Optimizing Transit Operations in Vancouver, B.C.: TransLink's Rapid Transit Model

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Authors:

Ian Fisher
GVTA/TransLink
4720 Kingsway, Suite 1600
Burnaby, B.C., V5H 4N2, Canada
Tel: 604 453 3058
Fax 604 453 4697
ian_fisher@translink.bc.ca

Wolfgang Scherr
PTV America Inc.
1300 N Market Street, Suite 704
Wilmington, DE, 19802, U.S.A.
Tel. 302 654 4384
Fax 302 691 4740
wscherr@ptvamerica.com

1 Introduction

The state of the practice in long-range transit planning is to apply models that integrate supply and demand. In the discipline of transit operations planning however, integrated models are less common in North-America than they are in Europe [Posch(2005)]. This paper presents the design and application of the Rapid Transit Model, an integrated operations planning model that combines a detailed picture of rail operations with time-dynamic passenger flow. The model is used by TransLink (Greater Vancouver Transportation Authority) to analyze operational options for rapid transit in the Vancouver BC area.

The RTM has been designed to perform what-if analysis for all kinds of operational scenarios involving network extensions, fleet assignment, route schemes and schedules. Both supply and demand are covered over 24 hours of the day. It is based on off-the-shelf technology (VISUM with transit operations extension, [PTV 2006]). An important additional objective was to create visualizations and animations that make transit operations comprehensible to lay people.

Before the RTM was created, TransLink had many years of modeling experience with a strategic planning (four-step) model that is instrumental in long-range planning, but offers very limited support for decisions in the areas of fleet, operational concepts and operational facilities. The two models have complementary roles. In the paper we will describe how the strategic planning model supplies demand forecasts as input to the RTM.

In section 2 of this paper, we will present the transit system of the Vancouver area and its relevant organizational context. Then – in section 3 – we will give insight in design and structure of the model itself, including the operations model with fleet, schedules and line blocking, the time-dynamic passenger assignment, and the 24-hour analysis platform. In section 4 we will share our experience from the first application of the new model, in a fleet requirement study. Section 5 draws conclusions and outlines the future directions of the model.

2 The Context: Rapid Transit in the Greater Vancouver Area

The Greater Vancouver Area in British Columbia is a growing metropolitan area 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 74 annual linked transit trips per resident in 2006, up from 63 in 1999. Greater Vancouver's geography is divided 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 Greater Vancouver 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 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 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 operated by BCRTC that carries over 210,000 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. 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 question of how to expand capacity has thus received great attention. Not surprising this modeling project was dominated by SkyTrain capacity questions.

3 The Model Structure

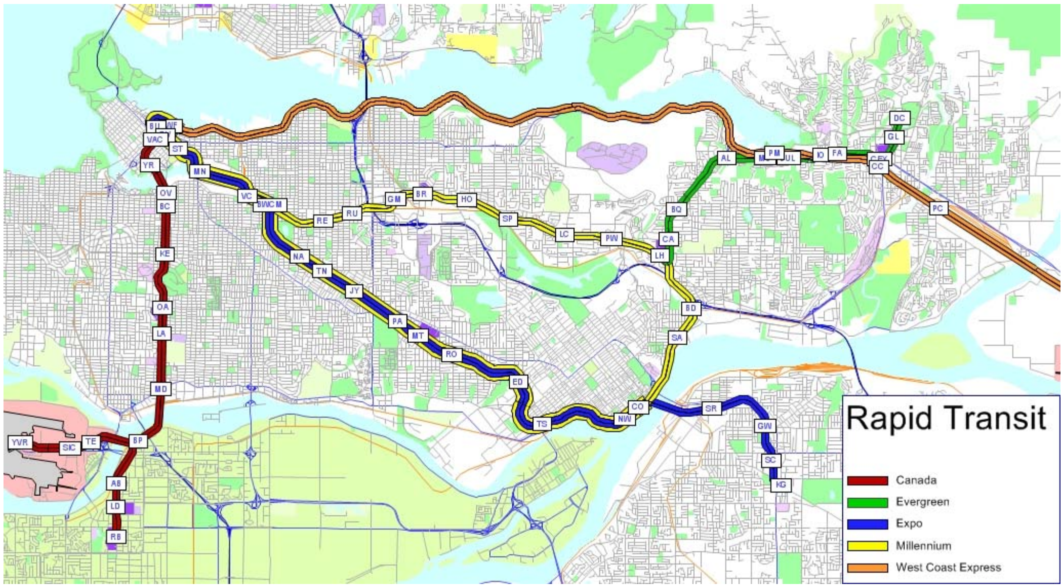
During the model building process several existing data sources from within TransLink, on both the supply and the demand sides that would otherwise remain unconnected, have been integrated. Operational planning of transit services needs a detailed understanding of both sides. Consequently, the Rapid Transit Model includes as supply components schedule, fleet and line blocking. All three go into the computation of transport capacities and service performance. On the demand side, the model integrates several types of ridership counts that have been transformed into one set of OD matrices, supported by a timetable-based passenger path flow model.

3.1 The Supply Model

The current build-out of the model includes the SkyTrain system, West Coast Express and two new rail lines, the Canada Line and the Evergreen Line. All these systems have been modeled for a typical 24-hour weekday that starts at 5:00 AM on day one and ends at 3:00 AM on day two.

Figure 1: The Rapid Transit Network in the Model

(The Expo, Millennium and West Coast Express lines are in operation, the Canada Line is under construction, and the Evergreen Line in planning).



The supply side of the Rapid Transit Model is composed of several data layers that are organized as a framework of interconnected object classes:

- Nodes and links that together represent the stops and stations, streets and rail tracks as a routable network graph.
- Stops that are attached to nodes or links of the network and which can include several physical stop locations as part of one stop, allowing modeling of, for example, multiple platforms of one station.
- Transit lines that can extend to several routes per line and several run-time-patterns per route; including a detailed data structure for run times, dwell time, layover and recovery times.
- Vehicle units and vehicle combinations represent the fleet and different types of trains with specific capacities and cost functions.
- Schedules describe the exact time of all departures (bus or train runs) for each route.
- Blocks are sets of individual schedule runs; a block (sometimes also referred to as “equipment cycle”) represents the work assignment for one train for a single workday. The total of all blocks is generated by the model’s blocking algorithm. An important result from the blocking is the total number of vehicles and trains needed to operate a given schedule.
- The fleet as a set of vehicles that are combined to trains and assigned to blocks.

To make sure that network assumptions are consistent among all scenarios and to avoid coding errors, we have organized the supply data as a **master network** in a single computer file. The master network file contains all the operations data for multiple scenarios that have been analyzed, as well as the OD demand data for all three planning horizons (2006, 2010, and 2021). The master network allows us to store various routes for each line with multiple operating schemes for each route. The route is the data object which contains all operating data (time patterns, schedules, vehicle assignments, blocks etc.). To define a specific scenario, the user selects a set of routes and a set of OD matrices. All model routines like line blocking, passenger path building and assignment, computation of performance statistics will then run only on the routes selected in a scenario. Overall the master network concept turned out to be a quite transparent way to share the model data among several modelers and planners.

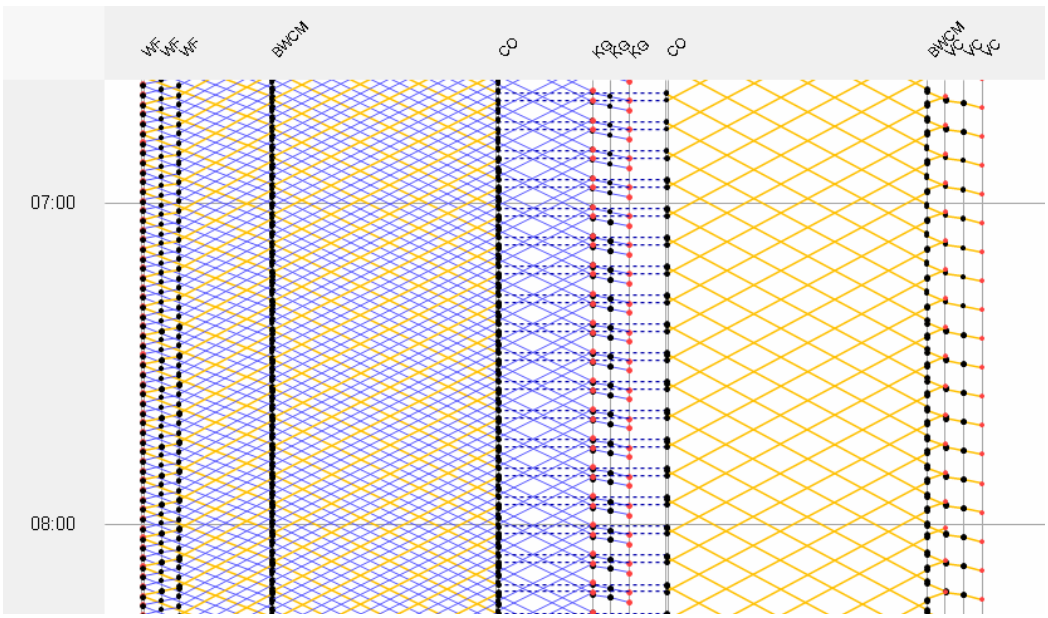


Figure 2: SkyTrain schedule as a time-space diagram, train runs color-coded per line

On the supply modeling side, line blocking is the key component that makes this an operational model. Line blocking is the process of linking individual scheduled runs together. As one result, line blocking determines how much fleet is needed to provide a given schedule. Important is that the line blocking is able to deal with more complex cases of interlining, where one block links together runs from multiple lines, possibly involving empty runs.

The line blocking routine that we use is a heuristic with a greedy strategy that is available within the VISUM package. For each line or route or vehicle run, specific constraints have been set regarding interlining and minimal layover or recovery times. In the existing state, the line blocking routine was calibrated to make sure that it reflects the real-world operations. In line-related statistics like number of blocks, train km, car km, seat km, car hours, etc., the model proved to very closely replicate the official operating statistics provided by BCTRC (SkyTrain's operating company).

The following Figure 3 summarizes the blocking for the Millennium line in the existing case, with 23 blocks, each represented by one bar in the Gantt chart. The 23 blocks are split into two different train types ("2 car Mark II" and "4 car Mark I"). "WF" and "VC" stand for the two termini. Blue bars represent service runs, while white bars show out-of-service time.

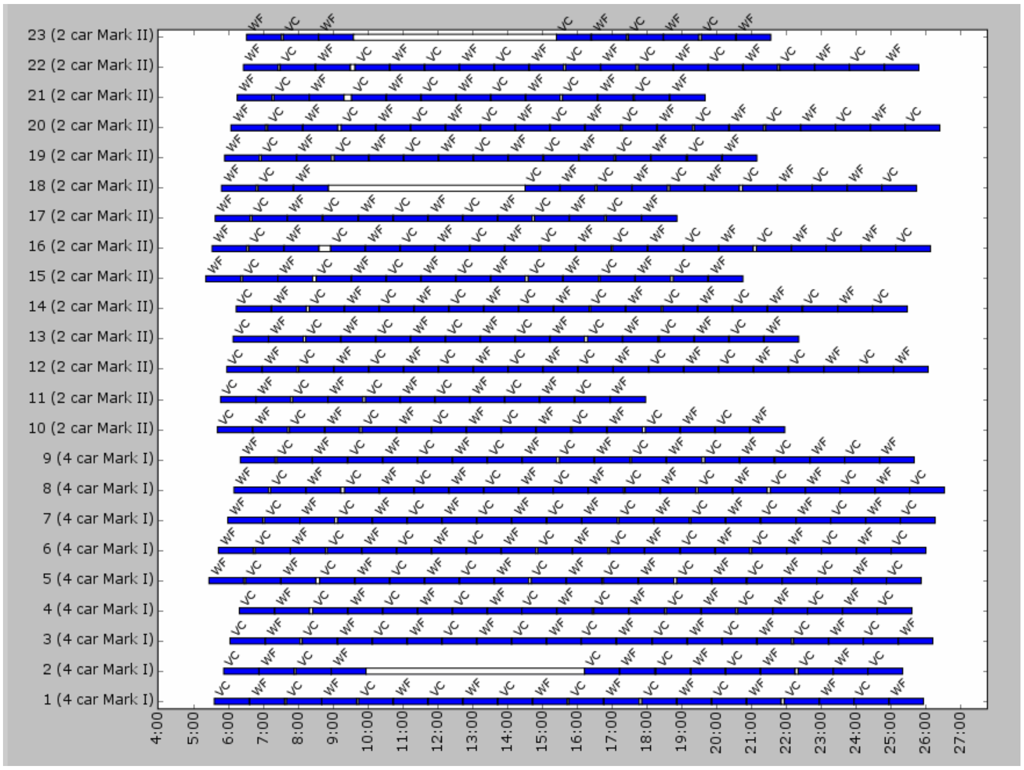


Figure 3: Blocks as a Gantt chart – example: current operations of SkyTrain's Millennium line with 23 blocks

3.2 The Demand Model

The demand model uses the supply model's time and schedule information to produce passenger flow in the entire network over 24 hours of transit service. The flow of passengers is computed using a timetable-based passenger assignment, where multiple alternative paths are generated dynamically during the entire day. This assignment model includes the following inputs: OD matrices, 24-hour distributions of the desired departure times, and the utility function for path search and path choice.

The **OD matrices** for the based year 2006 have been derived directly from survey data and counts, using a semi-automated matrix synthesizer [Friedrich and Noekel 2000]. The input for the matrix development was drawn from several recent surveys: a 2005 telephone-survey (which provided a seed matrix); 2003 and 2005 station boarding counts; a 2005 transfer survey; and 2006 loading counts. To represent different station-to-station flows at different times of the day, four matrices (AM, Mid-day, PM and evening) were created.

In **timetable-based assignment** [Friedrich 2001], passenger flow is computed based on time-exact itineraries. So the path from A to B contains not only the spatial information like stops and routes (as in headway based passenger assignments) but also the time-detail. The path-builder generates time-detailed itineraries for all OD pairs during the entire day. The path-choice includes not only the utility of the path but also the utility/disutility to depart with an earlier or later path. Transfer waiting times are computed based on the scheduled offset between arrival and departure at the stop.

Figure 4: Path example in timetable-based passenger assignment

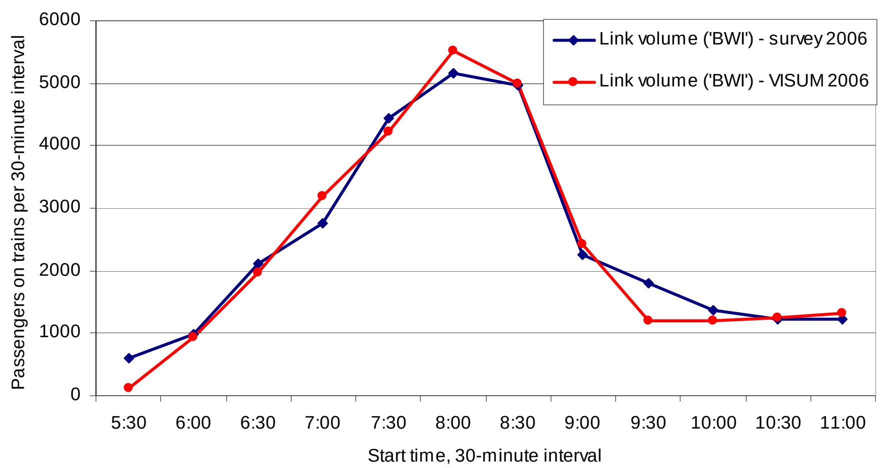
Time detail		Space detail		Service detail
From	To	from	To	
8:10	8:14	Origin	Stop 1	
8:15	8:31	stop 1	Stop 2	route X
8:31	8:34	stop 2	Stop 2	Transfer, change platform
8:34	8:38	stop 2	Stop 2	Wait
8:38	9:02	stop 2	Stop 3	route Y
9:02	9:05	stop 3	destination	Walk

Consequently, the timetable-based assignment is time-dynamic. Passengers are assigned onto individual train runs. In practice, the individual train loads are not analyzed, in particular not in a high frequency system such as SkyTrain with a peak headway of 108 seconds. In this study we evaluated passenger volumes aggregated to 15-minute intervals. As a result of the assignment, 15-minute volumes are computed for each network element such as lines, routes, links, stops and stop points.

For the base year 2006, all control parameters of the passenger flow model as well as the OD matrices have been calibrated so that the time-dynamics of passenger volume are replicated exactly, as well as the number of boardings, alights and transfers at each station. Figure 5 shows replication of the AM peak ridership in 30-minute intervals by the model. In this project it was important to calibrate the OD matrix and the departure time distribution to make sure that the build-up of the demand peaks at different sections of the network were replicated very closely by the passenger flow model. Without a close replication of the peaks it is not possible to analyze problems related to the passenger demand exceeding the capacity only during short times of the day. Goodness of fit statistics for 24-hour station boardings are, for example: R^2 of 99.7% and RMSE of 7%.

Figure 5: Calibration of time-dynamic link loadings

The particular link shown ("BWI") extends from the Broadway to Main-Street stations in the inbound direction and is the peak load point on the system.

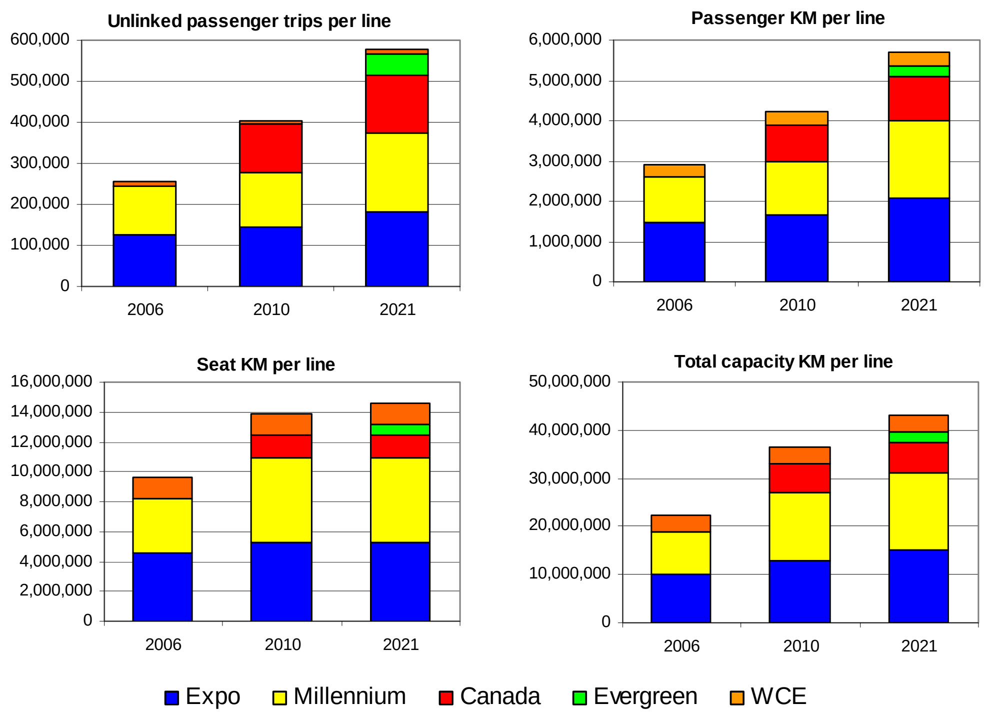


3.3 Modeling Future Rapid Transit

In the near future, there will be additional rail lines in the region: Construction is under way for the Canada Line, an automated, tunneled and elevated rail system scheduled to open in 2009. The region's first LRT, the Evergreen Line is planned to open in 2013. Both network extensions have been included in the model. Also, operational concepts have been developed for the future SkyTrain system with these new lines in place, including various fleet expansion scenarios.

Figure 6 shows aggregated results from integrated scenarios for 2006, 2010 and 2021. The 2021 scenario includes all future rail extensions (Canada Lines, Evergreen Line) and SkyTrain operations that are tailored to the projected passenger demand, as explained below.

Figure 6: Future scenarios of ridership, network and operations



The OD matrices for the future horizons 2010 and 2021 have been developed with a pivot point approach, where future trips equal the existing trips plus a growth specific to each OD pair:

$$Demand_{od}^{2010} = Demand_{od}^{2006} + Growth_{od}^{2006-2010}$$

The growth matrices have been derived from approved forecasts of TransLink's strategic four-stage model. The advantage of this pivot-point approach is that we preserve the "count truth" of the existing OD matrices within the future forecast. On the other hand, our forecasts are consistent with TransLink's strategic planning process and strategic model forecasts that include demand shifts because of demographics, land-development and mode-choice, all of which are not included in the design of this operational model. Another major benefit of this approach is that the strategic four-stage model gets directly linked into operational planning which is unfortunately not very common.

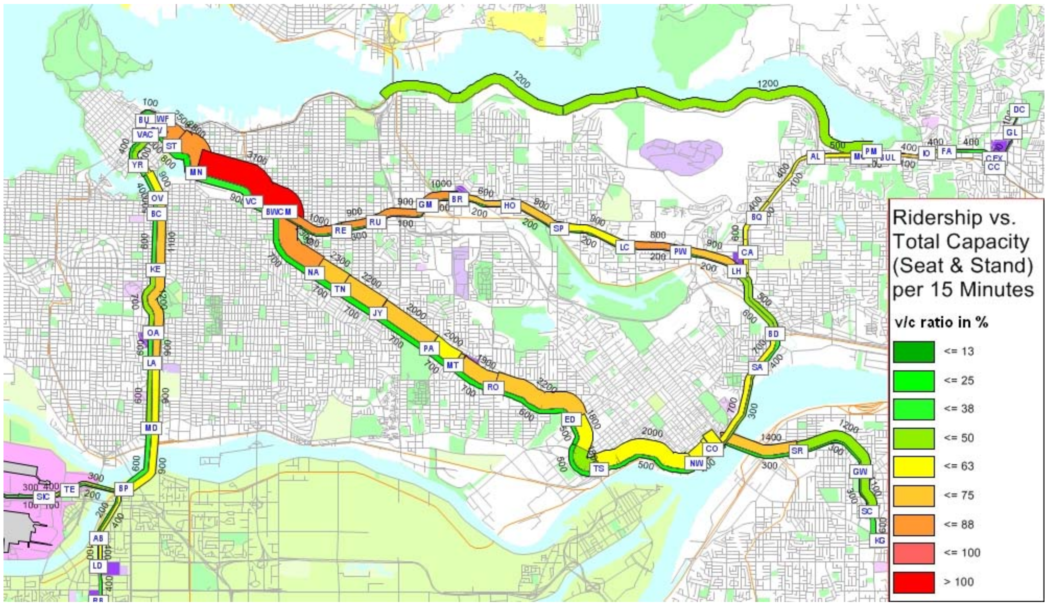


Figure 7: 15-minute passenger volumes and v/c-ratios

Note that only part of the West Coast Express line appears at the top of the map, representing the portion of the line covered by a train in the 15-minute analysis window.

4 Application in a Fleet Requirement Study

4.1 Methodology

The first application of the new model has been a study of the current and future SkyTrain system searching for answers for two questions:

- Would a change in the current operational concept (route scheme, headways, train assignment) mitigate the current capacity constraints by reallocating capacity where it is most needed, without creating new bottlenecks?
- How many train cars does SkyTrain need in the future?

These questions are equivalent to an optimization problem, with the objective being to maximize capacity on critical network segments. The operational constraints are a given fleet and the network (with stations, tracks, run and dwell times). Another constraint is the passenger demand that is to be met by train capacity but which is supply-elastic. The key variables are route schemes, headways and schedules, train composition and train assignment.

For this study we have limited the capacity analysis to the AM peak, because the most serious capacity problems occur during this time. Our methodology to solve the problem was not a mathematical optimization. Instead we did an enumeration of alternatives in spreadsheets and identified promising scenarios by eliminating the less effective ones. Then, in a second step, we performed a detailed, integrated demand and supply analysis of more promising scenarios with the Rapid Transit Model in VISUM. Several performance measures served to compare scenarios, the most important one being volume/capacity ratios.

4.2 Volume/Capacity Analysis

Much attention during the SkyTrain fleet analysis has been put on the volume-capacity situation and on the particular locations and times of day when capacity comes short. Figure 8 puts the total capacity (seats and standees) in contrast with the total passenger volume on the link that suffers most from a capacity shortage in the morning peak.

Figure 8: Time-dynamic passenger volumes and transport capacities of one network link (BW inbound, 2006 Base)

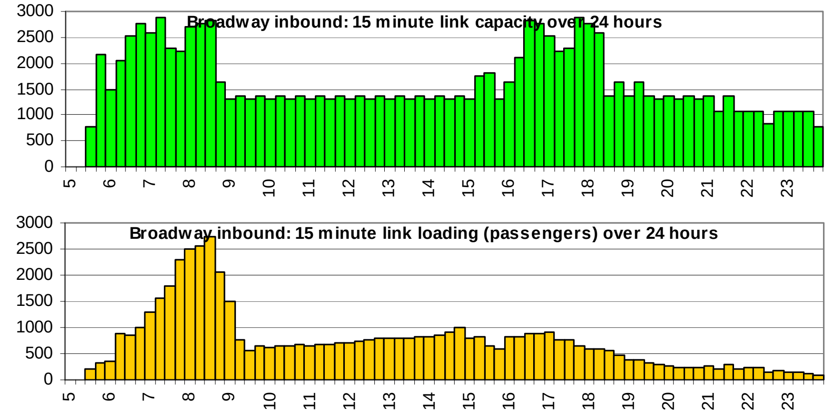
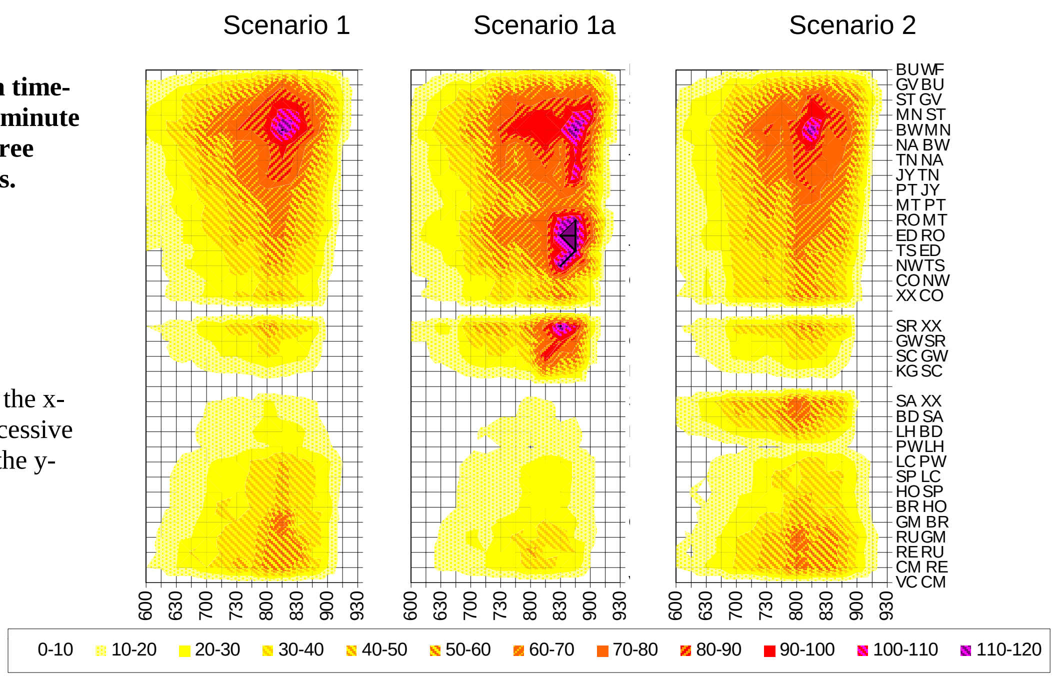


Figure 9: V/C in percent in time-space charts (15-minute time step), for three selected scenarios.

Time of day is on the x-axis; space as successive network links on the y-axis.

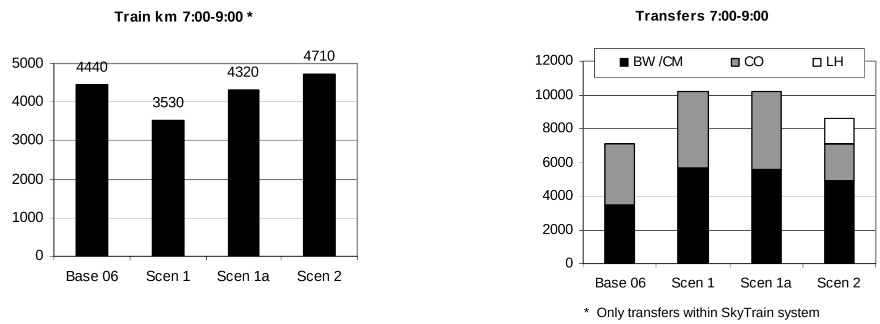


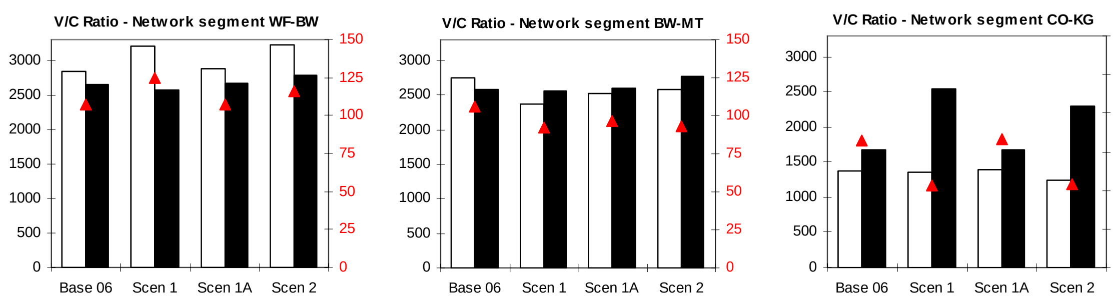
One way of v/c analysis is to aggregate both passenger volume and train capacity in small time intervals (e.g., 15 minutes), and then divide volume with capacity. Figure 9 uses this v/c ratio in percent and displays it in a time-space diagram. The problem with that method is that the capacity of an individual train run is added as a lump to only one time interval even though it serves passengers from two adjacent time intervals. As a result of this effect, and aggravated by variations of train size, we observe significant variations of the 15-minute capacities. The same variations then affect the v/c ratios. These "random" capacity variations can be seen in Figure 8 which shows 15-minute capacities for one particular link in contrast to the smooth curve of passenger volumes. We analyzed this kind of raw v/c ratio extensively in the fleet requirement study. In the end we used the raw v/c ratios mainly to screen bottlenecks within one scenario (see Figure 9), but not for scenario comparison. We developed a v/c ratio based on average peak-period capacity (see Figure 10) as a "cleaner" means of comparing scenarios.

4.3 Results: Fleet Requirements

Four scenarios have been analyzed in detail with the model. Each of these scenarios had a different route scheme and the most efficient train assignment possible for that route scheme. In the model the passenger flow is not constant but reacts to changes in schedules and operations. Therefore each operations scenario has been fine-tuned over a few iterations to make sure that train capacity meets the passenger flows as much as possible.

Figure 10: Scenario comparison - selected performance measures





We found that, under current conditions, none of the alternative scenarios improved on the current operating plan.. Our study confirmed that the current operations concept is highly efficient in matching capacity to demand. Only one scenario (1A) showed equivalent performance but is not likely to be tested in practice as it would likely require some infrastructure upgrades, and would add complexity for customers and operations.

While SkyTrain currently operates optimally, operations will have to be modified in the future as changing demand will require fleet extensions and network extensions. The operating scenarios analyzed for the existing case have been used as a basis to develop future operations. The preferred scenarios for SkyTrain operations in 2010 and 2021 use route schemes and headways very similar to today's operations. However, train capacities are increased as the fleet expands and older cars replaced. Complementary reinforcement ("short-turn") patterns have also been added to increase capacity along critical network sections.

The modeling work for 2010 and 2021 showed that, assuming current plans for purchase of new and replacement SkyTrain cars are achieved, there will be adequate capacity to meet projected demand and current over-capacity situations should be relieved. However, the system will remain quite crowded with near 100% capacity utilization at the maximum load points in the peaks. This result, plus an assumption of a very low fleet spare ratio, suggests future work will be needed to review fleet requirements and monitor actual vs. projected ridership, especially as new lines are introduced.

5 Conclusions and Future Directions

The Rapid Transit Model has proved to be very useful in the fleet requirement analysis, mainly because of the detailed understanding of operations, the 24-hour time-dynamic analysis and because of the integrated analysis of ridership and operations. A major benefit of the model is that all kinds of individual data pieces and isolated tools for selected operations planning problems are now integrated into one modeling and analysis tool.

In the future the interaction between the RTM and the regional strategic four-step model will be streamlined and extended. The RTM currently obtains future ridership as station-to-station flows from the strategic model. It is planned to modify the RTM to allow the use of spatial OD matrices derived from the strategic model, and to feed back run and dwell times for future transit services.

The Rapid Transit Model has made a transition from a consultant's application to a permanent tool used in-house by TransLink staff. It is planned to extend the network with bus and passenger ferry services. Upcoming applications will include studies on future SkyTrain extensions and an analysis of yard locations. Also, the model will be used to take a closer look at operational options in the off-peak, such as replacing longer trains with shorter ones. Another project will be to upgrade the passenger assignment model to a downstream capacity-restraint approach.

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