Simulation Model of Shared Right-of-Way Streetcar Operations

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Described in this paper is the Queen Streetcar model, a large FORTRAN program currently under development that simulates light-rail vehicle operations on the Queen Route in Toronto. This service operates in mixed traffic and on a reserved right-of-way over a 21-mi route. There are 140 passenger stops and 38 traffic signals along the route, and three separately scheduled streetcar services operate over portions of the route. The model is designed to analyze the impact of a range of operating policies on the regularity of streetcar service. Specifically, the model is intended to allow examination of operating procedures and then permit comparison with alternate means of regulating service, such as alternative short-turn strategies; use of a centralized automatic vehicle monitoring system; and introduction of traffic signal priorities for transit vehicles, reserved rights-of-way, or larger capacity vehicles, or both. The model proceeds by computing the amount of time that each streetcar will spend in a logical set of "states" within each link within the network, where streetcar states include moving in a link, loading and unloading passengers at a stop, and so forth. The model simulates operations during a 2:00 to 7:00 p.m. weekday period using 5-sec time increments. At each 5-sec interval, each streetcar currently in the system is examined to determine if it will remain in its current state for at least another 5 sec or if it is about to go to its next state. If the latter is the case, the appropriate next state is determined, the amount of time that the car will spend in this state is computed, and the system records are updated accordingly. Major sources of randomness within the model include passenger arrival rates and boarding times, and delays as a result of interactions with other traffic within the shared right-of-way.

The Queen Streetcar model is a computer program that simulates light-rail vehicle operations on an urban street. The model was developed as part of a larger study of streetcar operations on the Queen Street route in Toronto that focused on the short-turning of streetcars as a method of regulating service headways (*1*). The objectives of this study were to (a) analyze the sources of headway irregularities, (b) assess the effectiveness of the existing short-turn procedures in controlling these irregularities, and (c) evaluate alternative means of service operation in order to reduce the need for invoking short-turning control methods. Such service options include modifications to the route structure, introduction of new sections of reserved right-of-way for streetcars, introduction of traffic signal priorities for transit vehicles, use of larger capacity vehicles, introduction of a centralized automatic vehicle monitoring system, adjustment to service schedules, and variations in current route-control procedures.

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This wide range of alternatives is indicative of the variety of factors that affects surface transit operations. In addition, streetcar dwell times are determined by random numbers of persons boarding or alighting at each stop. Traffic signals interrupt the streetcars' progress along a route. Finally, a variety of random delays related to queueing or pedestrian interference can occur during mixed-street traffic operation. These complex stochastic interactions, combined with the cost of collecting large amounts of field data and the lack of proven analytical methods, make a comprehensive analysis of alternatives such as those listed previously extremely problematic. Computer simulation was considered a valuable approach for evaluating these alternatives in greater detail.

Although the original need for the model was precipitated by the larger study of streetcar operations on Queen Street, the model development and testing ran past the study time allotment, with the result that direct simulation results were not included in the original study. The principal benefit of the model to this study was the analysis required to construct it. In the conviction, however, that a detailed simulation model is still the only comprehensive analysis tool possible to study the range of operating strategies that can affect streetcar service regularity, the authors have continued the development of the model. The structure and use of the model and its current development status are described . An overview of the model is presented [for a more detailed documentation, see Miller et al. (*2*)] and the results of applying it to a test base case is described.

GENERAL MODEL DESCRIPTION

The Queen Streetcar model was constructed specifically to replicate in detail certain aspects of the Queen Street Route in Toronto. This service operates both in mixed traffic and on a reserved right-of-way over a 21-mi route. There are 140 passenger stops and 38 traffic signals along the route. Three separately scheduled streetcar services operate over portions of the route, which passes through the downtown area where other vehicular traffic is significant. Because of the length of the route, streetcars enter and leave the line at two separate carhouses. In general, it is an extremely large and complicated operating environment to simulate.

In order to control the magnitude of the program development, the simulation model simplifies the real processes wherever possible. However, streetcar service irregularities result largely from the cumulative effects of a large number of random processes. To simulate these effects realistically, it was necessary to develop certain elements of the model in considerable detail. In constructing the model emphasis was directed to those details of operation that had been observed to have the greatest effect on streetcar running times and delays, notably, the passenger loading/unloading process, and delays at signalized intersections. By contrast, the model, which is written in FORTRAN 77, provides only a simplified simulation of general urban street traffic operations. It currently runs on a micro-VAX 11 computer under the Berkeley 4.2 UNIX operating system. A single run of the model takes approximately 5 min of CPU time to execute.

Overall Program Operation

The structure of the model is based on the representation of the streetcar route as a series of links, connected to form a loop. Simulation of the system performance is conducted by calculating the time required for each streetcar to progress through each link. The simulation begins at 2:00 p.m. and runs for 5 hr to cover the entire afternoon.

Streetcars are assumed to operate over each link, in the absence of delay, at predetermined speeds. They are, however, generally delayed by a series of events that include random arrivals of passengers at each stop and subsequent boarding and alighting activity; random midlink delays caused by such events as left turns at unsignalized intersections; and delays at signalized intersections as a result of a red light or a queue of vehicles in front of a streetcar waiting to enter the intersection. A streetcar schedule is provided, and each streetcar attempts to maintain a given schedule by slowing down or speeding up as appropriate.

The short-turn procedure is modeled by establishing "inspector locations" and monitoring the vehicle headways and loads as each streetcar passes these points. A set of criteria is provided to flag the need for a short turn, and a location for the short turn is selected from among a series of preset locations along the route. When a streetcar designated for a short turn reaches the appropriate location, it leaves the route and reenters service in the opposite direction according to instructions provided by the inspector. Data to assess system performance, such as vehicle headways and passenger loads, are collected continuously throughout the simulation at selected points along the route. This information and other summary statistics are compiled periodically, or at the end of the simulation and provided as output on completion of the program. Before execution of the program, input data are compiled in a series of off-line files and read into the program at the beginning of execution. These files include such information as streetcar schedules, passenger demand patterns, traffic signal timings, vehicular traffic flows, and the location of all streetcars at the beginning of the simulation run. In addition, user-defined parameters are provided as input to the program, either from another data input file or interactively from the computer terminal. These inputs permit easy variation of key parameters such as inspector locations, as well as selective output options.

Route Structure Representation

Figure 1 shows a map of the streetcar services using Queen Street. The model focuses on the longest and most heavily scheduled of these, the 501 Queen Route, which runs along Queen Street from the Neville Loop in the east, through the central business district, and along the Queensway to the Humber Loop in the west. This route is modeled in its entirety and serves as the basis for the link definitions used in the model. Each link in the system ends at either a passenger stop or a traffic signal and begins immediately downstream of the previous link. Every passenger stop defines a unique link. In addition, at traffic signal locations where there is no passenger stop, additional links are defined. Streetcars can only enter or leave the link network at specific points. Three types of entry/exit locations exist in the model: carhouses, short-turn locations, and off-line entry/exit points for the 502 and 503 routes discussed next.

The 502 Downtowner operates between the McCaul Loop in the downtown area and the Bingham Loop, overlapping on the Queen line between McCaul Street and Kingston Road, as shown in Figure 1. The 503 Kingston Road Tripper operates between York Street in the downtown area and the Bingham Loop overlapping on the Queen line between King Street and Kingston Road. Separate streetcar schedules are provided as input data for the 502 and 503 routes. On the overlap portions of the Queen line, the 502 and 503 routes are modeled in almost the same detail as the 501 Queen cars. The exceptions are that no adjustments to speeds are made to maintain their schedules and no short-turns are executed.

At the points at which the other routes depart from the Queen line, their operation is modeled in a simplified manner. While off-line, details of passenger service and delays to these services are approximated by estimating the time at which each streetcar returns to the Queen line and reenters with an estimated passenger load. The return times are estimated by computing a random travel time (uniformly distributed around the scheduled travel time) that is added to the scheduled departure time from the end point of the line (i.e., from the McCaul and Bingham Loops for the 502 Downtowner and from York Street and the Bingham Loop for the 503 Tripper). The number of persons onboard and their destinations at the time of reentry is directly estimated by the product of the return travel time and a load rate, which is provided as input data.

As shown in Figure 1, the system divides into five natural sections. Section 1 is the Queensway portion of the 501 route, which operates over a reserved right-of-way. Section 2 is served by the 501 route operating within a shared right-of-way (Sections 3, 4, and 5 are also shared rights-of-way). Section 3 has both 501 and 502 cars operating within it, whereas Section 4 is served by all three routes. Finally, Section 5 is again served only by the 501 route. Each link is thus labeled by its section number in order to keep track of the different service levels. In particular, passenger origin-destination flows are computed on a section-by-section basis so that the model can load passengers onto appropriate cars (e.g., a westbound passenger in Section 4 destined for Section 3 will be permitted to board a 501 or a 502 car, but not a 503 car because the latter does not serve Section 3).

At the start-up of a simulation run, a given number of streetcars are already on the network, distributed according to their individual schedules. As the simulation proceeds, additional streetcars, termed swing cars, enter the system from the two carhouse locations, corresponding to the increase in

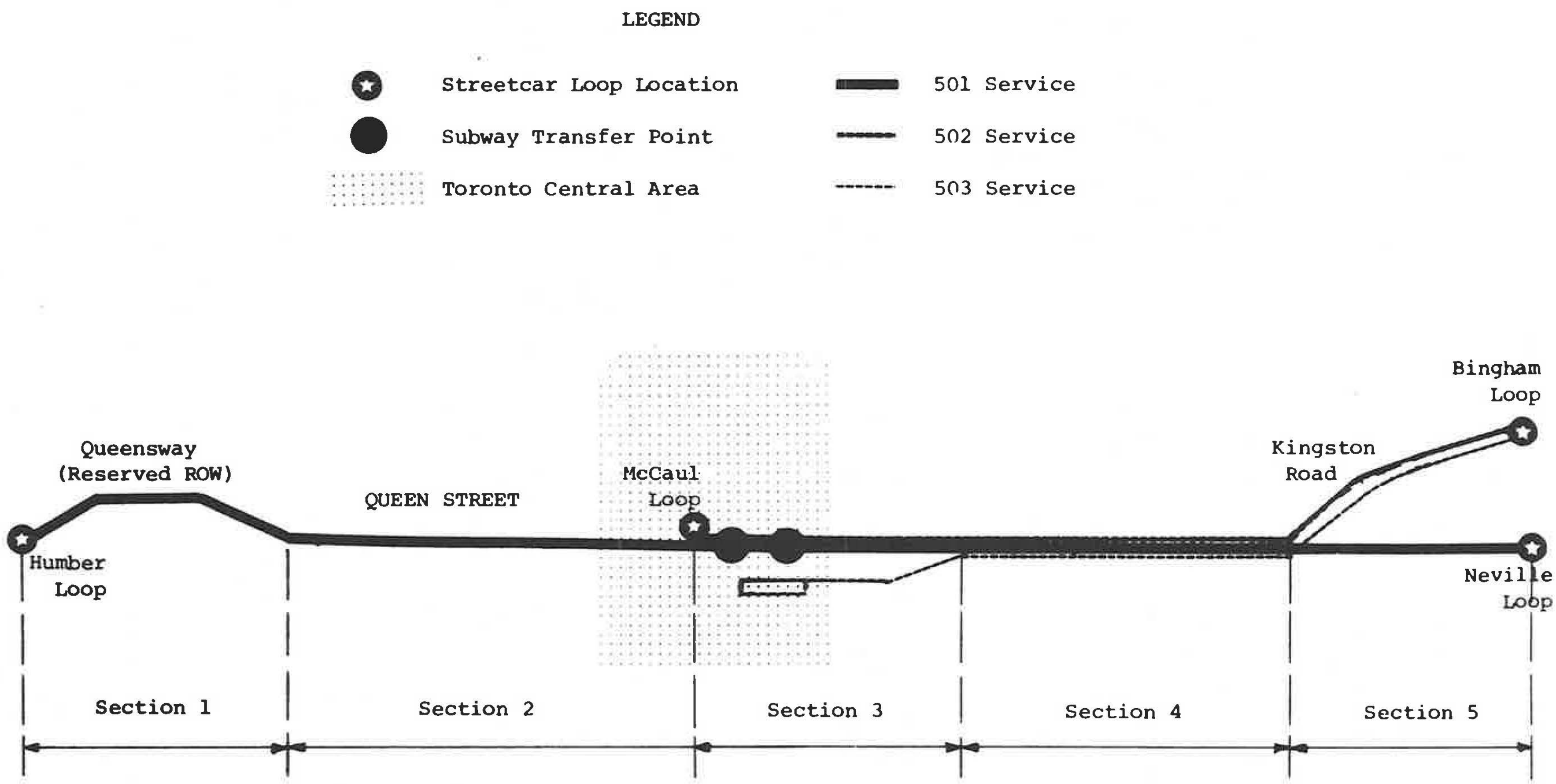

FIGURE 1 Queen Streetcar system.

service during the peak period defined by the schedule. Similarly, streetcars exit to the carhouse locations when their scheduled service ends.

During the course of the simulation, a variable number of short-turns are executed as directed by the inspector submodel. Streetcars leave the network at the end of specific links and reenter in the other direction at the beginning of another link. There are a total of 8 potential short-turn locations, four east and four west of downtown.

Adjustments to streetcar speeds to maintain the schedule are calculated according to time checks at specific timing points along the line, labeled T-points. Each streetcar compares its departure time with the schedule and adjusts its speed to the next T-point accordingly. For convenience, the T-points are also designated as locations for collecting streetcar performance data such as vehicle headways and passenger loads. To complement these locations, where the spacing between T-points is wide, additional user-specified data collection stations, labeled O-points, are included in the model.

Simulation Procedure

Simulation of streetcar performance is based on the calculation of time required for each streetcar to travel through consecutive links in the network. This time is divided into three major activities: moving between stops, loading and unloading passengers, and waiting to clear a traffic signal. On completion of these activities in one link, a streetcar moves downstream to the next link.

Operation of the system as a whole, including the progress of each streetcar, the entry and exit of cars to and from the line, and the short-turn execution, is updated throughout the simulation in time-steps of 5-sec intervals. At each time-step, all links are searched sequentially to determine if there are one or more streetcars either within the link or about to enter or leave the link.

Rather than move each streetcar forward in detailed 5-sec steps, however, progress is monitored by holding each car in a discrete state for a certain number of time increments. When this time expires, the next appropriate state is determined and the length of time the streetcar will remain in that state is calculated. The link review in each time increment then simply checks to determine if any state changes are due at this particular time. The streetcar states defined for use in the model generally correspond to the three major activities referred to earlier. In addition, other temporary or transitional states have been defined to facilitate the programming and the accounting tasks. A full list of the possible streetcar states is provided in Table 1.

The pattern of passenger arrivals at each passenger stop is simulated coincident with the modeling of the streetcars' progress through the network. At the time a streetcar arrives at a passenger stop, the time elasped since the last streetcar arrived at the stop is computed. This time interval is used by the passenger demand submodel to generate a number of passenger arrivals grouped according to their destination section. The passenger loading/unloading submodel then computes the number of passengers that will board this particular streetcar and the time required to do so.

TABLE 1 STREETCAR SYSTEM STATES

State	Activity
1	Having entered a link, a streetcar is moving toward the end of the link with a known arrival time (there are no streetcars ahead in the same link)
2	Loading/unloading at a stop at the end of the current link
3	Upon completion of loading/unloading (or in the absence of a stop), a streetcar is waiting at the end of a link to exit the link (delays include traffic signals, queues, etc.)
4	A transitional state that takes no time and is used for determining the streetcar's next movement, that is, to the next link, out of service, off-line, or to a short-turn loop
5	A streetcar in service but temporarily removed from the Queen line (for 501 cars, they are being short-turned; for 502 and 503 cars, they are traveling on separate route sections)
6	A transitional state for a streetcar that has entered a link and is moving toward the end of the link but with an unknown arrival time because at least one other streetcar is ahead in the same link

Model Sub-Components

The logic of the main components of the model is described in this section. The presentation has been tailored for ease of description, and the subtitles do not necessarily correspond to the structure of the subroutines in the program code itself. More complete documentation of the main program and the individual subroutines is provided by Miller et al. (*2*).

Moving Between Stops

An initial running speed is assigned to each streetcar at the simulation startup according to the section in which the streetcar is located. As the streetcar moves from one section to another, this base running speed is altered. Adjustments to the base running speed are made continuously throughout the simulation for each streetcar according to the schedule adherence monitored at the T-points. This streetcar speed and the length of the link are then used to compute the free running time of the streetcar in the link (i.e., the time the streetcar would arrive at the end of the link in the absence of delay).

Midlink delays to each streetcar can result from such events as left-turns by other vehicles in front of the streetcar at unsignalized intersections, pedestrian crossings, and parking maneuvers of other vehicles. The model groups all such occurrences together and calculates whether or not a delay will occur in each link. The occurrence of a midlink delay is first randomly determined, and, should the outcome be positive, a random delay length is then generated. Both the probability of occurrence and the distribution of delays are provided as input data.

Whether or not a queue exists at the end of the link is determined by the traffic flow entering at the beginning of the link ahead of the streetcar, the size of any residual queue at the traffic signal at the end of the link, and the presence of other streetcars already in the link. If there are no other streetcars in the link, the streetcar is considered to be in State 1, the size of the head queue in front of the streetcar is computed, and the time required to dissipate the queue is simulated. If another streetcar is present, the entering streetcar is considered to be in State 6, whereupon it is advanced only part way into the link. When all other streetcars have finally departed, the entering streetcar effectively reverts to State 1, and the final arrival time at the end of the link is computed (queueing delay calculations are discussed further in the next section).

The running time, mid-link delay time, and queue delay time are added to produce an arrival time for the entering streetcar at the end of the link.

Passenger Loading and Unloading

The passenger demand submodel generates arrival of passengers in two parts. Average arrival rates over 30-min periods are provided for each passenger stop as input data. The number of passengers arriving at a stop is computed according to these mean arrival rates and the time interval between streetcars reaching the stop, assuming that passenger arrivals are Poisson distributed. In addition to this continuous arrival distribution, it was considered necessary to account for observed "surge" loads of passenger arrivals corresponding to transfers from other transit services at stops on major intersecting transit routes. This is simulated in a manner similar to the midlink delays. A random occurrence is generated according to a preset rate, and, in the event of a positive outcome, a random load is generated, again within a defined distribution.

When the total number of arriving passengers has been computed, they are divided into destination groups according to section, based on observed sectional origin-destination distributions. Five separate queues of waiting passengers are therefore maintained at each stop, each being incremented or decremented according to arrivals and boardings. The passenger loading/unloading model is used to compute the amount of time a streetcar spends in State 2, termed passenger service time. Boarding and unloading times are computed separately, the latter being further divided into front and rear door unloading times. The total passenger service time is the greater of either the rear door unloading time or the sum of the front door unloading time plus the boarding time.

The number of persons onboard each streetcar is updated by the model at each stop. The total number of passengers onboard is stored separately for each destination section. At any given stop the number of persons who unload is determined by the section of the route on which the stop is located, the number onboard destined for that section, and the overall destination of unloading patterns within the section (provided as input data). Unloading times are simply calculated as the product of the number of persons alighting and a user-specified average time per passenger. The distribution of unloading passengers between front and rear doors is based on an assumed distribution of seated and standing passengers onboard the streetcar as it arrives at the stop.

Boarding times are calculated in a sequence of steps. The number of passengers wishing to board is first calculated depending on the number of persons in the five destination queues of waiting passengers, the streetcar route (501, 502, or 503), and, if the car is designated for a short-turn, the short-turn destination. The number of persons who actually board is then calculated depending on the remaining space on the streetcar after unloading is completed. In the event that there is insufficient room to board all waiting passengers, the number who actually board is drawn proportionately from the five destination queues.

With the number of persons boarding known, the boarding time is then computed as a random variable dependent on this number as well as the number of persons already onboard the car at the completion of unloading. It is assumed that variability in loading times is higher for small numbers of persons boarding and that average boarding time per person increases if more than a full seated load is already onboard. Once the initial passenger service time has been computed, a second iteration of the passenger loading calculation may be made. During the period that passengers were first unloaded and loaded on arrival of the streetcar, additional passengers may arrive at the stop wishing to board. If another streetcar is immediately behind, the arrival of this second wave is ignored, based on the assumption that these passengers will board the trailing car. If there is not a trailing car, and there is still room onboard the car at the stop, these additional passengers, or a portion of them, will also be loaded onto the streetcar with a corresponding extension of the passenger service time.

Other Street Traffic

The operation of streetcars on an urban street in mixed traffic slows running speeds considerably. In addition, the randomness of the delays that occur is a major source of variability in streetcar service. The list of potential types of delays is almost unlimited. Moreover, on a high frequency route with heavy passenger loadings such as the Queen line, interaction between streetcars running on a fixed track and other street traffic is complex. Because vehicular traffic is prohibited by law from passing a streetcar with open doors at a passenger stop (where there is no passenger platform), a loading streetcar will delay other vehicular traffic. Streetcars delay traffic, which creates a queue, which in turn may delay a following streetcar, and so forth.

The approach used to simulate this process in the Queen Streetcar model is to estimate traffic-related delays from the viewpoint of each individual streetcar only, on a link-by-link basis. Calculation of these delays depends on the model of traffic signal operations and the process of vehicle arrivals and departures into and from a link.

The model of traffic signal operations closely resembles the real world by simulating the actual timing plans used by the Metropolitan Toronto Roads and Traffic Department through the central traffic computer. These timing plans are provided as input data and include directional split phases, changes in timing plans through the 5 hr of simulation, and all are time coordinated through the specification of signal offsets. The only simplifications are that time is measured in 5-sec steps (rather than as a proportion of cycle length) and that no allowance is made for clearance intervals (amber or all red periods). Signals facing a streetcar are either effectively red or green.

Vehicle arrivals into a link are assumed to accumulate at constant rates, which are provided as input data. To model time variations in flow, the rates are altered each 30 min of simulated time. These rates are compiled directly from traffic count data at all signalized intersections provided by the roads and traffic department. Variations within a 30-min period are not modeled and disturbances to the arrival flow caused by upstream traffic conditions are ignored. The arrivals correspond to the estimated proportion of the traffic volumes in the left lane only (i.e., the lane in which the streetcars travel).

Vehicle arrival rates are used to compute the number of vehicles ahead of a streetcar as it enters a link (i.e., the head queue). If the last streetcar is still within the link, the queue remains unaltered until that streetcar departs. No allowance is made for traffic in the left lane to pass a streetcar ahead. If the previous streetcar has departed, then the time required to dissipate the queue is calculated. If there is no traffic signal at the link end (i.e., a passenger stop only), then the queue is assumed to discharge immediately. Otherwise the queue dissipation time is computed by means of a model of the vehicle departure process at a traffic signal.

Vehicle departures are modeled as two separate cases: before the streetcar arrival at the link end and after it has arrived. A streetcar is considered to have arrived when the head queue has shrunk to a size of two vehicles or less. It is assumed that a queue of two vehicles will not prevent the streetcar from proceeding with the load/unload process in State 2 directly.

In the first vehicle departure case (head queue greater than 2), the vehicles are discharged at the traffic signal according to a constant saturation flow rate built directly into the model. The time required to reduce the queue to at most two vehicles is computed in combinations of partial and, if necessary, whole signal cycles, according to the green time in each cycle. The streetcar is considered to have arrived at the link end at that point in time and will change to State 2. Any residual green time in the last signal cycle is then used to discharge either one or both of the remaining head queue vehicles.

On completion of the initial passenger service time in State 2, the streetcar changes to State 3, and a series of checks are made to determine if it can then proceed to the next link or if it will be delayed by either additional arriving passengers or by traffic-related factors. If there are additional passengers, the streetcar reverts to State 2 and continues loading as previously described.

Possible traffic delays result when the traffic signal is red, there is a small remaining head queue of one or two vehicles, or the next link is full. If the link is full, the model holds the streetcar in State 3 and checks each 5-sec time step to determine if enough space has been created to allow the streetcar to proceed. If the signal is red, the streetcar simply waits for a green signal. If there is a remaining head queue, then the second type of vehicle departure time is calculated. In all three cases, no additional passenger loading is assumed.

The second vehicle departure case is intended to model the effect of delays as a result of left-turning vehicles at a signalized intersection immediately before the streetcar's departure from the link (other left turns before the streetcar arrival at the link end are accounted for in the saturation flow rate used to dissipate the head queue down to two vehicles or less). Because there are at most two vehicles in the queue, there are either 0, 1, or 2 left-turning vehicles, with the actual number of left-turners determined by a sequence of Bernoulli trials applied to each vehicle in turn. If there are no left turns the delay is zero. If there is one left turn, the model assumes that 30 percent of the next green phase is required to clear the queue, whereupon the streetcar can then depart if there is any green time left. If there are two left turns, it is assumed that the entire green time is needed to clear the queue, and the streetcar is delayed until the next cycle. In any case, it is assumed that the two-vehicle queue will clear within the current cycle so that the streetcar will be delayed no longer than the beginning of the next green phase. An advanced green split phase or separate left-turn phase in the signal timing plan is treated simply as additional green time for the queue to clear.

The overall effect of this method of modeling traffic-related delays is to simulate the delays that occur as a result of other traffic on the basis of streetcar performance. Although the other traffic factors are assembled in various components, the processes are largely deterministic. With the exception of midlink delays, randomness in the delays because of these factors is entirely the result of randomness in the progress of the streetcars. The model also assumes implicitly that there are no road capacity problems deriving from the other traffic volumes alone. In the absence of streetcars, all traffic arrivals will clear at each traffic signal every cycle with no spillover of queues into upstream links. Only if a streetcar arrives and encounters a long passenger service time will queueing create congestion difficulties on the network.

Short Turn Model

The short-turning procedure is a control strategy directed by inspectors on the line for the purpose of regulating service headways. Streetcars are directed off the line at certain loop locations and instructed to reenter in the opposite direction of travel at specific times in order to place the reentering streetcar between two other cars that are widely separated. Passengers who are destined to stops further down the line and transfer to a trailing car are thus inconvenienced by having to get off the short-turning car. Because of passenger inconvenience and disruption to the vehicle schedules caused by the short-turning procedure, criteria are established by management to guide the inspectors in making short-turn decisions. In practice, inspectors use considerable judgment in applying these criteria. Because analysis of the short-turning procedure was the principal focus of the main study, the model tries to duplicate that procedure as closely as possible. Any computer simulation of a process involving human judgment, however, does have certain limitations. The model establishes certain rules and procedures that are followed rigidly. In practice, there is a variety of nonquantifiable circumstances that may cause an inspector to deviate slightly from these rules. Analysis of the simulation results is therefore restricted to examination of the effects of the rules and criteria rather than to the procedure as it is more widely applied.

The occurrence of a large gap between successive streetcars on the line is the basic cause of a decision to short-turn. The model identifies this condition by monitoring vehicle headways at locations identified as inspector locations. A critical gap size is defined as input data, which, when exceeded, flags the need for a short-turn. From that time forward, a search procedure is followed to find one or more streetcars behind the gap to be selected for short-turning. This search procedure is executed by continuously monitoring the status of streetcars as they pass the inspection locations and comparing their status with estabished criteria. The number of short-turning vehicles required for a certain gap is a function of the size of the gap. This number is selected in order to reduce the resulting gaps between successive cars to an average equal to the nominal headway on the route.

The eligiblility of a streetcar for short-turning is determined by the following criteria:

1. Must be a 501 Queen car;
2. Must not already be designated as a short-turn car;
3. Must not be scheduled to go out of service during the current run;
4. Must not have a large headway in front of it;
5. Must have no more than a critical passenger load onboard (provided as an input parameter);
6. Another 501 Queen car must be behind in the same link or, if the link is short, in the link behind;
7. Must be able to reach a short-turn loop location in sufficient time to turn around and reenter service in the gap; and
8. Two consecutive cars may not be short-turned.

If no such vehicle can be found, the search to find cars to fill that gap is abandoned. Gaps greater than the minimum criteria are stored in a file and serviced sequentially. When no further short-turn cars can be found for the gap on top of the list, it is removed and the next gap is serviced, if possible.

Possible locations for the short-turn are determined by estimates of the travel time from the inspector's location to the available downstream short-turn loops. Suitable short-turn locations are therefore determined by the inspectors' positions. The short-turn location is selected in order to insert the short-turning car onto the line at the earliest time. This corresponds to the location closest to the end of the line from which the car can fill the gap in the opposite direction at the earliest opportunity.

For a selected short-turn vehicle and location, the reentry time is chosen by determining aim-points. If the gap is small enough so that only one short-turn car is required, the aim-point corresponds to that point in time when it is estimated that the center of the gap will pass the short-turn loop location. This is determined from travel-time estimates between short-turn loop locations and the end of the line. If the gap requires more than one short-turn vehicle, the aim-points are determined by dividing the gap by the number of short-turns. The aim-points for a certain gap are serviced sequentially. This procedure permits multiple short-turns for a given gap to occur at two or more available locations. Short-turns are then executed in the model in the following steps:

1. A streetcar successfully found for short-turning at a determined short-turning loop is labeled (this label then subsequently affects boarding patterns onto the car as described previously);
2. At the link immediately upstream of the short-turn location, all passengers on-board the labeled car are off-loaded;
3. When the streetcar exits from the link immediately upstream of the short-turn location, it is directed off the line for a preset turnaround time (provided as input data);
4. The streetcar reenters the line into the beginning of the appropriate link at the time corresponding to the selected aim-point, or if that time has passed, as soon as possible;
5. The streetcar's schedule is redefined to be "on-time" at the aim-point time.

Model Evaluation

Validation and further development of the model is currently proceeding. To date, of the range of operating strategies that the model was designed to test, only the existing short-turn operating procedures have been examined in any detail. Other test cases, including the use of larger capacity, articulated streetcars and passive traffic signal priorities, have been constructed but not yet fully tested. The validation tests that have been performed to date on the Queen Streetcar model are summarized next. These tests consist of four runs using combinations of two initial 2:00 p.m. system states and two initial random number seeds. In all other respects, the inputs are identical for the four runs and are intended to represent base case or normal operating conditions. Comparisons of the simulation results obtained from these four runs are presented with observed statistics for Queen Street operations. These comparisons include passenger flows, streetcar travel times, loading counts, delays, and short-turn performance. The simulated travel times between time-points (T-points) averaged over the four base runs are given in Table 2. Overall, half-trip times between 4:00 and 6:00 p.m. are quite close to the travel times observed by the Toronto Transit Commission in its elapsed time surveys conducted in the fall of 1983. Similarly, the overall correspondence between simulated and observed times on a section-by-section basis is also generally good. The deviations from observed performance that do exist are likely because of the assumption of constant bidirectional sectional running speeds for the entire 2:00 to 7:00 p.m. simulation. Incorporation of running speeds that are sensitive to time of day and direction would undoubtedly rectify this problem. Table 3 gives observed and simulated flows for eastbound passengers during the 4:00 to 7:00 p.m. period, where the observed passenger flows were derived from TTC Riding Count Surveys conducted in the fall of 1983. To more accurately represent typical passenger volumes, the average flows from the four base runs are presented in the table. Total simulated passenger origins and destinations, by section, are quite close to the observed volumes, with similar results being obtained for westbound flows and the 2:00 to 4:00 p.m. period.

The September 1984 vehicle loading counts at selected locations formed the basis for checking simulated vehicle loadings between 4:00 and 6:00 p.m. Observed and simulated vehicle loadings at the selected location are given in Table 4. Simulated average vehicle loadings between 4:00 and 6:00 p.m. are close to those observed. The simulated loading distributions are, however, noticably skewed at the central locations as evidenced by the standard deviation about the mean and the percentage of vehicles with very light and very heavy loads. One factor that contributes to this high variance in vehicle loads is the short-turning strategy currently used in the model, which results in a large proportion of the short-turns being executed at the inner locations (i.e., Church-Victoria eastbound and Bathurst and McCaul westbound).

To illustrate the impact of this short-turning strategy on vehicle loadings, consider the Church eastbound location. The large percentage of vehicles eastbound at Church Street with very light loads (27.6 percent) and very heavy loads (29.8

TABLE 2 SCHEDULED, OBSERVED, AND SIMULATED RUN TIMES BETWEEN T-POINTS

(a) Average Simulated Run Times for Queen Streetcars (Min.)

Section	2-4 p.m. EB	2-4 p.m. WB	4-6 p.m. EB	4-6 p.m. WB	2-7 p.m. EB	2-7 p.m. WB
Humber Loop-Roncesvalles	7.0	7.8	7.0	7.8	7.0	7.8
Roncesvalles-Ossington	9.0	9.2	9.0	10.0	9.0	10.0
Ossington-Bathurst	5.0	4.5	5.0	4.2	5.0	4.0
Bathurst-Spadina	2.3	2.0	3.0	2.0	3.0	2.0
Spadina-McCaul	2.0	2.0	2.0	2.5	2.0	2.0
McCaul-Yonge	5.2	4.0	6.5	4.0	6.0	4.0
Yonge-Broadview	10.0	10.7	11.0	13.0	10.0	11.7
Broadview-Connaught	8.0	8.3	8.3	8.5	8.0	8.0
Connaught-Kingston	2.8	2.0	3.0	2.0	3.0	2.0
Kingston-Neville Loop	8.0	8.0	8.2	7.8	8.0	8.0
Humber Loop-Neville Loop	59.3	58.5	63.0	61.8	61.0	59.5

(b) Scheduled, Observed and Simulated Run Times Between T-Points Eastbound 4:00 to 6:00 p.m.

Section	Scheduled	Observed	Simulated 1	Simulated 2	Simulated 3	Simulated 4
Humber Loop to Roncesvalles	8	7	7	7	7	7
Roncesvalles to Ossington	8	9	9	9	9	9
Ossington to Bathurst	6	5	5	5	5	5
Bathurst to Yonge	10	11	12	11	12	11
Yonge to Broadview	10	9	11	11	11	11
Broadview to Kingston	9	11	11	11	12	11
Kingston to Neville Loop	9	12	8	9	8	8
Humber Loop to Neville Loop	60	64	63	63	64	62

Section	Scheduled	Observed	Simulated 1	Simulated 2	Simulated 3	Simulated 4
Neville Loop to Kingston	9	8	8	8	8	7
Kingston to Broadview	9	10	10	11	11	10
Broadview to Yonge	10	10	12	13	14	13
Yonge to Bathurst	10	12	8	9	8	9
Bathurst to Ossington	6	5	4	4	4	5
Ossington to Roncesvalles	8	8	10	10	10	10
Roncesvalles to Humber Loop	8	8	7	8	8	8
Neville Loop to Humber Loop	60	61	62	63	63	59

Note: Observed Run Times were calculated from TTC Elapsed Time Surveys, Oct. 1983.

percent) is partly attributable to the relatively large number of westbound short-turns at Bathurst Street (four in the 4:00 to 6:00 p.m. period) and McCaul Street (two in the 4:00 to 6:00 p.m. period). The short-turned vehicles enter service eastbound with no passengers onboard and travel a relatively short distance to Church Street where they are observed to be lightly loaded. The streetcars that are not short-turned westbound pick up a larger than expected number of passengers on their eastbound return trip, especially over the section from Roncesvalles to Bathurst. This tends to inflate the percentage of heavily loaded vehicles at Church Street. A similar argument holds with respect to the high loading variance at Bathurst Street westbound resulting from the large number of short-turns occurring at Church Street eastbound.

The model classifies streetcar delays under three general headings: passenger service time, queueing and signal delay, and other running delay. Passenger service time is simply the time required to load and unload passengers at a stop. Queueing and signal delays are those that impede the streetcar from reaching the stop at the end of the link or block it from entering the next link. Other running delays are associated with midlink delays such as left-turning vehicles, parking maneuvers, and pedestrian crosswalks. The simulated streetcar delays are summarized by section and time period for one of the test runs in Table 5. The model's performance in simulating streetcar delay is one area that has not been evaluated to date. A major obstacle in assessing the model's performance in this area is the lack of available data on actual streetcar delays in a format comparable to the model outputs. It is encouraging to note, however, that the simulated delays appear reasonable given the limited data available from previous TTC Speed and Delay Surveys (October 1983 and September 1984). The short-turn model and the current criteria that a car must meet to be signed for a short-turn are discussed in the General Model Description in Section 2. The model's performance for the four base runs is summarized in Table 6. Considerable variation exists across the four base runs in the number and size of the gaps observed and the inspector's ability to find short-turn cars. On average, the inspector is able to find only one-half the number of cars required to completely fill the observed gaps.

TABLE 3 OBSERVED VERSUS SIMULATED PASSENGER FLOWS (EASTBOUND 4:00 TO 7:00 P.M.)

Eastbound 4:00 to 7:00 p.m.

Origin / Dest'n	Section 1	Section 2	Section 3	Section 4	Section 5	Section[3] 7	Total	Difference Sim. vs. Obs.
Section 1	302[1]	495	198	42	5	-	1042	
	359[2]	513	190	34	1		1097	+5.3%
Section 2	-	1125	1194	887	204	-	3410	
		1045	1161	866	196		3268	-4.2%
Section 3	-	-	1270	1232	808	539	3849	
			1267	1238	797	539	3841	-0.2%
Section 4	-	-	-	884	369	221	1474	
				905	357	218	1480	+0.4%
Section 5	-	-	-	-	245	-	245	
					241		241	-1.6%
Total	302	1620	2662	3045	1631	760	10020	
	359	1558	2618	3043	1592	757	9927	-0.9%
Difference Sim. vs. Obs	+18.9%	-3.8%	-1.7%	-0.1%	-2.4%	-0.4%	-0.9%	

1. Observed: Based on TTC Riding Count Summaries - October 1983
2. Simulated: Average from the four simulation base runs.
3. "Section 7" represents the Kingston Road catchment area served by the 502 and 503 streetcars.

TABLE 4 VEHICLE LOADING SUMMARY, 4:00 TO 6:00 P.M.

Location		Mean	Std. Dev.	% 25	% 80
Eastbound					
Church	-obs.	48	17	6.0	3.3
	-sim.	58	41	27.6	29.8
Broadview	-obs.	49	22	11.5	10.5
	-sim.	53	32	27.5	27.5
Kingston	-obs.	29	17	43.1	1.0
	-sim.	23	18	56.8	0.0
Westbound					
Bathurst	-obs.	60	28	11.9	29.2
	-sim.	57	41	30.4	30.4
Parkside	-obs.	40	22	30.3	4.0
	-sim.	36	28	44.7	7.9

Note: Observed vehicle loadings are based on the Vehicle Loading Survey, Sept. 1984

Simulated vehicle loadings are those produced in Run 1.

TABLE 5 STREETCAR DELAYS

Section	2:00 to 4:00 P.M.			4:00 to 6:00 P.M.			6:00 to 7:00 P.M.		
	PST	Q+S	Other	PST	Q+S	Other	PST	Q+S	Other
				Eastbound					
1	2.7	4.4	0.7	7.4	12.9	2.8	5.0	14.7	3.9
2	8.9	8.8	3.6	15.4	14.9	6.2	11.9	17.1	4.3
3	11.1	8.2	2.5	20.7	22.6	5.9	14.9	20.2	5.2
4	9.9	4.9	3.8	19.5	9.9	6.8	13.1	12.7	5.1
5	7.6	3.1	4.4	16.0	9.0	8.6	13.7	10.5	6.5
				Westbound					
1	9.2	4.3	0.7	16.9	7.0	3.2	12.0	11.8	4.1
2.	8.2	6.9	2.3	19.3	16.3	5.5	11.9	22.5	4.1
3	10.2	8.8	3.2	17.7	22.1	4.4	10.0	32.3	4.4
4	7.9	7.8	3.9	12.5	12.1	6.6	6.8	18.2	5.3
5	3.8	4.6	2.7	8.7	10.3	7.8	5.3	14.6	6.6

Note: Streetcar delays are expressed as a percentage of total section travel time.
PST — Passenger Service Time.
Q+S — Queueing Plus Signal Delay.

TABLE 6 SUMMARY OF SHORT-TURN MODEL PERFORMANCE

Inspector Location	Run No.	Gaps Observed	Short-Turns Required	No. of Cars Short-Turned	Gaps for Which No Cars Were Short-Turned
Eastbound: Victoria	1	19	34	10	12
	2	13	27	17	2
	3	14	35	14	5
	4	13	31	17	2
	Avg	15	32	15	5
	2x	12	24	24	0
Westbound: Simcoe	1	16	30	17	4
	2	16	38	21	5
	3	14	34	16	5
	4	15	34	20	4
	Avg	15	34	19	5
	2x	16	31	26	3

One-third of the gaps go unattended as the inspector cannot find suitable cars to short-turn in time to meet the returning gap in service. The distribution of short-turn locations for the four base model runs is given in Tables 7 and 8. The large majority of short-turns was executed at the four inner short-turn locations. In practice, inspectors direct most of the short-turning cars to the outer locations to restore service regularity as quickly as possible.

The number and location of short-turns predicted by the model is a reflection of the input criteria used to judge a car's suitability for short-turning discussed earlier. The model undoubtedly adheres more rigidly to the criteria than do inspectors in the field. During the 4:00 to 6:00 p.m. period, for example, average vehicle loads at the inspector locations were in excess of 50 passengers; therefore, few cars in the model were eligible to be short-turned, whereas under real conditions, inspectors might be expected to relax this rule. Further, the criteria that there must be a 501 car close behind made the task of finding a suitable short-turn car more difficult. To test the model's sensitivity to this criterion, Run 2 was rerun with the trailing car criteria removed (this run is labeled Run 2x). The substantial improvement in the model's short-turning performance is given in Table 6. Not only was the eastbound inspector able to short-turn all the required cars, but he was able to direct the short-turns to the outer locations. Similar, although less dramatic, improvements in the westbound inspector's performance are also observed.

TABLE 7 EASTBOUND SHORT-TURN LOCATIONS FOR THE FOUR BASE MODEL RUNS

	Location			
Run No.	Church	Parliament	Connaught	Kingston Road
1	9	0	0	1
2	11	4	1	1
3	7	3	1	3
4	11	4	1	1
Total	38	11	3	6
Percent	65.5	19.0	5.2	10.3
2x	0	4	5	15

TABLE 8 WESTBOUND SHORT-TURN LOCATIONS FOR THE FOUR BASE MODEL RUNS

	Location			
Run No.	McCall	Bathurst	Shaw	Sunnyside
1	2	5	1	8
2	9	7	1	4
3	5	6	4	1
4	6	5	5	4
Total	22	23	11	17
Percent	30.1	31.5	15.1	23.4
2x	1	10	4	11

SUMMARY

A large FORTRAN simulation model of streetcar operations within a complex shared right-of-way operating environment has been described in this paper. The model is currently operational, but requires further validation and fine-tuning before it can be used to analyze alternative streetcar operating policies. In particular, an improved set of short-turn criteria that result in more realistic short-turn patterns must be developed, and the traffic delay components of the model must be validated in greater detail than has so far been done. Nevertheless, the results obtained to date are very encouraging. With further development, it is the authors' intention to test the other strategies that the model was constructed to address, including alternate short-turn strategies and the introduction of traffic signal priorities for transit vehicles, reserved rights-of-way, and larger capacity vehicles. With an analysis tool such as the Queen Streetcar model, these and other possible operating strategies can be examined and compared in a comprehensive manner, leading, it is hoped, to a better understanding of the trade-off involved in improving light rail transit performance.

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