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DynaMIT 2.0: The Next Generation Real-Time Dynamic Traffic Assignment System

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Abstract—Real-time transportation models are proven to be highly useful for traffic management and generation of traveler guidance information. The current state of the practice in real-time transportation modeling is represented by DynaMIT, which generates consistent anticipatory information about the future state of the transportation network based on current real-time data. DynaMIT has been effectively applied across a variety of locations and sensor configurations. The next generation of real-time models will be multi-modal and include representation of dynamic pricing and commercial vehicles. To support this, these models will be based on activity-based demand and will make use of the latest software design strategies, enhanced data availability and personal/vehicle connectivity.

Keywords-Dynamic Traffic Assignment; Online Calibration; Real-Time Model.

I. INTRODUCTION

This paper presents a review of the state of the practice of real-time dynamic traffic assignment (DTA) models as well as some recent enhancements and proposes a set of requirements for the next generation of such models. The high-level operation of real-time traffic simulation models is to first take in data from real-time sensors and estimate the current state of the transportation network. The immediate future conditions of the transportation network are then forecast and the information is provided to travelers for guidance. The forecast state of the network can be used to manage the traffic network through control systems often called Advanced Traffic Management Services (ATMS). These systems include control over signals, ramp metering, variable speed limit signs and lane use signs that are used to manage traffic flow. The models are also used as information systems, or Advanced Traveler Information Systems (ATIS) to provide guidance to travelers to help them make better decisions about timing of trips and routes to take. To be effective, these models must provide an accurate simulation of the transportation network supply and demand as well as their interactions [1].

The next generation of real-time DTA models will broaden the scope of the current real-time models in multiple dimensions including: the way that the trips are generated and the modes (e.g., public transit) are represented; the incorporation of commercial vehicles; the response to antic-
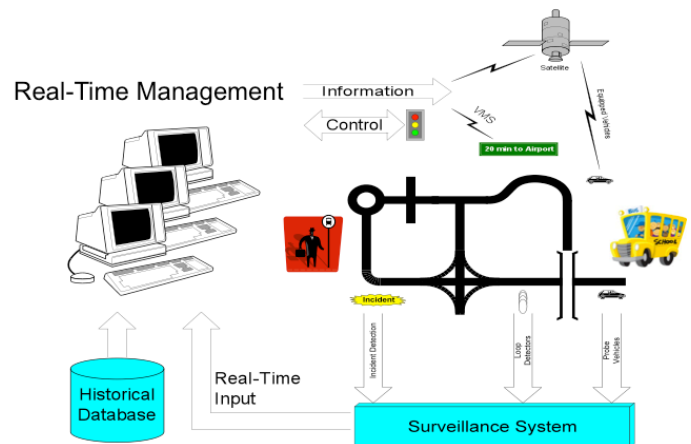

Figure 1. The generic structure of real-time traffic management model

ipated personal devices as source and distributors of information; and dynamic pricing of the transportation network.

Next we introduce DynaMIT, the state-of-the-art DTA system. The structure of DynaMIT is elaborated and the input/output of its components are presented. We present the enhencement of DynaMIT we have worked on: the on-line model calibration with real- time sensor information. We present the formulation of our approach and we outline a mini case-study of our initiative.

The remainder of this paper is organized as follows: Section 2 outlines the framework of real-time traffic simulation models and Section 3 uses DynaMIT as an example to illustrate the main points. Section 4 gives examples of related recent enhancements and applications. Section 5 details the requirements for the next-generation of transportation real-time models, while Section 6 provides some concluding remarks and directions for future research.

II. REAL TIME SIMULATION MODEL

Figure 1 shows the key components in a real-time system. The real-time system on the upper left takes, as its input, a historical database of network conditions and real-time information from the surveillance system. Information collected through the surveillance system primarily consists
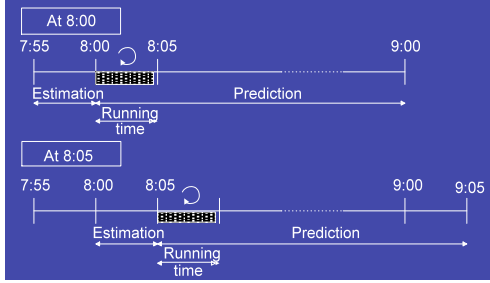
Figure 2. The operation of traffic state estimation then followed by state prediction in real-time

Figure 3. The structure of DynaMIT the state-of-the-art DTA system.

of static sensors (such as loop or cameras) as well as mobile sensors (such as transponder-based automatic vehicle identification (AVI) technology [2] that transmit traffic flow and other information at certain points in the transportation network. The impact of emerging technology, which would provide more real-time data, e.g., personal smart-devices, is described in the last section of this paper. The flows at the top of the figure show the transmission of guidance information through the ATIS and exercising of control through the ATMS from the real-time management system.

Within the real-time management system is a hybrid behavioral and network model. The behavioral model forecasts the demand using a static origin/destination (O/D) matrix to generate trips. In each iteration, the O/D matrix is recalibrated based on the real-time data of traffic volume. The behavioral model also includes a component that considers the reaction of travelers to the guidance provided by the real-time management system. The network simulation model represents the transportation supply, including lane configuration and capacity as well as signal information. The interactions between supply and demand are realized as (the output of the model can be represented as) queue lengths, travel times and volume of traffic on the network.

The purpose of the operation of the real-time model is to calibrate up to the minute information and forecast traffic conditions over the next hour. This operation takes on the order of minutes, allowing for plenty of time to act on the forecast and distribute the traveler information, Figure 2. In Figure 2, state estimation is first performed at 8:00 upon receiving sensor information from 7:55-8:00. After the estimation is complete, state prediction is performed from 8:00 onwards. The same estimation-prediction process is repeated at 8:05.

III. DynaMIT

DynaMIT is a state-of-the-art real-time DTA system for traffic estimation and prediction developed at MIT Intelligent Transportation System Laboratory [3][4]. The system is composed of two sub-systems: 1) State estimation and 2) State Prediction. The operational structure of DynaMIT is presented in the following figure.
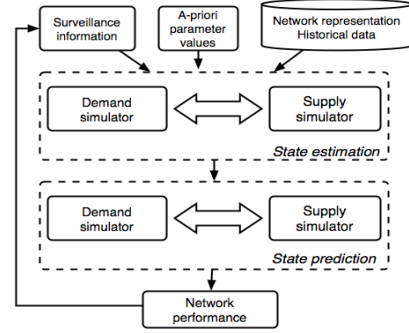
State estimation combines the available surveillance with historical information to estimate the current state of the entire network. Pre-Trip demand is simulated, allowing drivers with different characteristics to dynamically change their departure time, travel mode, and trip route. This is followed by OD flow estimation and network estimation. The estimated network condition is then compared to surveillance information. Inconsistent estimations are unaccepted and a new iteration of estimation is initiated.

Based on this estimate of the current state of the network, the DTA model predicts future traffic patterns, taking into account the response of the drivers to the provided guidance and traffic information. This is first done by doing Pre-Trip predictions. This is then followed by OD prediction and network state prediction. The network information disseminated includes predicted flow rate, travel time, link speed and density. The implementations of virtual sensor within DynaMIT include point vehicle count, link travel time, link and segment speed, link and segment density, point to point vehicle count, and point to point travel time.

The outputs of the overall system are consistent forecasts of network conditions, including link density, flow speed, as well as travelers' characteristics including their travel time, route choice and departure time. The anticipated information is used to generate guidance and will be incorporated into the next round of calculations [5].

IV. MODEL ENHANCEMENT: ON-LINE CALIBRATION

One of the key enabling factors for the deployment of such a DTA system is the availability of an array of sensors that provides timely, accurate and reliable traffic information. Recent advancements of sensor technologies and their applications in surveillance systems have not only pioneered new methods of collecting and communicating network information, but also revolutionized the way traffic information is utilized within modern DTA systems for enhanced accuracy and effectiveness. With advancements in technologies, information collected from network sensors

can now be gathered in a timely manner for the calibration of DTA systems at their operational time, resulting in significantly improved modeling accuracy and reliability. This process of using available sensory information to adjust DTA models in real-time is known as DTA model on-line calibration.

The inputs to the on-line calibration process are a priori model parameters, historical data and real-time surveillance data. These historical data can be obtained from a process known as "off-line" calibration. The outputs of the on-line calibration process are consistent model parameters that will be used for model predictions. Figure 4 pictorially shows these processes and their interactions.

A. Formulation

The online calibration process is modeled using the state-space formulation. Here we use the formulation developed at [6]. The state-space model consists of a transition equation and measurement equations. The state consists of Dyna-MIT's parameters and OD flows. Explicitly, Let π_h denote the vector of OD flows and model parameters subject to on-line calibration at time interval h. ($\pi_h = \{\chi_h, \gamma_h\}$, χ_h is the OD flows at time h and γ_h is the model parameters at time h). Let S denote a DTA simulator and M_h^{obs} denote a vector of observed traffic conditions for time interval h (For example, travel time, segment flow counts). Let M_h^{sim} denote a vector of corresponding simulated traffic conditions from S.

The transition equation captures the evolution of the state vector over time. The general formulation is that: $\pi_{h+1} = \tau(\pi_h, \pi_{h-1}, ..., \pi_{h-p}) + e_h^{auto}$, where τ is a function that describes the dependence of π_{h+1} in its previous p states. e_h^{auto} is a vector of random errors. In this context, an autoregressive function for τ is used. The transition equation is:

$$\pi_{h+1} = \sum_{q=h-p}^{h} F_q^{h+1} \pi_q + e_h^{auto} \qquad (1)$$

The measurement equations are in two parts. The direct measurement equations capture the error between the state vector and its a priori values. That is:

$$\pi_h^a = \pi_h + e_h^a \qquad (2)$$

The indirect measurement equation links the state vector with the sensory observations, explicitly, so that:

$$M_h^{obs} = S(\pi_h) + e_h^{obs} \qquad (3)$$

The state-space model is now complete. Ashok and Ben-Akiva, proposed to write the state-space model in its deviation form from its historical [7]. The recommendation stems from two main reasons. Firstly, the deviation form implicitly incorporates the wealth of information contained from the offline calibrated parameters and OD flows. Secondly, the
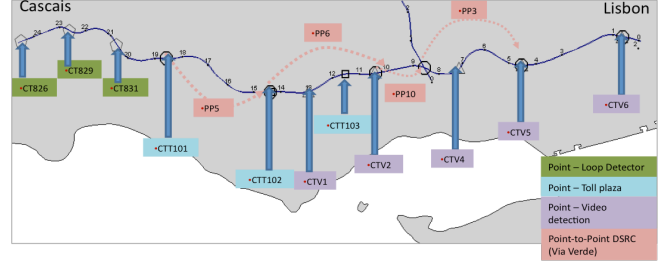

Figure 5. Network and sensor map

deviation form allows the normality assumption to hold for the error terms in the model. Without using the deviation form, the state variables, such as the OD flows, will have a skewed distribution. Normality assumption is useful in the application of Kalman Filtering techniques. For these reasons, we write: $\Delta \pi_h = \pi_h - \pi_h^H$, and our final state-space model in the deviation form is:

$$\Delta \pi_h^a = \Delta \pi_h + e_h^a \qquad (4)$$

$$\Delta M_h = S(\pi_h^H + \Delta \pi_h) - M_h^H + e_h^{obs} \qquad (5)$$

$$\Delta \pi_{h+1} = \sum_{q=h-p}^{h} F_q^{h+1} \Delta \pi_q + e_h^{auto} \qquad (6)$$

B. Case Study

The network used in the analysis is the Brisa A5 motorway. It is a 25-km inter-urban expressway between Lisbon and Cascais. The motorway consists of 85 road segments and 56 nodes representing significant points in the network. The motorway is primarily equipped with toll collection systems and loop detectors that measure vehicle counts. The sequential identification of vehicles between consecutive toll plazas using Via Verde technology also provides average segment speeds. The schema of the network and sensor deployments is in Figure 5.

The experiment is conducted during the morning peak hour from 6:30 to 8:30 during a typical week day. The model is first calibrated off-line to produce historical values of OD flows as well as speed-density relationship parameters. The performances indices state estimation as well as 3 steps state predictions are summarized in Figure 6. The simulated sensor counts from these processes are plotted against their corresponding sensory values. The on-line calibration demonstrates a high degree of accuracy and the R2 calculated from the linear regressions on the simulation-observation scatter plots are close to 1 (0.968 for state estimations, 0.943 for 1 step predictions, 0.908 for 2 step predictions and 0.904 for 3 step predictions).
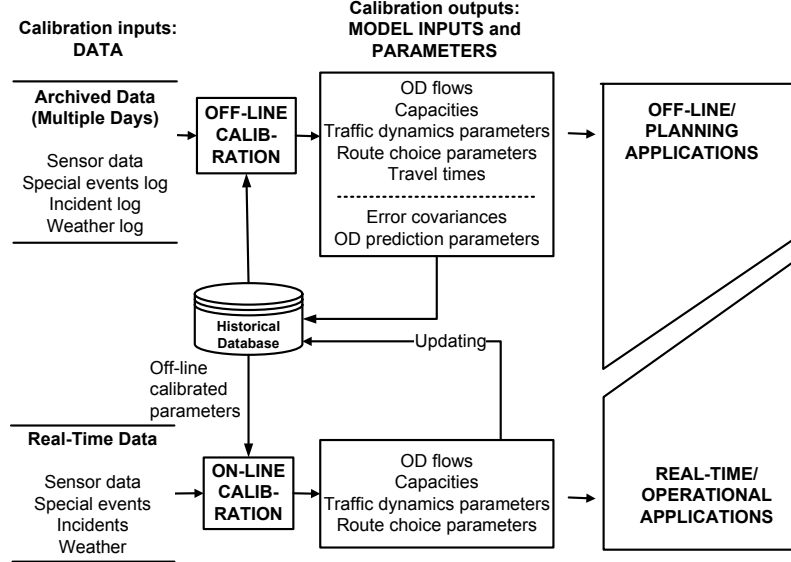
Figure 4. The operation of traffic state estimation then followed by state prediction in real-time, as well as off-line calibration of the model [8].
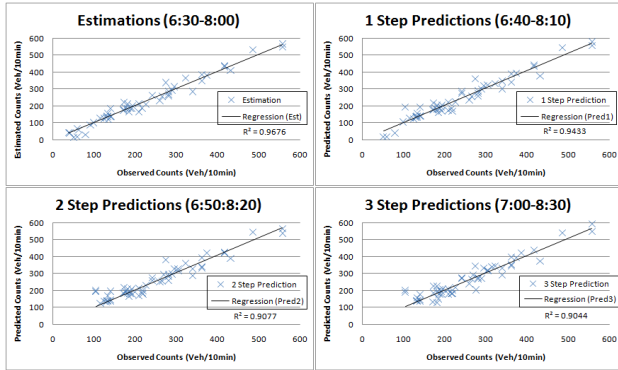

Figure 6. Accurate state estimation and prediction, compared to the observed sensor values

V. DynaMIT 2.0 The Next Generation Real-Time Model

The next generation real-time model will broaden the scope of the current real-time models in multiple dimensions including: how the trips are generated; the modes represented; incorporation of commercial vehicles; response to anticipated personal devices as sources and distributers of information; and dynamic pricing of the transportation network.

A. Activity-Based Modeling

Moving from static O/D-based demand to activity-based demand is a key improvement in the next-generation real-time model systems. Activity-based demand modeling al-lows for much higher flexibility in traveler choice, including not making the trip at all (the at-home tour). In activity-based modeling, a daily activity plan is generated for each agent in the system (both households and firms). The trips made by the agent are then produced from this activity plan, which allows for chaining of multiple activities into a single trip or tour. Therefore, the agents will be sensitive to network conditions in there activity choice, e.g., an agent may not make the shopping trip in the morning when traffic is heavy, but instead run the errand when they go to lunch [1]. One example of an activity-based transportation model, although not using real-time data, is MATSIM, developed by researchers at ETH in Zurich (www.matsim.org).

B. Multi-Modal Network

Public transportation and other non-private auto transport modes are becoming more important given the continuing densification of cities and increasing sensitivity to the environmental impacts of transportation. Therefore, the next-generation real-time models must explicitly represent public transportation as well as future city-vehicles and taxis to support non-private auto use of transportation networks. A multi-modal model has unique requirements for both supply and demand.

1) Multi-Modal Supply Requirements: Modeling the supply-side of fixed route public transportation will include a detailed representation of travel times, network topology, vehicle capacities and potential service management actions [9].

Public transit travel times are sensitive to traffic con-

gestion, signal delays and passenger activity. For traffic congestion, a public transit vehicle does not interact with traffic in the same way as a private car. For example, other drivers know that a bus will be making regular stops and thus will be more inclined to pass the bus than they would another car.

Representing passenger activity and loading per vehicle requires a representation of each run. This is because of the case where multiple routes are operating on the same street. A passenger waiting at a stop may take the first bus to arrive or choose to wait for the next one depending on the network organization and their expected travel time per route.

Vehicle capacity is important to capture because, if the bus is at capacity, then waiting passengers will be unable to board and will have to wait for the next bus.

Finally, due to variations in weather, traffic and passenger demand, the transit agency may make minor changes to the normal operating procedures adaptive. This may be realized as holding a bus mid-route, adding or dropping a trip, or short-turning a bus before the terminal. Two examples of this level of transit representation are MIT-SIMLab (web.mit.edu/its/mitsimlab.html) and BusMezzo (www.ctr.kth.se/mezzo.php), although neither model uses real-time data for online calibration.

A representation of mobility-on-demand and taxi service represents a new frontier of simulation modeling. Mobility-on-demand vehicles pose a particularly interesting challenge as the vehicles require recharge time and may only be picked up and dropped off at certain points.

2) Multi-Modal Network Demand Requirements: The choice to make a trip using public transit involves a more complex upfront and enroute decision process than that of driving a car.

Public transit service is non-continuous and the accessibility depends on the network design. A traveler choosing to use public transit must select their departure time and bus schedule based on their destination and expected time of arrival as it matches the schedule, which is likely to differ from the travelers desired arrival time.

Enroute, a traveler is faced with more options as they can choose to react to the current state of the network (traffic slowing down the bus, crowding on the first vehicle to arrive, etc) by changing routes or modes. Many public transit trips also involve one or more transfers between modes. MILATRAS (MIcrosimulation Learning-based Approach for Transit Assignment) is a recent work that developed a high-fidelity agent-based transit choice model, using ArcGIS and Paramics to provide the transit network and stochastic rider experience respectively [10].

C. Commercial Vehicles

Commercial vehicles can account for almost 10% of VKT in cities. A trip or tour made by a commercial vehicle may be for a variety of purposes: pickup and/or delivery, which would entail one or more brief stops before returning to the depot; service calls, which would involve stops of greater length than a pickup/delivery; and long-haul, which are trips that may have an origin and/or destination outside of the network being modeled but will use the network for some portion of the trip. Previous work generating commercial vehicle tours developed an optimization model to minimize travel time and associate the appropriate vehicle size to the trip, but do not use real-time information [11].

D. Pervasive Personal Devices

The currently available and anticipated future GPS-enabled mobile devices, such as personal smart-phones, as well as vehicle navigators with local connectivity will provide a wealth of opportunities for increased traffic and mobility data collection and provide traveler information in more places and with more refined and relevant data.

Designed and deployed for personal use, those mobile/handled devices can be used for vehicle-to-infrastructure and vehicle-to-vehicle cooperation, powered by wireless communications services. This collaboration environment enables new opportunities for those mobile devices, either for route guidance improvement or advisory warnings, but also new challenges for back-end data processing systems to integrate and make use of incoming new data feeds.

A more capable personal device, and/or vehicle can also act as a mobility advisor. These devices would display the latest data generated in a centralized manner from the Traffic/Transit Management Center. The devices may also leverage information from the local network (such as a vehicle-to-vehicle mesh-network) to revise the centralized data with decentralized information [12].

In a private auto, mobility advisors would be useful to alert the traveler to traffic levels and incident locations as well as to help identify parking locations. Through the decentralized vehicle-to-vehicle network, these devices can serve as collision avoidance assistance by identifying speed changes in the surrounding traffic. For the public transit traveler, a mobility advisor could provide next vehicle arrival and available capacity information. The traveler may specify their destination in the device and receive real-time trip planning. Google Mobile maps are already providing some of these services through the online trip planner that is multi-modal within public transit and includes traffic information.

E. Congestion Pricing

Congestion pricing and High Occupancy / Toll (HOT) lanes are demonstrating their effectiveness and becoming more politically tenable. The next generate real-time model should determine the optimized toll prices based on an objective function of (travel time, emissions etc.). These optimizations would be evaluated within the model and the impact predicted through traveler reactions with updated route choice, mode choice, departure time, etc. [13].

F. Service-Oriented Architectures

Service-Oriented Architecture (SOA) is essentially an architectural style that attempts to mesh collaborative services located worldwide and available for use on buses. A service is a unit of work done by a service provider to achieve desired results for consumers. Software agents are both provider and consumer on behalf of their owners. There are new things in this new SOA generation: i) the concept of Service, and ii) the concept of Web Services. A Service is a function that is well-defined, self-contained, and does not depend on the context or state of other services. Web Services are the set of protocols by which Services can be published, discovered and used in a technology neutral, standard form. In short, Web Services refers to the technologies that allow for making connections and Services are the end point of a connection.

In this new architectural SOA-based model, DynaMIT software is able for establish connections with multiple traffic data sources in order to integrate complementary and heterogeneous traffic data feeds, once related in space and time.

From here, DynaMITs SOA evolution is not just an architectural style seen from a technological perspective, but also a set of new input data models, fusion practices, and processing outputs to be accessed and managed from open counterpart systems and applications.

VI. Conclusion

The current state of the practice in real-time transportation models is a valuable control and information generation utility to support ATMS and ATIS services. This paper presents DynaMIT as an example of such a model and discusses the recent enhancements in on-line calibration.

This paper identifies several aspects of real-time models that should be improved in the next generation implementation: activity-based trip generation, multi-modal network representation, representation of commercial vehicles, use of personal devices for data capture and information distribution, and congestion pricing.

The trip generation of these models is based on a static O/D, rather than an activity framework that could include the option of travelers to not make the trip at all. An activity-based trip generation process is a much more flexible and realistic representation of travelers.

The next generation of real-time models should include support for multi-modal trips. The current models are limited to general vehicle traffic and do not include explicit representation of public transportation, commercial vehicles, or anticipated future technologies such as mobility-on-demand services. Representations of the supply and demand aspects of multi-modal transportation networks require several important extensions to the model to represent the discontinuous nature of the network and service.

Commercial vehicles can account for up to 10% of Vehicle Kilometer Traveled (VKT) in an urban network. These vehicles have a unique travel pattern as they make deliveries and respond to service calls.

Personal devices, such as smart phones, are bringing a wealth of new data to the table and new pathways for delivery of traveler information. The new data should be fused with data from the static sensors, such as loop detectors, to provide a more complete picture of network conditions. These devices, when integrated with vehicles, can act together on a local scale to notify travelers of traffic conditions in their immediate vicinity.

The reaction to congestion pricing and HOT lanes is of great importance to the administrators of these systems. Accurate prediction of these reactions is critical for setting the appropriate price points.

The next generation model should be built with a flexible Service-Oriented architecture in order to integrate complementary and heterogenous data feeds as well as provide support to a variety of control and traveler information system outputs.

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