRT transitions from center to side running. Practitioners may not be aware of such interpretation as it is not available in PTV VISSIM’s user manual.

LRT Statistics: Reporting on standard traffic outputs such as average and maximum delays and queues may be sufficient for traffic operations. However, descriptive statistics such as percentiles and distributions are needed for reporting on LRT travel times and operations. Such statistics are important for the rail modelling team for their analysis such as headway sensitivity tests, traction power, and run times. VISSIM's node evaluation outputs are not the correct tools to pass inputs to the rail operations and modelling teams. For example, the average LRT delay and stopped delay from VISSIM's typical node evaluation includes both stopped and non-stopped trains. However, for rail operation purposes, non-delayed trains need to be excluded from the delay outputs. Therefore, LRT operations from the raw vehicle by vehicle (train by train) outputs need to be extracted and post processed. Only delays including trains that only decelerated due to signal status but did not stop in addition to stopped train delays should be included. Sufficient understanding of rail modelling software inputs and outputs are necessary for accurate and representative conclusions.

In some cases, testing and reporting on the distribution of LRT delays at intersections is needed for a more accurate data transfer to the rail modelling team. Delays do not follow a normal distribution, most of the time they follow a gamma distribution or other forms of distribution, fitting the distribution and calculating the shape and scale parameters may be needed as part of the exercise. An example of LRT delay distribution for a modelled Transit Signal Priority signal for 168 trains going through the intersection is shown in **Figure 1**.

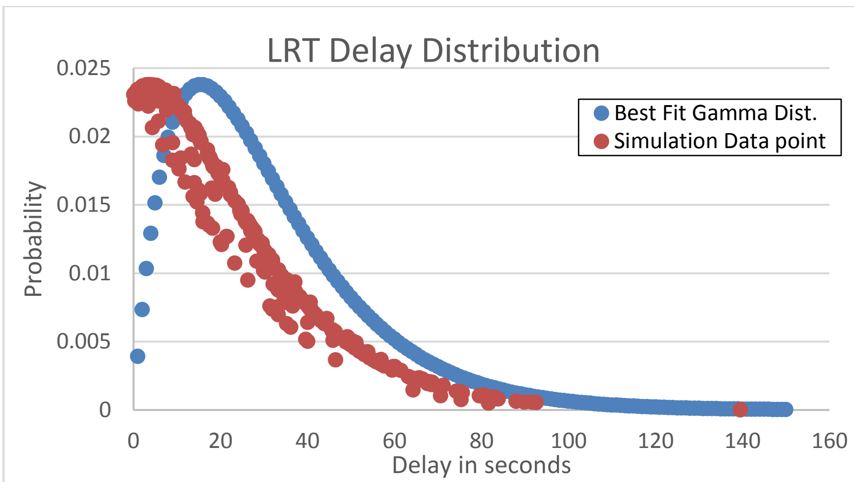

Figure 1: LRT Delay Distribution at a TSP intersection

Reporting on travel time should be accompanied with statistics to describe the expected variation. Similar to LRT statistics, the typical node evaluation outputs provide only the variation between the different runs. To provide accurate statistics based on train to train interaction, this calculation needs to be performed using the raw vehicle based output files. Travel times usually follow a normal distribution, subject to the sample size (number of vehicles that where processed). Reporting on minimum, average, maximum, standard deviation, and a percentile value (90^{th} or 95^{th} percentile) would result in sufficient description of LRT and traffic travel times.

Pedestrians Delay: Reporting on pedestrian delay can be essential when introducing an LRT line where most transit riders will access the LRT by walking. Adding different TSP strategies along the LRT corridor can have a significant impact on pedestrian delay. Practitioners should be extremely cautious when reporting on pedestrian delay. As mentioned earlier delays do not typically follow a normal distribution and the variance can be high and may become unacceptable from an operational perspective. Pedestrian operations depend mainly on the recall mode at the signal controller and the implemented priority at an intersection. Aggressive LRT priorities, such as preemption, will likely deteriorate pedestrian service. On the other hand, softer forms of LRT priorities, such as TSP, would have lower impact on pedestrian operations. An example of service variability for pedestrian phases and length of serviced cycle based on signal detector records from VISSIM at a preempted signal is shown in **Figure 2**.

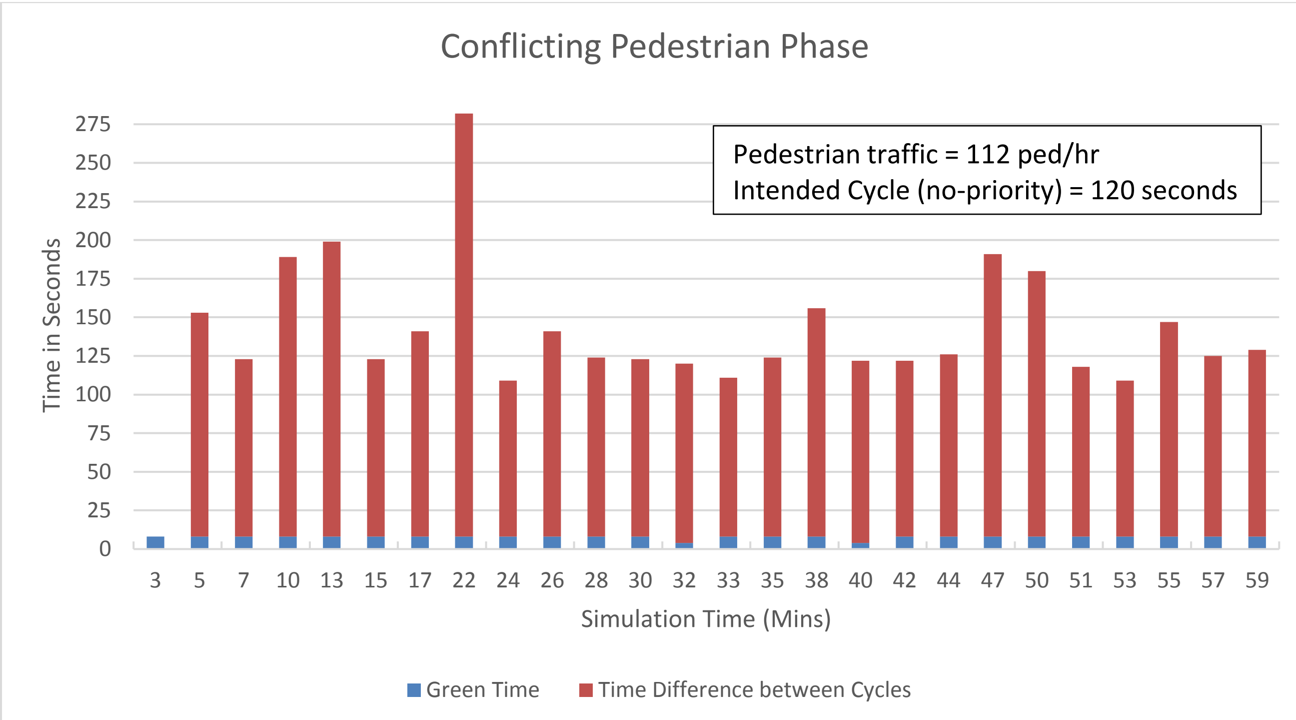

Figure 2: Pedestrian service at a Fully Pre-empted Intersection

Signal Operations Statistics: LRT priorities impact signal timings and operations negatively for conflicting movements (cross street and left turns). Quantification of such impacts may be necessary at the detailed signal design stage and can be helpful for the proponent and/or the City depending on who operates and maintains signals along the alignment. Such statistics can be extracted from the signal statistics and green time distribution outputs. An example of the impacts of east/west LRT operations at a preempted signal is shown in **Table 2**.

Table 2: Impacts of LRT on phase green time

Average of 5 Runs	1	2	4	5	6	8	102	104	106	108	301	302
Movement	WBL	EBT	SBT	EBL	WBT	NBT	South	West	North	East	EB LRT	WB LRT
Total Green	806	3238	1818	453	3581	1818	564	208	592	197	2373	2373
Average (non-comulative)	13	46	30	9	47	30	7	7	7	7	29	29
Yellow	3.5	3.5	4	3.5	3.5	4						
Red	3.5	3	3	3.5	3	3						
# served	60	71	61	52	76	61						
Theoritical Phase length	17	34.5	38	17	34.5	38						
Theoritical number of phases	80	80	80	80	80	80						
% change due to LRT	-10%	33%	-27%	-40%	47%	-27%						

*** 100 series are pedestrian phases, defined by crossing location**

As shown in **Table 2**, priority events reduce the intended northbound and southbound through phases green time by 27% compared to no priority operations.

COMMON MODELLING PRACTICES

Traffic and Rail engineers and planners maintain a logical flow of the technical analysis and evaluation of design and operations. Initially, traffic practitioners start assessing operations with no LRT in place, move to adding LRT to the alignment and finalize how LRT will operate at predefined horizon years, typically an opening year and an ultimate horizon year. On the other hand, rail modelling practitioners start assessing operations solely from an LRT perspective at full preemption along the corridor. Rail practitioners assess at a later stage the impact of different priorities on the LRT depending on outputs from the traffic team. Different sets of software are used by each team to assist in designing and modelling the system. Furthermore, many assumptions are implemented by each team that need to be communicated and implemented in both traffic and rail models.

Modelling software

Traffic Forecasting:

Long range transportation forecasting is typically performed by the City or a consultant associated with the City using macro assignment models such as EMME or VISUM. The traffic demand per movement for the study horizon years is carried forward to perform capacity evaluation and traffic modelling.

Capacity Evaluation:

To understand traffic operations with no LRT priority in place and select LRT priorities at a preliminary level, capacity evaluation is performed using software packages such as Synchro or Vistro. Such capacity evaluation exercise can be applied to the modelled opening year and future ultimate horizon years. However, it should be noted that such software does not have the capability to report on heavy pedestrian areas and on LRT operations. Some practitioners may try reporting on LRT using Synchro by adding a dummy phase on maximum recall based on high level assumptions; however, this approach overlooks:

- The variable nature of LRT arrival at signals, which depend on operations at corridor wide intersections and headway variability,
- Detector placements and level of signal priority for LRT, which can hold LRT phases for variable lengths of time, and
- Impact of pedestrian conflicts and bus bays on lane based saturation flows.

Therefore, it is only recommended to use capacity evaluation to develop preliminary signal timing plans and decide on very preliminary LRT signal control strategies. Capacity software can also assist with preliminary coordination plans, if this method is desired. Additionally, capacity evaluation can provide an indication if the macro models are over assigning demand to the corridor.

Traffic Modelling:

There are various software packages that perform traffic modelling; the most common software within the context of LRT modelling projects in Canada is PTV’s VISSIM. VISSIM is a microsimulation software that can model the interaction between different transportation modes such as passenger vehicles, pedestrians, cyclists, and LRT. VISSIM has great flexibility in modelling signal operations with LRT priority options. Typically, VISSIM models will incorporate optimized signal timing input from Synchro and the train’s operational parameters, such as speed profiles from rail modelling software such as OpenTrack.

Rail Modelling:

Like traffic modelling software, there are various commercially available software packages that can perform rail simulation. A common software package is OpenTrack. OpenTrack is initially used to run trains based on full priority, whereby the LRT does not slow down or stop at traffic or rail signals, to get the LRT's shortest run time and speed profiles based on grades and alignment characteristics. LRT characteristics and speed profiles are then used as VISSIM inputs. OpenTrack is also used to generate rail performance outputs such as traction power curves, single track operations and headway sensitivity analysis for the alignment based on the train's manufacturers specifications.

In the last milestones of the modelling project, the rail modelling team receives signal operations statistics from the traffic modelling team. These statistics are mainly related to how LRT operates at transit signal priority intersections, where LRT may be expected to stop. The statistics include stop probabilities, average LRT delays and distributions.

Future Model Development

Traffic Modelling:

The first step towards future horizons model development is determining the intersection control strategies of LRT at the network's intersections. Depending on the vision, or City policies, the network can be first evaluated with full priority or preemption at all studied intersections. Then LRT's priority can be downgraded at locations where there are major traffic operational issues. On the other hand, it can be practical to decide on LRT priorities based on initial capacity assessments using Synchro or other capacity software. The decision on LRT priorities is tied to the purpose of the project and the importance of achieving a specific run time, if exists by the city and the transit authority. It is very important to initiate this discussion with the City before starting the modelling process. It should be noted that using full priority for the LRT and introducing high traffic operational delays may be acceptable to the City. However, such operation may result in significant delays for pedestrians and buses using the corridor, which can represent a significant share of the LRT system's users. A decision tree can be designed to assist in selecting the most proper priorities at intersections in collaboration with the City or jurisdiction.

Traffic engineers are required to understand LRT operations from a rail perspective, therefore, communication with the rail team is essential. This includes discussing rail control systems and methodologies of replicating it in the traffic modelling exercise.

Rail Modelling:

At the final stages of the modelling exercise the rail team requires LRT operational outputs from the traffic models. These outputs are:

- LRT Average Delays: Delays for LRT vehicles that stopped or decelerated only.
- Delays' Distributions: The distribution parameters of LRT delays.
- Stop Probabilities: The percentage of stopped trains over the total number of trains.

VISSIM's interface node evaluation outputs should not be used to report on the above as it includes both delayed and non-delayed trains. Therefore, VISSIM's raw output files need to be post-processed for reporting.

INNOVATIVE MODELLING APPROACHES

To address some of the modelling challenges, practitioners and different agencies developed and used innovative methods and strategies towards:

- Selection of LRT intersection control strategies,
- Processes and interaction and between the project team,
- Software development and integration,
- Automation of technical inputs/outputs exchange, and
- Specialized Signal Control Modelling.

Processes and Interaction and between the Project Teams

LRT projects are multidisciplinary and include work performed by different teams at the planning stage. At the operations and system design end, three main specialties overlap and feed into each other. These specialties include: Traffic forecasting, traffic modelling and operations, and rail modelling and operations, **Figure 3**.

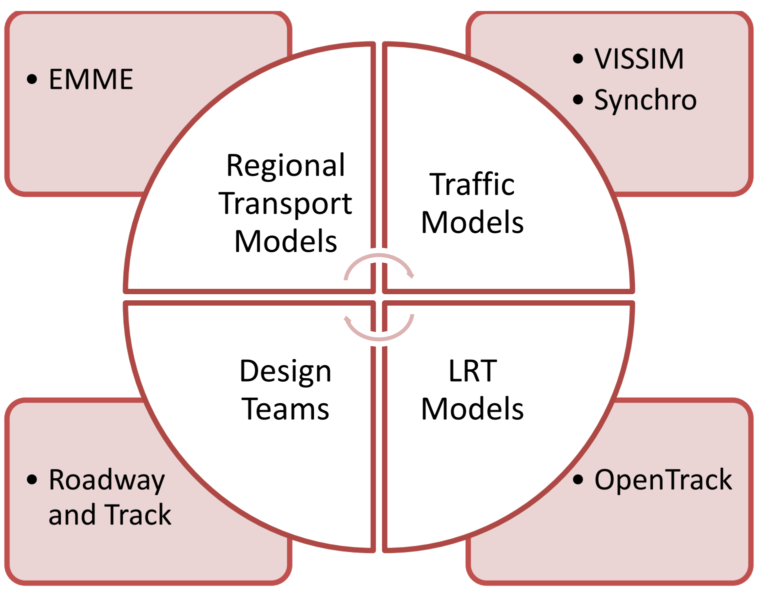

Figure 3: Typical LRT Planning Teams

A suggested process is listed below:

1- Regional transport modelling (RTM) outputs are passed to the traffic team for initial assessment and recommendation of intersection control strategies.
2- Full preempt run is performed through the rail modelling team.
3- Preliminary traffic modelling is performed using traffic models.
4- If the optimized network and best possible control strategies are resulting in network gridlocks,
   a. If minor roadway and track improvements are required, improvements are communicated to the design teams,
   b. If major improvements are required or if no improvements can be implemented, another regional transport model run may be required.
5- Repeat 1 through to 4 if another RTM run is required.
6- Supplement rail modelling team with traffic micro-simulation LRT modelling outputs.

Selection of LRT Intersection Control Strategies

LRT control strategies and priorities may be governed by the City's or transit authority's policies including target run time. If the agency allows a higher level of priority or preemption, the modelling exercise may start with full preemption at all locations and then would proceed with downgrading the LRT priority at locations with major operational challenges. However, this approach may lead to deteriorated level of service for busses using the network and other active modes of transport (walking and cycling). As these may constitute a significant share of the LRT system users, it may be more appropriate to develop a tool, a decision tree, to assist with LRT intersection control strategies. The decision tree can be built to reduce LRT priority where there is high emphasis on:

1. Level of service for highly active pedestrian crossings,
2. Coordination for cross streets at major corridors,
3. Service for conflicting movements leading to transit centers and bus corridors, and/or
4. Other important operational aspects.

An example of a decision tree is shown in **Figure 4**, where LRT control strategies have been categorized into 5 levels. The decision tree levels are based on offering a full range of priorities for at-grade systems without gated crossings. Decision trees could be developed based on the project needs and the alignment characteristic and may include other forms of LRT systems such as gated systems, which can operate under full rail preemption.

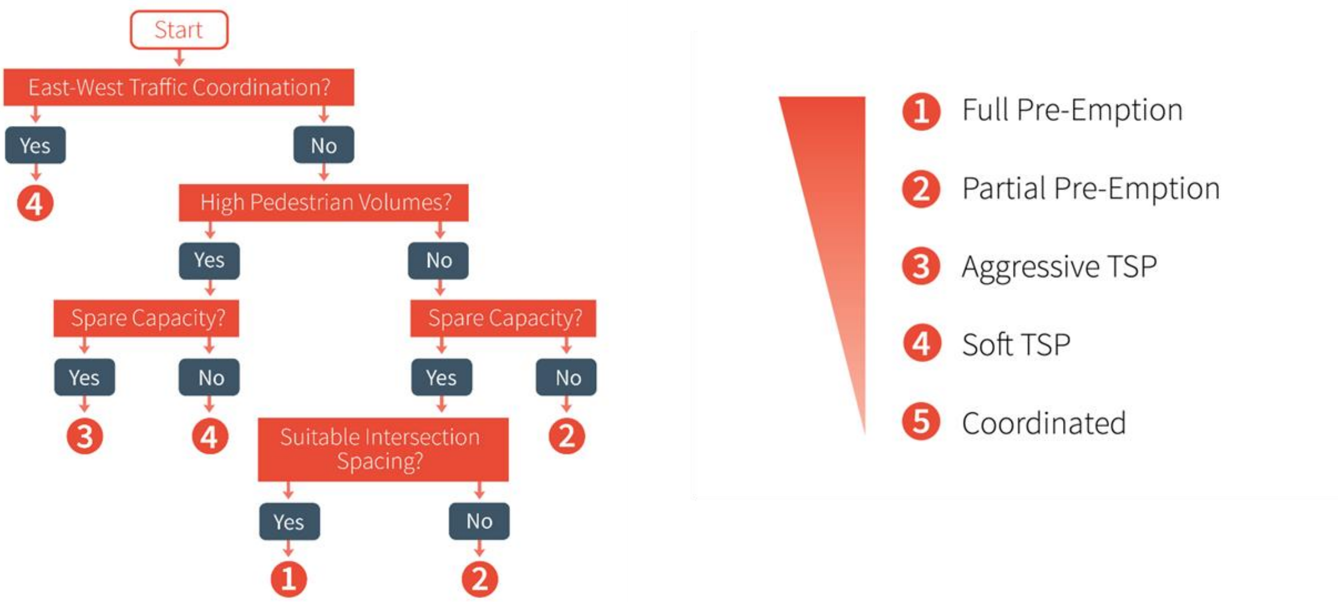

Figure 4: LRT Control Strategies Decision Tree

As shown in **Figure 4**, the levels of LRT priority were classified as follows:

- Full Pre-Emption: LRT designed to avoid stops or slowdowns. LRT check-in detectors are placed based on the longest conflicting phase, typically pedestrian phase (worst case scenario).
- Partial Pre-Emption: Due to detection distance limitations, detectors are placed closer to the intersection. Once LRT is detected, the signal will start clearing conflicting phases and will

initialize the preemption sequence. There is a low chance of LRT stopping at the intersection briefly.

- Aggressive TSP: Detection is closer to the intersection. Once LRT is detected, the signal controller will be able to rotate, skip, truncate, or extend phases to serve LRT faster.
- Soft TSP: Similar detection distance to an aggressive TSP; however, the signal controller can only truncate or extend traffic phases to serve LRT faster. There is a higher chance of LRT decelerating or stopping at an intersection.
- Coordinated/pre-timed (No TSP): Signals are optimized for the major traffic movements. Traffic signals can be coordinated where needed.

Based on **Figure 4**, the team would look first on the cross-corridor coordination. If coordination is important for cross corridor progression (typically a major roadway), a soft TSP will be attempted as it has a low impact on signal coordination. If coordinating the cross street is not important, pedestrian service is investigated. Then intersection spare capacity followed by intersection spacing are investigated. A decision tree could be designed in collaboration with the City's staff to incorporate the City's vision and policies. General impacts of LRT priorities on operations are summarized in **Table 3**.

Table 3: Impacts of LRT Priorities on Operations

Priority Level	LRT Operations	Vehicle Operations	Pedestrian Operations
1 – Full Priority	No impact	More delay, but typically lower volume intersection	More delays, phases skipped
2 – Partial Priority (High)	LRT phase will start at the earliest possible time since detection.	Conflicting phases will be cleared once LRT is detected.	More delays, phases skipped
3 – Partial Priority (Medium)	Higher TSP, Low delay	Options for early green, green extension, phase rotation, phase skipping	May have some impact
4 – Partial Priority (Low)	Low TSP, higher delays	Shorter early green or green extension	Lower delays
5 – Pre-timed (none)	Follows signals, no priority	Similar to existing operation	Similar to existing operation

***Arrows reflect the direction of increase in operational delays**

Software development and integration

There have been many advances with commercially available software and tools to increase the accuracy of traffic assignment models. A popular approach to minimize or eliminate the feedback loop between micro and macro modelling (RTM and microsimulation) is dynamic assignment modelling. Dynamic Traffic Assignment (DTA) can be performed at a microscopic or mesoscopic level if the offcorridor network is included in the modelling exercise. This level of traffic modelling can be performed using the same software package where microsimulation is performed in the case of VISSIM or Aimsun. Some commercially available software packages are dedicated to performing this level of assignment such as INRO's Dynameq software package.

In some cases, the City may have its own network modelled at a mesoscopic level such as the case in the City of Edmonton. In this case, direct iterations between microsimulation and RTMs are eliminated. Instead, an easier, less time consuming, iterative process between microsimulation and the City's DTA model can be performed. To provide better input volumes into the VISSIM models, the City developed a capacity constrained mesoscopic model in Dynameq. This dynamic assignment model (DTA) is fed with the capacity-constrained traffic demand volumes in EMME and allows signal timings to be coded at the intersection level. The DTA is also capable of modelling at a high-level TSP at intersections.

Private developers or consulting firms contribute to software development and integration. For LRT projects, Hatch developed a communication protocol internally between PTV VISSIM traffic modelling software and OpenTrack rail modelling software. This software, SmallSim, was developed to eliminate the differences of LRT operations between VISSIM and OpenTrack and runs and communicates between both software packages in real time.

The concept of SmallSim is that the LRT vehicles are removed from Vissim and run in OpenTrack. LRT check-in and check-out detector locations and LRT signal heads are coded in both software packages and the communication protocol is as follows:

1- As the LRT vehicle approaches a signalized intersection, it triggers a check-in detection point in OpenTrack;
2- Detection is triggered and communicated to SmallSim, which in turn triggers the same detector in VISSIM and initiates the transit priority event;
3- Signal status is updated on a second by second bases in VISSIM and is communicated back to SmallSim;
4- Signal status is communicated back to OpenTrack, once signal is green for LRT, LRT proceeds through the intersection;
5- LRT triggers Check-Out detection once it is fully out of the intersection in OpenTrack, which is communicated back to SmallSim,
6- SmallSim triggers the check-out detection in VISSIM, which in turns terminates the priority event.

This process and communication protocol is carried forward to the whole network at all intersections second by second, which results in accurate MOE projections and LRT run times.

Automation of technical inputs/outputs exchange

Typically, each team working on the project would automate their internal processes to meet their analyses and evaluation needs. An ideal example is developing excel templates to summarize and read VISSIM outputs into reportable formats. On the other hand, when transfer of data is required between both rail and traffic teams, it is preferable to agree on a format that is easily readable by both teams. Defining each output and how they would be extracted is essential. Multiple examples are explored below.

<u>Detector Calculations:</u> For fully preempted intersections, check-in detector calculations can be very complicated especially at locations around platforms or multiple speed zones. The typical way of performing this calculation is through manual calculations or through some approximation via excel spreadsheets. This process can result in many calculation errors and requires extensive checking. However, there is a relatively easy error free automated approach to perform this calculation using OpenTrack outputs.

One of OpenTrack's outputs is a the second by second train location along the alignment, stopping only at stations. This output is summarized in an excel format "Physic File." The traffic team can utilize the second by second location of the train to find the required detection distance for every intersection based on the longest conflicting minimum phase time, typically conflicting pedestrian phase (worst case scenario). The process can be automated via excel lookup functions and can be integrated with the dwell times at platforms for every peak and horizon year. This would result in the same detection distance for all modelled peaks and horizons; wherever dwell times differ, detection delay can be added accordingly.

<u>LRT Delay Outputs Transfer:</u> As discussed earlier in previous sections, the rail team requires LRT operational outputs for trains that were delayed. Typical VISSIM node evaluation outputs include all trains; therefore, post processing VISSIM's raw outputs is required. The challenge with the way OpenTrack handles delayed trains is that the software only accepts probability of stopping for LRT and stopped delay. If trains decelerated but did not stop, OpenTrack would not consider this delay (one of the reasons SmallSim outputs are an accurate way of capturing run time). A way around this issue is to factor the delay experienced by decelerating trains into the delay experienced by stopped trains. Spreadsheets format and calculation methodology should be discussed by both traffic and rail teams.

<u>Detectors Information Transfer:</u> For networks modelled using SmallSim, detector, and signal heads locations and IDs need to be read by communication protocol for a successful transfer of seconds by second signal status. Before developing VISSIM's and OpenTrack's networks, a common approach of coding signal controllers in VISSIM is discussed and carried forward. Spreadsheets can be developed to read all required data from VISSIM and incorporate them in SmallSim.

Specialized Signal Control Modelling

In few situations, VISSIM's RBC module for signal controllers may not be sufficient for highly specialized LRT signal control and priority events. Traffic modelers may need to program such cases using Vehicle Actuated Programming (VAP) or Component Object Model interface (COM). Programming signal controls using VAP may be needed in cases where the traffic signals are expected to operate priority events based on a decision tree. COM can be helpful in cases where trains may need to communicate their location based on second by second progression to signal controllers. There are other scenarios where such advanced programming may be needed such as operating gate sequences during priority events or others.

CASE STUDY: VALLEY LINE WEST MODELLING

Due to the complex nature of planning an urban integrated, in street running LRT and due to the many modelling challenges mentioned previously in the paper, an integrated modelling exercise was required to accurately capture the impacts of the proposed Valley Line West LRT line.

As traffic modelling is considered as the intermediate link between other processes, the traffic team lead the project operational modelling effort. Before the models' development, the team planned the model development through meetings and collaboration with the rail team, forecasting team (City's Urban Analysis-Systems Analytics team), and City's traffic operations team. Processes and data transfer procedure were discussed at the early stages of the modelling work. Expected signal operations, LRT control strategies decisions at intersections, and how controllers handle priority sequences were workshopped. The planned iterative approach between all teams is shown in **Figure 6**.

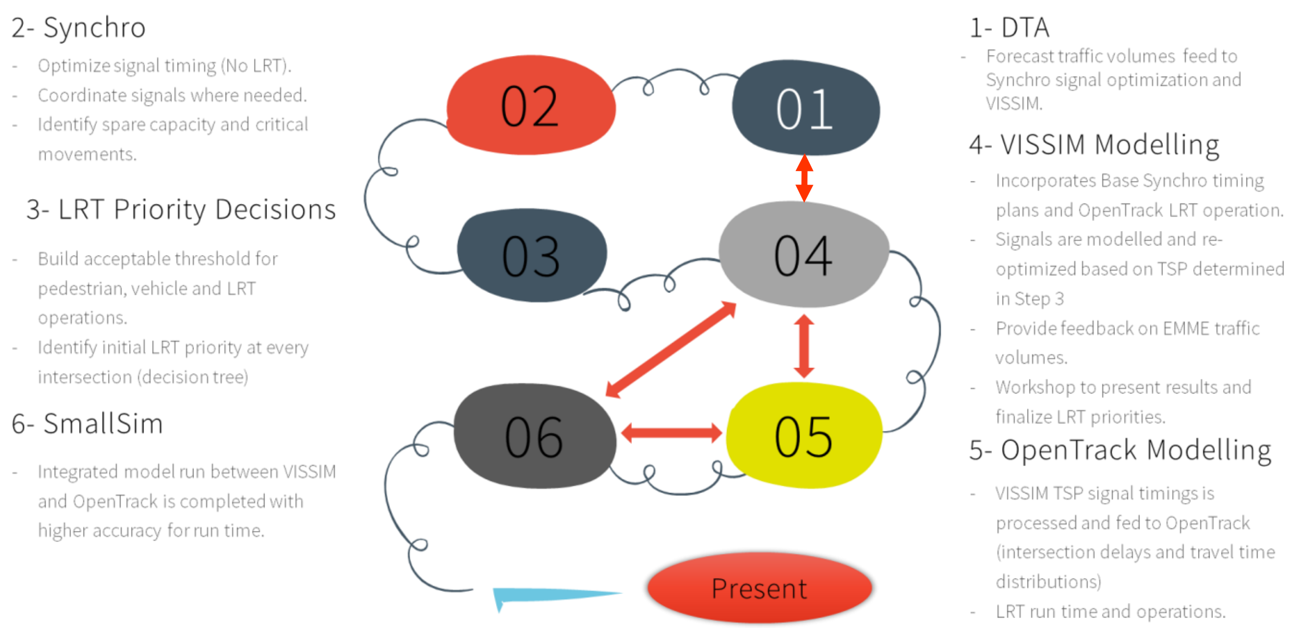

Figure 6: Valley Line West Planned Modelling Process

As shown in **Figure 6**, an iterative approach was followed to develop the traffic volumes in the DTA and refining and optimizing the traffic signal control strategies for the LRT in VISSIM. With each iteration, the optimized signal timings, as well as issues where the traffic volumes exceed the capacity of the roadway network, were fed back to the DTA and the design teams. Traffic volumes were redeveloped through a second iteration with DTA, which in turn were fed back into the VISSIM modelling. This iterative process also allowed for any design changes to the LRT and roadway to be fed into the modelling process. It should be noted that while the TSP strategies were optimized in VISSIM; base signal timings and any signal coordination was optimized in Synchro.

A feedback loop was also undertaken between the VISSIM model and the OpenTrack rail simulation. OpenTrack was initially run with full pre-emption whereby the trains only stop and slow down at the stations. The train speed profiles were then used as inputs into VISSIM and for LRT check-in detector calculations. After the initial signal control strategies were developed in VISSIM, the LRT stop probabilities were extracted from the VISSIM model and fed into the OpenTrack model. OpenTrack was then used to evaluate the train performance, which included looking at performance measures such as run time, headways including sensitivity testing and traction power curves.

As the Valley Line West is planned to be an urban integrated in street running system, it was important to understand the full impacts to the traffic, LRT and pedestrians. While VISSIM is a good tool for evaluating the impact of the signal control strategies on the traffic and pedestrians, using stop probabilities extracted from VISSIM is only an approximation. VISSIM does not include the impact of traction power, the train control system, and approximates the effect of grades on LRT's performance. On the other hand, OpenTrack is a good tool for evaluating train performance. Therefore, in order to more accurately produce results for both the traffic and the LRT, an integration between VISSIM and OpenTrack may be developed using SmallSim.

The advantages of the collaborative and interactive approach followed in Edmonton's Valley Line West LRT were:

- **A clear defined process:** Through workshops and a technical assumptions report at the early stage of the project, the project teams' roles, expectations, data transfer processes, and other technical assumptions and processes were set. The process included the design and modelling teams.
- **No manual traffic diversion assumptions:** A second DTA iteration was performed based on a first draft of the VISSIM models for each peak and horizons. This resulted in more realistic turning movements demand at the intersection level as the optimized signal timings from VISSIM were incorporated into the DTA model.
- **Automated exchange/transfer from DTA to VISSIM:** An automated process was developed to convert network wide DTA demand matrices to VISSIM volume inputs and routes. Setting this procedure saved considerable time in the traffic modelling side; typically, these inputs are coded manually and are a significant portion of the modelling exercise time and budget.
- **Automated exchange/transfer between the rail and traffic teams:** Excel spreadsheets were prepared to calculate detector locations based on OpenTrack's second-by-second train locations and speeds. Spreadsheets were developed to extract VISSIM's raw data and perform all statistical calculation to be provided to the rail team.
- **The application of SmallSim:** Both rail and traffic models were completed with the same assumptions and coding techniques in preparation for SmallSim runs at the last stages of the project.

DISCUSSION AND CONCLUSIONS

LRT corridor modelling is a resource intensive and extensive exercise that requires inputs from multiple teams: forecasting, traffic, rail, and roadway and track design. LRT signal control priorities are likely to be influenced by the City's vision and policies, but can be guided from an engineering perspective. Both vision and level of service can conflict; an example would be prioritizing LRT run times and producing acceptable level of service for traffic and pedestrians. It is typical to expect traffic movements which conflict with the LRT to deteriorate with the introduction of LRT. An example of the impacts of different LRT priorities could have on the percentage of phase green time is shown in **Figure 7** for a major intersection. The existing signal plans currently had all left turns as permissive phases. With the introduction of LRT, parallel left turns (northbound and southbound) become fully protected due to safety considerations.

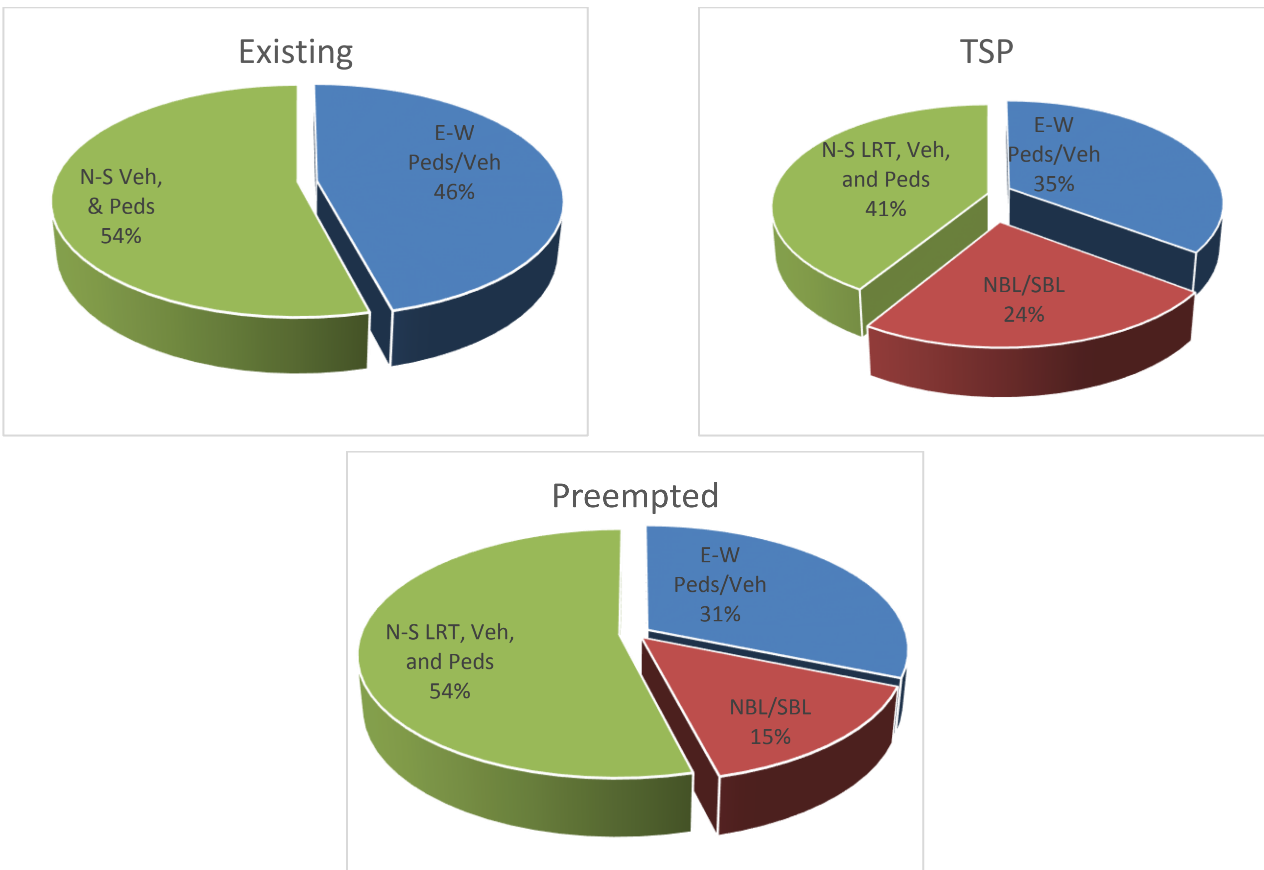

Figure 7: Impacts on Phase Splits for TSP and Preemption at A Major Intersection

Urban integrated LRT requires extensive planning, which includes an evaluation of the impacts of the planned line from both rail and traffic perspectives. Knowledge, full understanding of the project needs, familiarity with the alignment and the study area, in addition to a well-planned interactive collaboration between different teams will lead to a successful completion of the project. It is always recommended to discuss any project operational challenges with the City as they will likely be responsible for operating and maintaining the network.

There are continuous innovations with traffic modelling at the planning stage. Traffic models are moving towards the era of real-time network optimization, which may in the future be integrated with traffic control centers. Different software developers have already developed add-ons or algorithms to perform real-time network optimization. This may become the future for smart cities. The impact of autonomous vehicles on traffic/LRT operations is yet to be explored. Current studies investigate operations from a vehicle (car, bus or LRT) perspective or a traffic controller perspective. However, the interaction at complex situations where LRT, traffic, and pedestrians interact at a traffic controller requires further studies. Although evaluating the impacts of autonomous vehicles is possible with commercially available microsimulation modelling software, timelines for their introduction in the market is unknown and projections are still highly debated.

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