Planning of Vancouver's Transit Network with an Operations-Based Model

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1 Introduction and Background

The Province of British Columbia, Canada has outlined in the recent Provincial Transit Plan a strong commitment to improve and significantly expand the transit system in the Metro Vancouver region over the next 12 years. TransLink (South Coast British Columbia Transportation Authority) is the agency responsible for the regional transportation system, including transit, providing strategic planning, funding and supervision of the operations. In this context, TransLink cooperated with PTV to develop a model that can support decision making and comprehensive analysis for the implementation of the regional transit plan. The Regional Transit Model (RTM) was initially developed in 2006 for rail analysis (Fisher/Scherr 2007 [1]). In a second implementation phase which is presented in this paper and which concluded mid-2008, the RTM has been extended to represent all transit services in the region, notably all bus lines.

Unlike traditional regional transportation planning models, the RTM provides a detailed picture of transit operations. The RTM includes three major components: 1) a ridership model with time-table based passenger flow; 2) an operations model including detailed fleet data, schedules, line blockings and operations statistics; and 3) a graphical user interface for comprehensive visualization and mapping functionality. The model also serves as an analysis database that integrates data from several other systems: bus, rail and ferry schedules, geographical information of stops and routes, data from the automatic passenger count (APC) system, other ridership counts, and OD matrices from the regional travel forecasting model. The strength of the Regional Transit Model is its ability to compare alternative planning and operations scenarios. It allows analysis of operations and ridership impact using measures such as: number of vehicles or train cars needed, train-car-km, seat-km, future boardings, passenger transfers, volume/capacity ratios, etc.

This paper summarizes the development and calibration of the Regional Transit Model, including the data sources, assumptions, methodologies, and the results. Practical examples where the RTM has been applied will be presented:

- Mitigation of at-capacity segments of SkyTrain, an automated LRT system.
- Future operations and fleet strategy for SkyTrain.

- Operations planning for the future extensions of the rapid transit network.
- Bus service adjustments around new rail lines.

2 Transit in Metro Vancouver and the Provincial Transit Plan

Metro Vancouver is a growing urban region with a population of 2.2 million residents that is projected to grow to 3 million by 2031. Transit plays an increasing role in urban transportation with 78 annual linked transit trips per resident in 2007, up from 63 in 1999. Metro Vancouver's geography is defined by several ocean inlets and major rivers that form natural transportation choke points. The north edge of the region is bordered by mountains while the US border defines the southern edge. Additionally, large swaths of agricultural land are protected from urban development. These conditions, combined with a sparse freeway network and a regional plan focused around transit, have made the region relatively densely populated and contributed to healthy transit use.

The South Coast British Columbia Transportation Authority, known as TransLink, is the regional transportation planning and funding agency and is responsible for transit as well as major regional roads. The multimodal, integrated regional transit system is operated by several companies, though two TransLink subsidiaries, Coast Mountain Bus Company and the BC Rapid Transit Company (BCRTC), carry 96% of passenger trips.

The regional transit system integrates several modes: the bus and electric trolleybus system includes local routes as well as limited stop ("B-Line") routes that are part of the rapid transit network; a commuter rail line ("West Coast Express") operates between Mission and Vancouver; a passenger ferry ("SeaBus") links downtown Vancouver with North Vancouver. The backbone of the rapid transit system is SkyTrain, an automated, driverless train system (ALRT) operated by BCRTC that carries over 240,000 passengers per day, one-quarter of transit system boardings.

The two SkyTrain lines ("Expo" and "Millennium") total 50 km (31 miles) and include 33 stations. Trains operate on a combined peak headway of 108 seconds on the common segment between the Waterfront and Columbia stations. The first and busiest line is the Expo Line, opened in 1986, while the Millennium Line opened in 2002. Trains on each route share the majority of the Expo Line corridor, including its tunnel in downtown Vancouver. Currently, SkyTrain operates at and over capacity during the peak hours. At one key station, passengers traveling inbound during the morning peak sometimes have to wait for up to three trains to be able to board.

The bus network is diverse, including 15 electric trolleybus lines served by 228 standard and articulated vehicles. Over 200 diesel bus routes are operated with a fleet of over 1,200 buses, ranging from articulated buses able to carry up to 120 passengers down to 24 passenger Community Shuttle minibuses.

Early in 2008 the provincial government announced an ambitious Provincial Transit Plan that provides for significant transit expansion by 2020. TransLink will be implementing this plan in Metro Vancouver. Some of its major components include:

- Opening the 19 km Canada Line grade-separated, automated rapid transit line in 2009;
- Doubling the capacity of the Expo SkyTrain line and adding a 6 km extension;
- Building the 11 km Evergreen Line SkyTrain (a branch off the Millennium Line) by 2014;
- Building a 12 km UBC Line, connecting SkyTrain to the University of British Columbia (UBC), the second largest transit destination in the region;
- Adding bus rapid transit (BRT) on seven regional corridors; and,
- Significant bus fleet expansion with clean energy buses.

The plan's goal is to increase the weekday share of all-day trips in the region taken by transit from 12% in 2007 to 17% in 2020 and 22% in 2030. Planning and implementing the improvements to support such dramatic increases will require efficient and effective planning tools.

3 Model Architecture and Data Sources

The RTM is built using the VISUM software platform. It describes 24 hours of an average weekday with both supply and demand of transit. The model is time-dynamic; it uses inputs that vary over time and generates outputs in 30-minute intervals, covering the full 24 hours of the day.

Data Sources

No dedicated surveys have been undertaken to develop the model. Instead the RTM is by design based on existing data sources only. Moreover, an important achievement of the model is that multiple existing sources have been integrated. Some of these data sources covered only one particular mode or part of the system, of only demand or supply. The RTM integrates the best knowledge and data regarding transit in metro Vancouver into one consistent data platform. With this platform the entire regional transit network can be analyzed and forecasted systematically.

The following data have been integrated:

- Supply data sources
  1. Operation schedule for bus, ferry and commuter rail, including vehicle assignments
  2. Operating rules for the SkyTrain ALRT system (run and dwell times, headways)
  3. Stop and station data base (compatible with APC/AVL data)
  4. NAVTEQ street network
- Demand data sources
  1. OD matrices from the regional travel demand model on 800 zones
  2. Automated Passenger Counter (APC) boarding statistics for bus and ferry
  3. Boarding survey data for SkyTrain and Commuter Rail

An important principle of the model architecture is that all data object identifiers have been defined to be compatible with the original data sources. As a result, it is possible at any time to readily update data components. The most prominent examples are the operations schedule and the APC ridership data, which can be updated at any time using automated import routines.

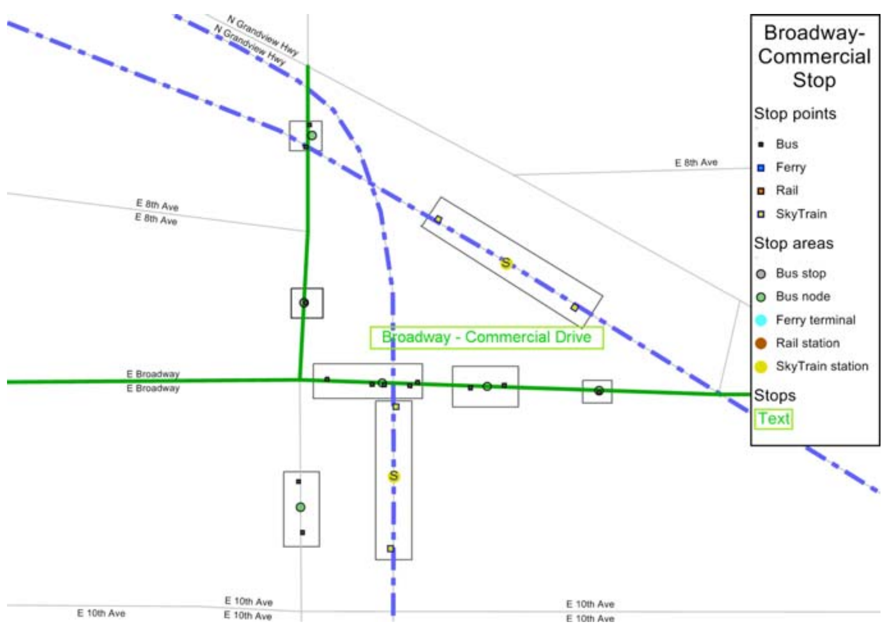
Supply Model

The RTM's supply model is composed of several data layers that are organized as a framework of interconnected object classes, according to VISUM's network data model: streets and tracks are modeled using a node and link graph. Stop points are attached to links or nodes. As Figure 1 shows, stop points are grouped to stop areas and stops. This three-tier stop model represents three different views of stop data in an integrated way, allowing multi-level analysis:

- The physical locations where vehicles and trains stop is the most detailed level. It is equivalent to operations systems such as AVL or APC. In VISUM: "stop points".
- The schedule level, representing clusters of bus stop points or the different platforms or levels in stations; typically the level as represented in a scheduling system. In VISUM" this layer is called "stop area".
- The transfer level, called "the stop" in VISUM is the highest and most abstract data layer for stops. One stop can represent multiple stop areas in transit hubs or transit centers

Figure 1 pictures how the intermodal hub around the two SkyTrain stations "Broadway" and "Commercial" and several clusters of bus stops around those stations are organized in the RTM.

Figure 1: Stop detail at the intermodal hub "Broadway-Commercial"



Transit lines can extend to several routes per line and several time profiles, which are run-time patterns that often differ by time of day on the same route. Each time profile includes a detailed data structure for run times, dwell time, layover and recovery times. The vehicle journey is the most disaggregated level at which operations are represented in RTM's data model. A vehicle journey represents one individual bus or train trip in the schedule and specifies departure time, time profile and vehicle type, as well as the recovery time after each run and etc. Vehicle journey information is used not only for line blocking and other operating analysis, but also in the timetable-based passenger assignment method.

Vehicle units and vehicle combinations represent the fleet and different types of trains with specific capacities and cost functions. Table 1 shows the transit systems included in the model and some key network and operating statistics for the year 2007.

Table 1: Basic Operating Statistics of Different Transit Systems (Base Year 2007)

Name	Lines	Line Routes	Time Profiles	Vehicle Journeys	Stop Points	Seat KM	Total Capacity KM**
SkyTrain	2	5	13	940	70	4,119,100	9,471,000
Commuter Rail	1	2	2	10	8	720,300	1,742,300
B-Lines	3	17	119	990	152	751,700	1,624,700
Standard Bus	149	796	2,538	11,201	6,595	6,331,400	12,558,800
Community Shuttle	61	206	363	3,628	2,419	599,400	734,700
Train Bus	1	2	2	5	16	14,600	27,400
Trolley Bus	15	158	696	3,379	953	1,113,800	2,676,800
Ferry	2	4	4	159	4	157,800	233,800
TOTAL	**234**	**1,190**	**3,737**	**20,312**	**8558***	**13,808,000**	**29,069,500**

Notes:
* The total of stop points are the number in the existing network, but not the sum of the column, because one stop point may be shared by different transit system.
** The total Capacity includes the seating and standing capacity.

Figure 2 displays the transit operations on a VISUM map. It shows how the network data model covers all transit modes across the region of Metro Vancouver. The part of the region shown in Figure 2 is approximately the area of the City of Vancouver, which includes the Central Business District (CBD).

An important piece of the operations analysis is the line blocking procedure. Blocks are sets of individually scheduled runs; one block (sometimes also referred to as “equipment cycle”) represents the work assignment for one train or bus for a single workday. The total of all blocks is generated by the model’s blocking algorithm. The most important result from the blocking is the total number of vehicles and trains needed to operate a given schedule at different times of day. Based on these estimates, the RTM computes the fleet requirements for different future operating scenarios. Depending on the type of service, line change and interlining can be enabled during the calibration of line blocking for the existing case 2007. VISUM’s line blocking is based on simple assumptions for minimum layover and preparation times; so it can not replace scheduling and run-cutting software. Still the method gives a realistic estimate of future fleet requirements.

A strength of the RTM is the ability to compute operations statistics that cover performance as well as cost/benefit. Examples are operating hours, revenue hours, seat-km or total capacity km, volume/capacity ratio, number of vehicle blocks, linked or unlinked ridership, travel time, cost and fare revenue. These statistics are available for different geographic aggregation levels from individual stops or line routes, up to line, mode, district and system totals. In addition VISUM allows computation these numbers by time of day. In the RTM, the time detail is in 30-minute intervals over 24-hours, so that the model really computes time-dynamic output for both ridership and operations.

Figure 2: RTM network model for the City of Vancouver

Demand Model

The demand model has three major components: Origin-destination (OD) matrices that represent 24-hour passenger demand on an average weekday; the 24-hour temporal distribution of desired departure time; and a time-dynamic passenger assignment method. A description of the demand model calibration will follow in the next section of the paper.

The demand model is based on 800 traffic analysis zones. The input includes four OD matrices in each model year, which represent the travel demand for four different times of day (AM, Mid, PM, Eve). These matrices have been derived by automated matrix calibration based on counts (for the existing year) and by a delta-method for the future years. The time distributions of desired departure time have been derived from counts and adjusted during model calibration.

The OD demand is assigned to the network with a time-dynamic assignment method, VISUM's timetable-based assignment (Friedrich/Noekel 2001 [2]). This method uses the operations schedule ("timetable") of all transit routes to first determine multiple, alternative paths for all OD pairs. Then the method builds time-dynamic connections on each path during 24 hours. These connections are equivalent to the itinerary data a passenger can obtain from a passenger information system, with the exception that VISUM will provide several, alternative connections at any time of day.

A fare model allows computation of the average revenue for each trip and estimation of the total ticket revenue for future scenarios.

4 Model Calibration and Forecast

For the existing year 2007, the goal of the calibration process is to make sure that model outputs are consistent with observed data.

Calibration of the Operations Model

On the operations side, the observed data include operating speeds, travel times and the number of vehicles or trains used per line or per group of lines. These data are obtained from the operating companies. The number of vehicles used in operations is the basis to calibrate the line blocking procedure until it replicates the fleet that is needed to operate the systems. For the calibration of the rail systems, an exact match of the number of trains was achieved. For the bus operations, small errors of +/-5% have been accepted for individual lines, while the total bus fleet used in operations has been matched very closely.

Calibration of the Demand Model

On the demand side, the calibration process is more complex. Ridership counts from multiple sources have been processed to obtain the calibration basis. These count data covered all train stations, several links and all individual lines except community shuttle buses. Just in time for the model calibration, the APC system was able to release statistics for all standard bus lines, including total daily boardings, time-dynamic boardings and on/off statistics along selected lines.

The calibration methodology itself is a multi-step process which can be summarized in five major tasks:

- Adjustment of network coding: To achieve reasonable path choice, two coding assumptions are adjusted all over the network: where passengers can transfer and at what cost; and which stops are accessible via zone connectors from each traffic analysis zone (TAZ). The walking speed and the maximum length of the zone connector have been defined for each transit system (SkyTrain, WCE, SeaBus, B-Lines and regular buses) to reflect the attractiveness of each system experienced by passengers. The transfer walking time has been calculated based on the X and Y coordinates of each pair of two stops. The line connecting these two stops can be viewed as the hypotenuse of a right triangle and the third vertex shares the same X coordinate as the starting stop and the same Y coordinate as the ending stop. The walking distance is calculated as the sum of the two legs of the triangle. In addition the extra time needed in elevators or stairways and impedance from traffic has been taken into account.
- The assignment procedure parameters and the general cost function of route choice have been set with reasonable assumptions; it is notable that the rapid transit modes have been

given discounted cost of in-vehicle time to represent the higher attractiveness, as supported by the count data.

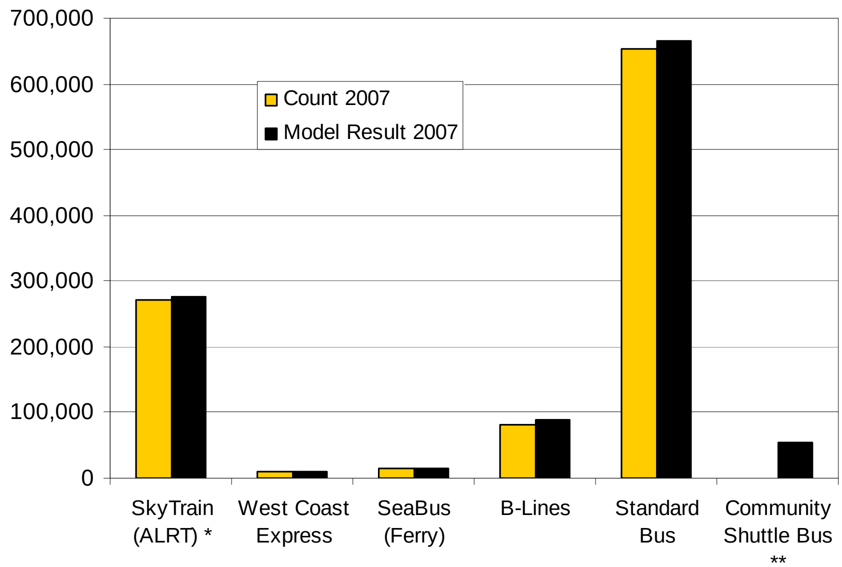
- Matrix calibration: The AM and PM Peak-period transit demand are developed based on the emme/2 regional travel demand model, which is used for long-range planning by TransLink. All transit counts are then the input to the automated matrix adjustment process called TFlowFuzzy (Friedrich/Noekel 2000 [3]), which help to fit the OD matrices into the counts.
- Completion of demand for non-peak hours: In addition to the AM and PM peak matrices, the RTM has two more matrices for the midday and evening period demand. These two matrices have been derived as linear combinations of the AM and PM peak period demand. The weighted midday and evening passenger survey data from the 2004 trip diary were utilized to find reasonable coefficients. Then TFlowFuzzy matrix calibration was applied for the non-peak demand as well.
- Adjustment of departure time distribution: Another input of the passenger assignment model is the distribution of desired departure time. To begin with, the distribution was derived from boardings counts. Then the study area in the RTM has been divided into four subareas and a unique departure time distribution curve has been created for the trips between each subarea pair. The general assumption is that the further a passenger travels, the earlier the person starts the trip, especially in the morning. The departure time distribution curves are calibrated based on empirical 24-hour distributions of boardings and alightings at major rail stations and on groups of bus lines with 24-hour APC data.

Figure 3: Validation of unlinked trips per transit mode

(total number of boardings on an average weekday)

*: older counts growth-factored to 2007

**: no count available



The validation of the passenger demand model is a multi-tier procedure, which involves the ridership statistics at different levels: from network-wide statistics down to the individual station or line statistics. Figure 3 through Figure 5 show examples of the multi-tier validation. Figure 3 shows the total number of unlinked trips per transit system in the network which need to be compared with the counts. Figure 4 compares the daily number of boardings per bus line between the model and the APC counts. At the station level, Figure 5 shows how well the time-of-day distribution of passenger boardings matches the survey data on two major SkyTrain stations in the downtown area.

Figure 4: Validation of daily number of boardings per bus line (model versus APC)

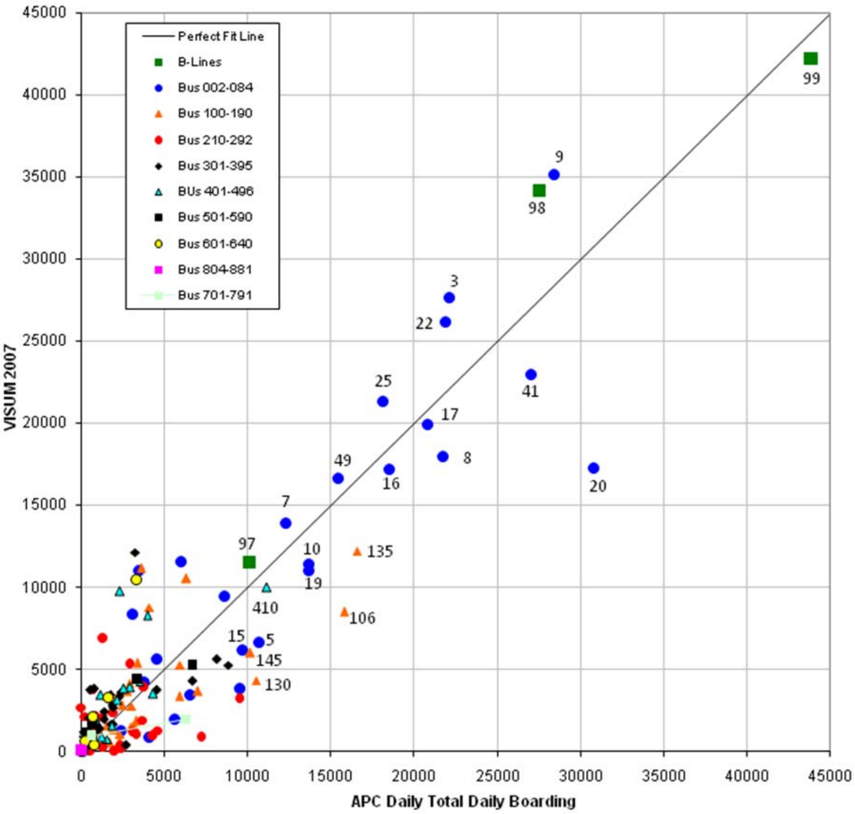
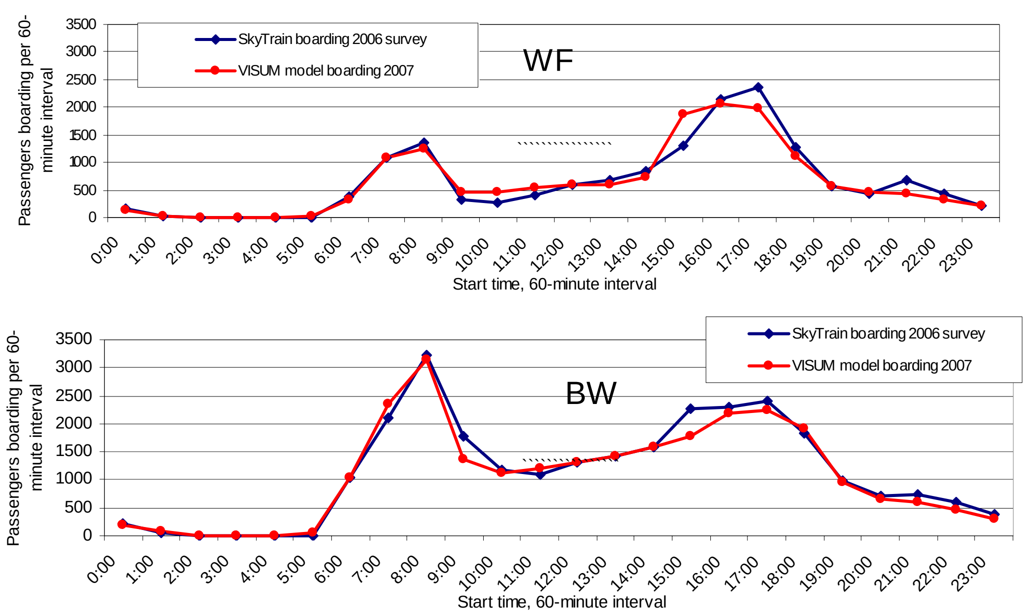


Figure 5: Validation of 24-hour time-distribution of SkyTrain station boardings (model versus survey)



Forecast of Passenger Demand

The future year demand is developed by blending the existing demand matrices with forecasts from the regional long-range planning model. Based on the assumption that a large part of the future demand is identical to the existing, we used the following "Delta Method":

Future Year OD demand = Existing Year Calibrated OD + Δ

where:

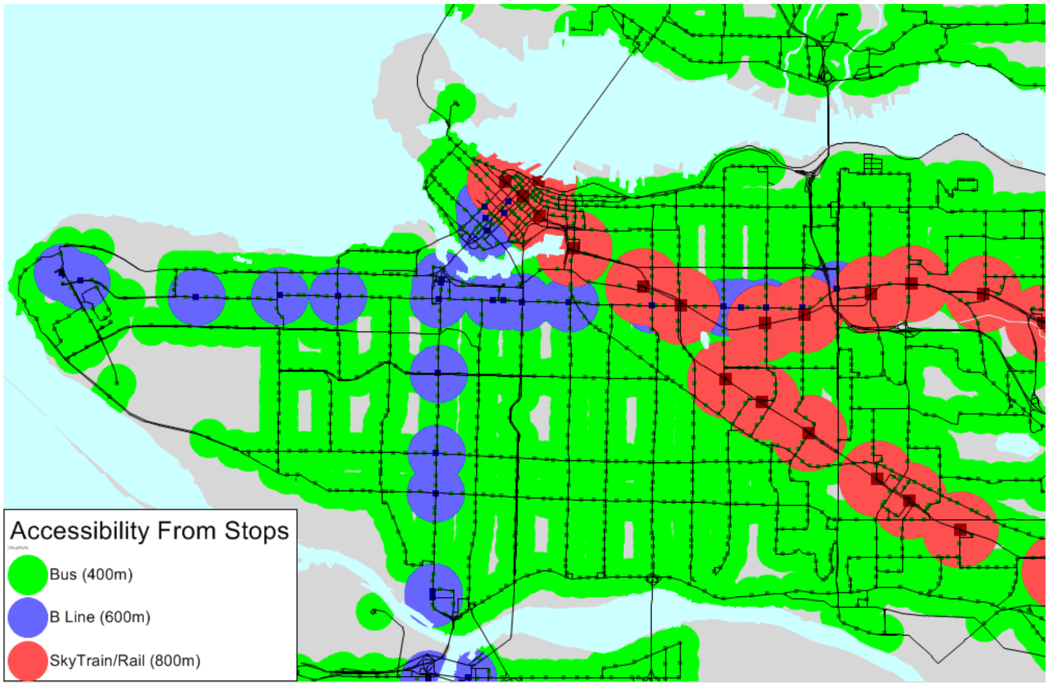
Δ = Demand growth in the long-range planning model

It should be noted that within the TransLink organization, the two models have complementary roles: the RTM assists in transit operations and service planning, while the long-range planning model (on the emme/2 platform) helps to predict the impact of new land use and urban development and shifts in modal split.

5 Comprehensive Operations Analysis

The RTM helps to understand and analyze transit operations by computing indicators of the system as a whole, by measuring performance for multiple future scenarios or projects and by computing efficiency statistics down to individual lines, routes, stations or network segments.

Figure 6: Stop catchment areas



The following table lists some typical transit planning questions and explains how the model helps to find an answer to the question.

Table 2: Typical Planning Questions Supported by the Model.

Question/Problem	How the model supports the answer
How good is the performance of individual transit lines?	Compare measures of effectiveness like: • passenger km versus seat km • operating cost versus shared fare revenue • Volume/capacity ratio on the line segment with the highest demand
Which technology option (BRT, LRT, ALRT) is the most appropriate for providing the necessary capacity for a new rapid transit corridor?	Compare all scenarios with the model analyzing operating speed, travel time impact, connectivity impact, ridership volumes, etc.
How many train cars or bus vehicles will be needed for a particular new transit line? What will be the total fleet that is needed in the future?	RTM's line blocking shows how many vehicles are needed. By computing the need for the entire transit system the model supports an informed plan of the future fleet expansion that is necessary to meet future capacity needs.
How much rapid transit capacity is metro Vancouver providing compared to another city?	Train-car-km, total network length or total number of unlinked passenger trips are typical benchmarks to compare with other urban areas.
What percentage of people traveling by bus during the morning peak would need to stand?	The RTM computes for existing and future scenarios the volume/capacity ratio for 30-minute periods, which allows to define levels of service and to detect future capacity issues.
Where should we locate major development if we want it to be served by transit that provides 30 minutes or less travel time to major business and government centers?	Travel time isochrones (Figure 8) show the accessibility of individual locations by transit.
How does a new rapid transit line fit into the existing system?	Future demand, transfers with existing lines, operational constraints are typical measures to respond to this question.
How can efficient operations be designed for the off-peak time?	The RTM covers peak and off-peak. Longer trains can be uncoupled and replaced by shorter trains during off peak. The RTM can also assist estimating the cost of uncoupling and the compatibility with schedule requirements.
Is it better to operate longer or shorter rail lines? What is the best route alignment for a future rail line extension?	The model can help to analyze how capacity is met (typically better by shorter lines) and what the impact on passengers is (greater or fewer transfers). The model also allows analysis of mixed operations with parallel longer and shorter routes.
Where are possible locations to park the future fleet of rail and bus vehicles.	Locations for new depots or rail yards can be analyzed for their impact on operating cost.

In addition to tables and reports, an important ability of the RTM is the visualization of these numeric outputs in comprehensive maps and animations. All the statistics and analyses can be divided in three levels, which we will explain with representative examples:

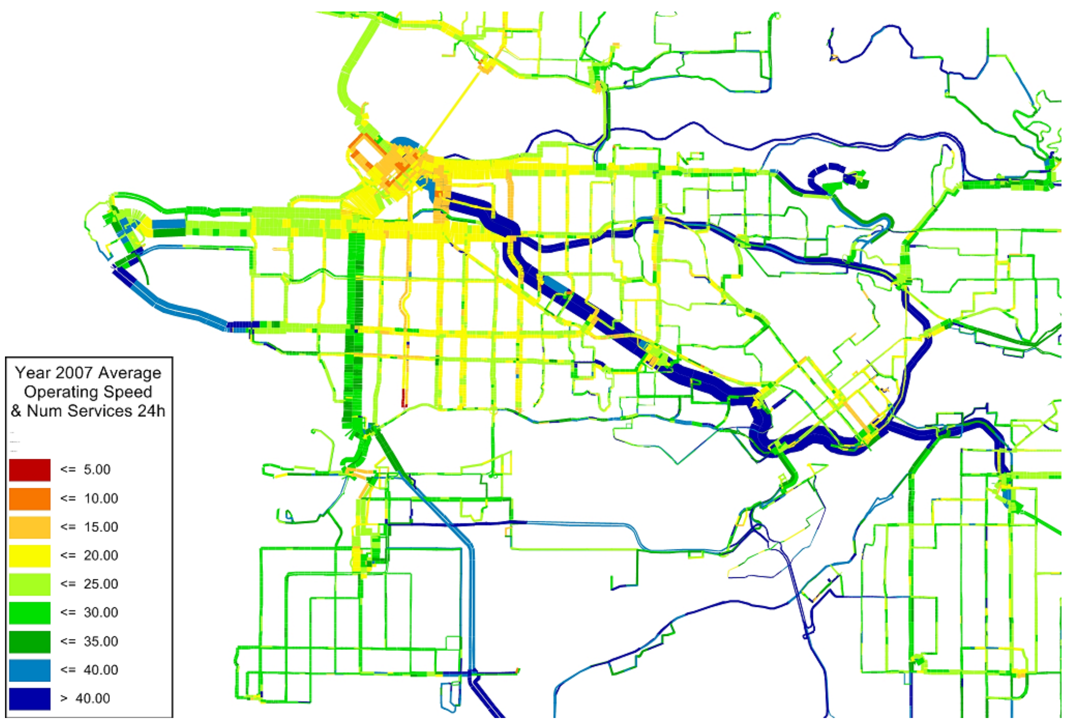
1. Level 1 is supply-based statistics, using only operations data and topology
2. Level 1a – line blocking
3. Level 2 adds a passenger view and network connectivity to the supply data
4. Level 3 integrates demand and supply by combining operations analysis and passenger demand

The RTM is capable of comprehensive operations analysis and produces results such as:

- Maps of average scheduled speed and service frequency (Figure 7 below).
- Ridership load maps and volume-capacity analysis, time dynamic over 24 hours (Figure 9 below)
- Stop catchment and coverage (Figure 6 below).
- Accessibility analysis such as travel time contour maps (Figure 8)
- Operating statistics per mode, line, route pattern, stop area and stop.

Figure 7 shows the scheduled average operating speed (line color) for transit as well as the number of transit service trips (line width). The figure clearly illustrates the high frequency and speed service of the SkyTrain system, which can be identified from the blue color. In addition the fast bus lines "B Lines" along Broadway and Granville are clearly shown as providing quick and frequent bus service.

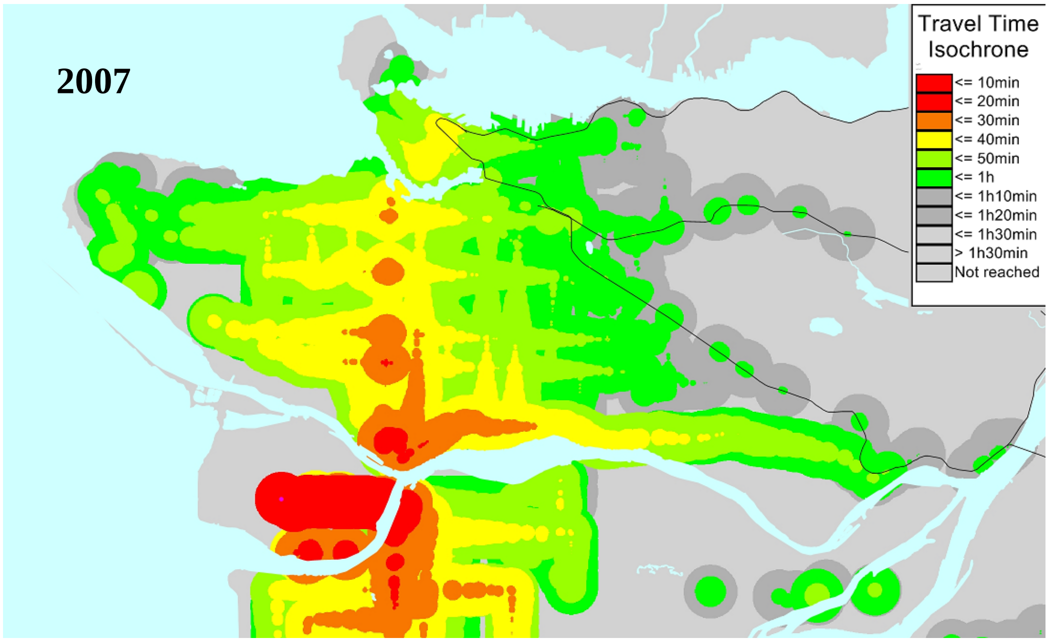
Figure 7: Average operating speed and number of services per link (level 1 analysis)



(Schedule winter 2007-2008)

Figure 8 shows travel time that a traveler from Vancouver International Airport will experience to access different parts of the region. It illustrates that the new Canada Line rail service " will increase accessibility of the airport compared to 2007. This kind of illustration is a convenient way to display to a non-technical audience the impact of major transit investments on mobility. It is also helpful to support location choice decisions based on transit accessibility.

Figure 8 Travel time analysis from a given station (Airport YVR) in comparison of 2007 and 2011 – Level 2 of analysis



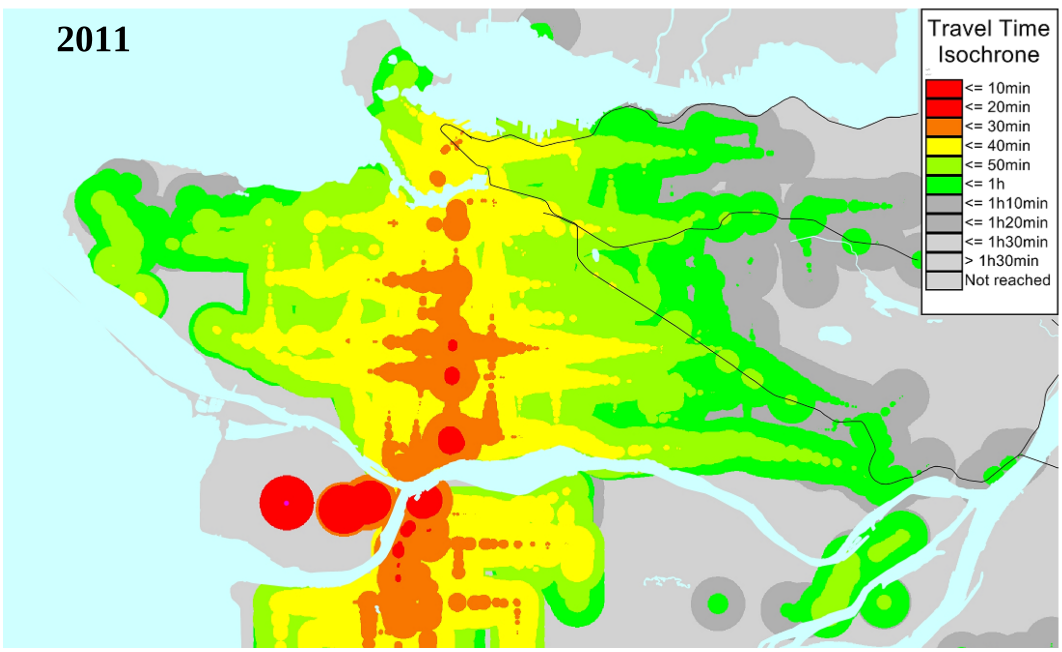


Figure 6 displays the coverage of the region with transit service, where the catchment radius is 400 metres for bus and 800 metres for rail.

Figure 9 shows the 15 minute dynamic passenger volume and level of service for the rail network in a particular operations scenario for 2015. Red colors indicate ridership at capacity with the possibility that passengers remain on the platform to wait for the next train. Green colors indicate a comfortable journey where most users will be able to find a seat.

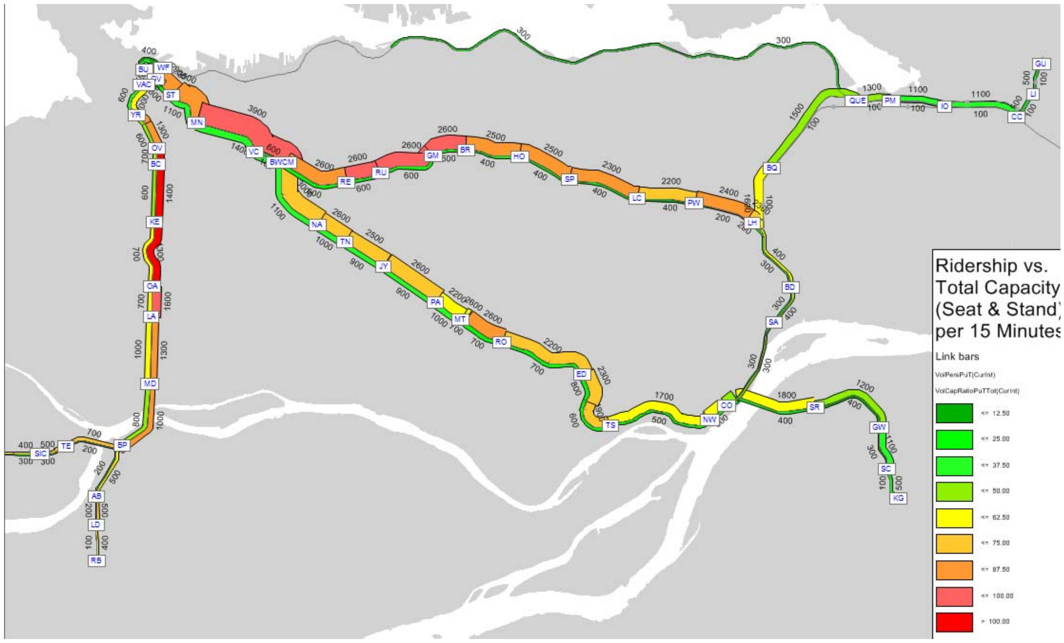


Figure 9: 15 minute dynamic passenger volume and level of service

Time: 8:15-8:30 Preferred scenario with Evergreen Line as SkyTrain 2015.

6 Application in Current Transit Planning Projects

The first series of applications of the RTM focused on SkyTrain, an ALRT system, which is the backbone of Vancouver's regional transit network. Currently, two lines operate in a split-tail, with a combined headway of 108 seconds on the main trunk, where both lines operate in parallel. During 2006 and 2007, SkyTrain suffered capacity problems mainly on one inbound segment during AM peak hours, with passengers being left on the platform because of cramped trains. Two future extensions of the system are analyzed at this time.

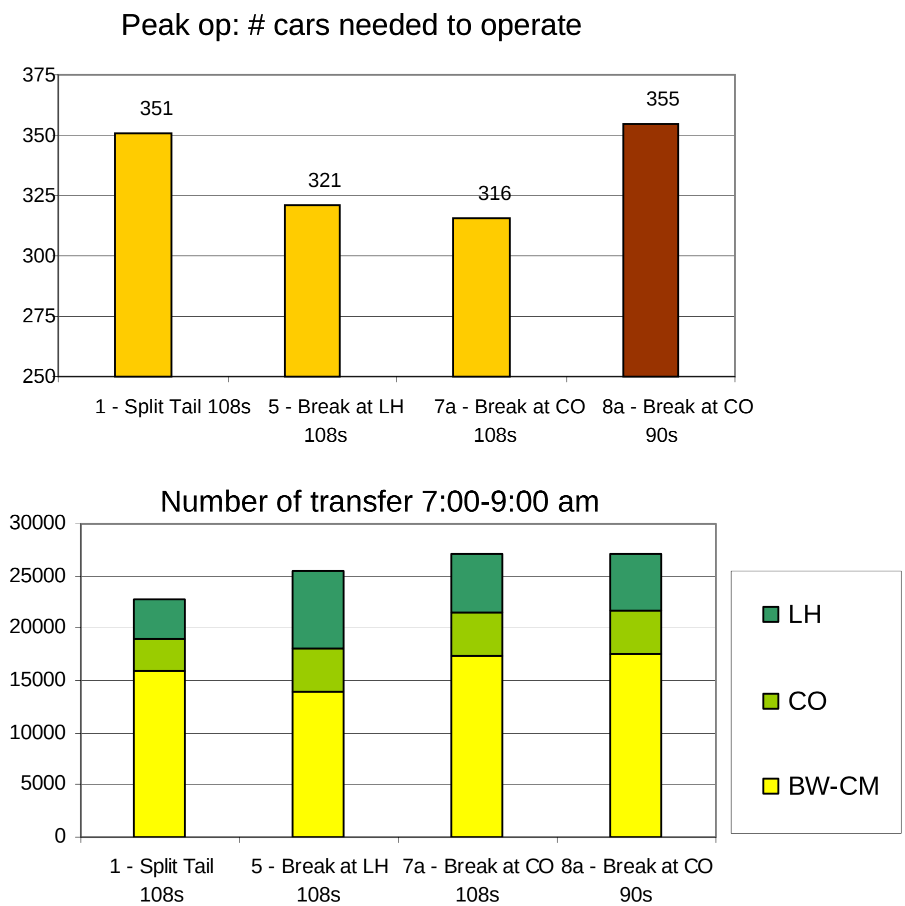
For the existing SkyTrain system, the RTM has :contributed to the regional planning with the following studies and conclusions:

- Based on an extensive analysis of alternatives, the RTM helped to conclude that the present operations are optimal with regard to capacity, as there is no better way to operate with the existing fleet on the existing network.
- The future capacity of the critical segment WF-BW can be expanded to 220% of today's capacity; assuming that the headway will be reduced from 108s to 90s, the fleet will be expanded and will allow for 5-car trains rather than the currently maximal 4-car trains.
- Fleet Strategy: It is desirable to add 3-car train units to the fleet (in addition to the current 2-car units) to allow 5-car consists in the future. A time-line for future fleet orders has been developed based on RTM simulations of future scenarios. The time-line recommends purchasing the first 3-car units in the near future as soon as possible.

For the future SkyTrain extensions, namely the Evergreen Line and the UBC Line (for which SkyTrain is one technology option), the RTM has been used to analyze operating scenarios and based on the scenario comparison, operating concepts have been developed. Figure 10 shows examples of performance measures that were estimated with the RTM to compare scenarios from their ridership impact as well as their operations impact.

Another application of the RTM has been the analysis of the bus network adjustment in the context of the opening of Canada Line, a new automated light metro line which will open in 2009. Several bus routes will be discontinued, others will be realigned to feed directly into the new rail stations, service frequencies will be adjusted. The RTM estimated the ridership for each bus line and the number of buses needed for the adjusted operations.

Figure 10: Scenario Comparison for future extensions of the rapid transit system.



7 Conclusions and Future Perspectives

Metro Vancouver is going through a period of rapid growth of public transportation, with increasing demand and supply. Between 2007 and 2011 the region will see the largest service expansion in 30 years. The population in the region is growing rapidly, while ridership has shown an even faster growth rate than population due to increasing use of transit for all trips. In this context, planners are challenged with multiple projects that need to be analyzed and many questions to be answered.

Since its first implementation in 2006, the Regional Transit Model (RTM) has rapidly become a key resource for planning, capacity analysis and development of future operations scenarios. The RTM's main features are the integration of supply and demand in one analysis system. It uses existing regional transit operations databases and therefore is fully compatible with the operations The RTM has contributed to several capacity studies of the existing rapid transit system and has been used to develop operating concepts for future extensions of the rapid transit network. It also has contributed to bus service planning around the Canada Line, a new automated light metro which is currently under construction and will open in 2009.

Upcoming application studies will include an alternatives analysis of the future Broadway-West rapid transit line. Also, several Bus Rapid Transit (BRT) initiatives and other upgrades of existing bus lines will be analyzed. It is also planned to use the RTM for area transit plans which focus at operations within individual communities in the region. At a smaller scale, the RTM is being used to analyze passenger flows and transfers within stations to determine fare collection and pedestrian circulation requirements.

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References

1. Fisher, I. and W. Scherr (2007): *Optimizing Transit Operations in Vancouver, B.C.: TransLink's Rapid Transit Model.* 11th TRB Transportation Applications Conference, Daytona Beach FL.
2. Friedrich, M., I. Hofsaess and S. Wekeck (2001): *Timetable-Based Transit Assignment Using Branch and Bound.* TRB Annual Meeting 2001, Washington D.C.
3. Friedrich, M., K. Noekel and P. Mott (2000): *Keeping Passenger Surveys up-to-date: A Fuzzy Approach.* TRB Annual Meeting 2000, Washington D.C.
4. Kurth, D., S. Childress, E. Sabina, S. Ande, L. Cryer (2007): *Transit Path-Building: To Multipath or Not to Multipath.* 11th TRB Transportation Applications Conference, Daytona Beach FL.
5. Pine, R., J. Niemeyer and R. Chisholm: (1998): *Transit Scheduling: Basic and Advanced Manuals.* Transit Cooperative Research Program. Report 30. National Academy Press, Washington D.C.
6. Posch, T. (2005): *Supernova – the evaluation tool.* In: Eurotransport, Issue 2, 2005.
7. PTV (2006): *VISUM 9.4 Manual*, Karlsruhe, Germany.
8. TransLink (2003): *On Track – The SkyTrain Story*. 3rd Edition, Burnaby B.C.