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Mesoscopic simulation for transit operations

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ABSTRACT

This paper presents a transit simulation model designed to support evaluation of operations, planning and control, especially in the context of Advanced Public Transportation Systems (APTS). Examples of potential applications include frequency determination, evaluation of real-time control strategies for schedule maintenance and assessing the effects of vehicle scheduling on the level of service. Unlike most previous efforts in this area, the simulation model is built on a platform of a mesoscopic traffic simulation model, which allows modeling of the operation dynamics of large-scale transit systems taking into account the stochasticity due to interactions with road traffic. The capabilities of Mezzo as an evaluation tool of transit operations are demonstrated with an application to a real-world high-demand bus line in the Tel-Aviv metropolitan area under various scenarios. The headway distributions at two stops are compared with field observations and show good consistency between simulated and observed data.

1. Introduction

Public transportation systems are increasingly complex, incorporating diverse travel modes and services. As a result, various Advanced Public Transportation Systems (APTS), designed to assist operators, have been developed and implemented (Casey et al., 2000). The need to integrate and efficiently operate these systems poses a challenge to planners and operators. As new technologies and applications are proposed, tools to assist in their development and evaluation prior to field implementation are needed.

In the context of general traffic operations, simulation models have been established as the primary tool for evaluation at the operational level. Most of the advances in these models related to transit systems have focused on implementation of transit signal priority (Khasnabis et al., 1996; Liu et al., 1999; Chang et al., 2003; Werf, 2004; Lee et al., 2005; Fernandez et al., 2007), operation of bus stops (Liu et al., 1999; Silva, 2001; Ding et al., 2001; Werf, 2004; Fernandez et al., 2007) and bus lanes (Liu et al., 2006; Fernandez et al., 2007).

Transit simulations provide a dynamic perspective on transit operations, enabling comparisons of various scenarios and representation of complex interactions between the network components: general traffic, transit vehicles and passengers. However, although simulation models can have many advantages for public transportation research, there has not been much effort in the development of transit simulation models. Algers et al. (1997) reviewed 32 microscopic traffic simulation models and reported that only 52% represent public transportation at all, 42% model transit priority, and only 6% model transit traveler information systems. At the same time, the majority of users they interviewed were interested in large-scale applications at the urban or regional level. These users ranked modeling of public transportation the second most important capability in traffic simulation models. In the time since their study was conducted, several microscopic traffic simulation

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models have significantly enhanced their transit capabilities. However, Boxill and Yu (2000) still report that the capability of existing simulation models to effectively simulate APTS applications in large networks is limited. While they found that few microscopic models simulate well the local impacts of APTS, none of the mesoscopic models they reviewed had any transit simulation component at all.

As noted above, most efforts in modeling public transportation and APTS have focused on microscopic simulations. However, these models are inefficient when applied to large-scale applications because of the unnecessary level of detail and extensive computational effort they require. In contrast, mesoscopic simulation models, which represent individual vehicles but avoid detailed modeling of their second-by-second movement, may be useful for system-wide evaluation of transit operations and APTS, as they are for general traffic.

This paper reports on the development of a mesoscopic transit simulation model designed to support evaluation of operations planning and control, especially in the context of APTS. Examples of potential applications include frequency determination, evaluation of real-time control strategies for schedule maintenance, restoration from major disruptions and assessing the effects of vehicle scheduling on the level of service. The rest of the paper is organized as follows: First, Mezzo, the mesoscopic traffic simulator that is used as a platform for the development of the transit simulator is described. Next, the overall framework and implementation details of the transit simulation model are presented. The application of the transit simulator is demonstrated with an application to a high-demand bus line in the Tel-Aviv metropolitan area. The demonstration includes a validation, study of travel time variability and demand levels and a sensitivity analysis showing the impact of the recovery time policy on performance. Finally, a discussion and concluding remarks are presented.

2. Mezzo

The transit simulation model is built within the platform of Mezzo, a mesoscopic traffic simulation model (Burghout, 2004; Burghout et al., 2006). Mezzo is an event-based simulator, which models vehicles individually, but does not represent lanes explicitly. Links in Mezzo are divided into two parts: a running part, which contains vehicles that are not delayed by the downstream capacity limit; and a queuing part, which extends upstream from the end of the link when capacity is exceeded. The boundaries between the running and queuing parts are dynamic and depend on the extent of the queue. Vehicles enter the exit queue in the order that they complete their travel in the running part. The earliest exit time is calculated as a function of the density in the running part only. Travel times on the running part are determined by a speed-density function. The default function is:

$$V(k) = \begin{cases} V_{\mathrm{free}} & k < k_{\min} \\ V_{\min} + (V_{\mathrm{free}} - V_{\min}) \cdot \left[1 - \left(\frac{k - k_{\min}}{k_{\max} - k_{\min}}\right)^{a}\right]^{b} & k \epsilon [k_{\min}, k_{\max}] \\ V_{\min} & k > k_{\max} \end{cases} \tag{1}$$

where V_{free} and $V_{\min}$ are the free flow speed and minimum speed, respectively. k is the density in the running part of the link. $k_{\min}$ and $k_{\max}$ are the minimum and maximum densities thresholds. a and b are parameters. This speed-density function determines that the vehicle moves at free flow speed when the density is lower than $k_{\min}$ and has a constant minimum speed if the density exceeds $k_{\max}$.At the downstream part of the link, the vehicles join a single queue of vehicles waiting to move out of the link. Queue servers process the vehicles in this queue and pass them onto the next link if it is not full. Separate queue servers with their corresponding capacities are used for each turning movement in order to capture link connectivity and lane channeling. Each turning movement server searches backwards from the head of the queue for vehicles that intend to use the turn movement it regulates and processes them in sequence. A maximum queue look-back limit may be defined for each turning movement in order to represent dependencies among turning movements (e.g. when a queue in one movement blocks access to the lanes used by another turn movement). The turning servers are modeled stochastically with truncated normal service times.

Vehicles in Mezzo are generated at mean rates specified by time-dependent Origin–Destination (OD) flow matrices. By default, the interval between generations of vehicles for each OD pair follows a negative exponential distribution. Vehicle types are set randomly according to a pre-specified vehicle mix distribution. Pre-trip route choices follow the multinomial logit model with a set of pre-defined routes and historical link travel times. En-route, drivers may switch their routes in response to information they receive. The route switching model also uses the multinomial logit model structure. Information received by the drivers is used to update the travel times and routes sets that drivers use in evaluating the utilities of the various routes. The simulation outputs measures of performance at the link, trip and OD pair level. Outputs include time-dependent statistics on speeds, densities, inflows and outflows, queues lengths and travel times.

Mezzo is implemented modularly using the object-oriented programming approach in order to enable further enhancements and developments. Each entity in the simulation model (e.g. node, queue, vehicle, OD pair) is represented as an object with its related variables and functions. As an event-based simulation model, the event list calls the action objects at the appropriate times at which they are booked. Mezzo is also capable of hybrid microscopic–mesoscopic simulation (Burghout et al., 2005) and has been applied in evaluating bus-priority within adaptive signal control schemes (Burghout and Wahlstedt, 2007). A complete description of the structure of Mezzo and its implementation details is presented in Burghout (2004).