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AN ONLINE TRANSPORTATION SYSTEM SIMULATION TESTBED

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ABSTRACT

A testbed for evaluation of online distributed simulations of transportation system infrastructures is described that includes a modest portion of an urban road network in the midtown region of Atlanta, Georgia. The testbed includes sensors, servers, wireless communications, and mobile transportation simulations configured to model the testbed region. The system architecture for this testbed is described. Results of experiments evaluating wireless communication performance are presented. An implementation of an online traffic simulation based on a commercial simulator was developed, and results comparing the system's predictive accuracy with observed travel times through the simulated region are presented to illustrate a typical use of the testbed and to identify certain requirements for achieving reliable travel time predictions using online simulations.

1 INTRODUCTION AND MOTIVATION

Embedded online distributed simulation is a promising approach for the management of next generation transportation infrastructures. Its decentralized structure offers potential advantages such as exploitation of real-time data closer to its source than conventional centralized approaches and increased resilience to failures. Preliminary work in the laboratory showed that an embedded online approach termed ad hoc distributed simulations offer promise in producing simulation results comparable to a traditional replicated simulation experiment for transportation simulation applications (Fujimoto 2007). The distributed nature of transportation systems, the increased sophistication of in-vehicle computing systems, the increased availability of wireless communications, and the bottom-up nature of distributed simulations composed of in-vehicle simulators makes transportation applications particularly well suited for this online distributed simulation approach.

The work described in (Fujimoto 2007) relied upon idealized assumptions regarding communications and assumed synthetic traffic patterns. These issues could prove the system intractable or unreliable in real world settings. Of particular significance were previous assumptions regarding nearly instantaneous, reliable communication among the elements of the distributed simulation. Wireless communication for inter-vehicle communication can be expected to be far from ideal. Both message latency and loss would be expected to be significant factors in a real-world implementation.

An online simulation testbed was developed in order to test the viability of embedded simulations under realistic test conditions. The initial deployment of the testbed focuses on verifying the predictive capabilities of a single simulation client for a section of a roadway spanning approximately four city blocks within a major metropolitan city. The road network includes four signalized intersections and WiFi communication throughout the entire area, and provided linkages to a wired communications infrastructure. A detailed microscopic simulation model of this area was developed using VISSIM (PTV 2005), a commercial transportation simulation package. Live traffic through the area covered by the testbed was measured and used to drive the transportation simulation.

In order to establish the wireless communications performance within the testbed, a field study was conducted under real-world conditions. Message latency was measured in order to assess delays and losses that could be expected in an actual deployment. Studies were conducted to determine if regional models could adequately represent vehicle travel times when presented with observed vehicle flow rates. Measured traffic flows provided inputs to the simulation model and results were compared to observed vehicle travel times for everyday traffic utilizing the area covered by the testbed.

The testbed was motivated by a simulation methodology known as ad hoc distributed simulations. An ad hoc distributed simulation is a collection of autonomous on-line simulations working together to model an operational system. Each simulator in the distributed simulation utilizes on-line data to construct a snapshot of the current state of a portion of the system, and simulates forward to project future states. These predictions are distributed among other simulators that utilize them in their own simulations. The distributed simulation includes an optimistic synchronization algorithm that uses rollbacks to incorporate new on-line sensor data into the simulation, followed by automatic recomputation of projections of future system states. Ad hoc distributed simulations differ from conventional distributed simulations in that they are created bottom-up rather than top-down. In contrast to conventional distributed simulations where the area modeled by each simulators is a partition of the overall system, the simulators making up an ad hoc distributed simulation autonomously define the region they model, possibly resulting in multiple simulators modeling the same portion of the physical system. As such, this approach combines concepts from conventional distributed simulations and replicated trials. The ad hoc distributed simulation approach is described in more detail in (Fujimoto 2007). Although ad hoc distributed simulations motivated the creation of the testbed, the testbed itself is more general than this approach, and can be used for other types of on-line transportation simulations or applications.

The remainder of this paper is organized as follows. In the next section, we briefly review related work. The implemented system architecture of the testbed is then described. We present our communication experimental method and discuss the observed message latencies. The following section reviews the actual simulation experiments, comparing the model predictions with observed vehicle travel times.

2 RELATED WORK

Advances such as sensor networks and the increased deployment of wireless communications have increased interest in approaches to on-line simulation. For example, this approach has been receiving increased attention recently in the context of dynamic data driven application systems (DDDAS) (Darema 2004). For example, the LEAD project focuses on the prediction of regional scale weather phenomena based on on-line measurement (Plale, Gannon and Reed 2005). Atmosphere-fire models are used to create a suite of simulations relying on fire-atmosphere feedback and environment data to capture the evolution of fire (Mandel, Bennethum and Chen 2005). AMBROSia (Autonomous Model-Based Reactive Observing System) is a framework developed to optimize and control the set of data samples taken at any given time by taking into account the objectives and limitations of the simulation (Golubchik, Caron, and Das 2005). Kennedy and Theodoropoulos (2006) have proposed the introduction of artificial intelligence to DDDAS. COERCE, is a semi-automated transformation process for building simulations that support dynamic modification and refinement to match runtime conditions (Brogan, Reynolds and Bartholet 2005). Online simulations have also been referred to symbiotic simulations, emphasizing the potential symbiotic relationship between on-line simulators and the system being modeled. They have been proposed for decision support systems for manufacturing applications, as described in (Lendermann et al. 2005).

In transportation modeling, (Sisiopiku and Rouphail 1994) provides a comprehensive review of models using sensor data to estimate arterial performance metrics and discusses their limitations. More recent work echoes these limitations (Liu et al. 2006). Another review focusing on travel time estimation using loop detectors is presented in (Zhang and Kwon 1997). Though offering much potential, online simulation using the models described in these references has not achieved widespread use in transportation systems today. In many cases this is due to challenges in their data requirements, or unsatisfactory performance in test implementations.

3 TESTBED ARCHITECTURE

Online distributed simulation systems rely upon a collection of sensors, simulation clients, and communication infrastructure to collaboratively model an area. Here, composite values of key parameters are stored and time stamped in a data structure known as space-time memory (STM) (Fujimoto 2007). Here, the STM is centralized at a server and collects estimated values of state variables (e.g., traffic flow rates for individual links of the network) and the time values for which these estimates are valid. It acts as an intermediary for all communication and data requirements. Sensors provide readings directly to the STM. Additionally, the simulation clients request values only from the STM. This simplifies the system architecture as clients need not know the data's origination. Data may come from archived, real-time, or predicted sources.

This testbed provides an infrastructure for real-world experimentation with online simulations. The current implementation supports individual simulation clients reading and writing values to the STM while simulating the testbed area. The software architecture of the system is shown in Figure 1. In addition to client simulators, sensors provide the instrumented data to feed the simulators. The STM both collects and disseminates information to the other elements and is physically housed in a server. Sensor nodes will write values into STM, while simulation clients will both read and write data values to STM. This implementation does not support rollback, required in (Fujimoto 2007), but is sufficient to verify the ability for the simulators to predict accurate travel times based on flow rate information.

Communication is handled by middleware known as the Transportation Runtime Infrastructure (TRTI). Like RTI software in the Department of Defense High Level Architecture (HLA), the TRTI provides group communication services using a publish/subscribe mechanism (IEEE 2000). The simulated area is subdivided into a set of geographic regions to which a client can subscribe in order to receive all simulation messages published to that region. This also allows for mobile nodes because simulators may successively subscribe and unsubscribe to regions. Here, we use the terms simulator and logical process (LP) synonymously.

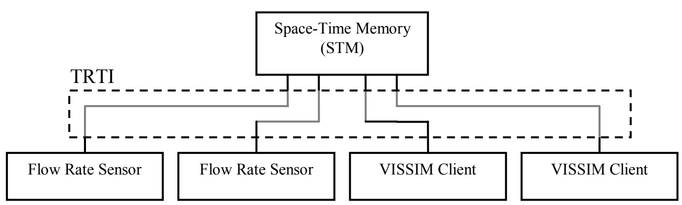

Figure 1: Overall system architecture. All communication is routed through the TRTI

The area chosen for the testbed is the 5th Street region of the midtown region in Atlanta, Georgia, that includes a portion of the Georgia Tech campus. The region's communication resources and traffic flows provided a representative testbed that could later be expanded into a wider implementation. The entire area includes full WiFi coverage (802.11g) and is linked to a wired network infrastructure. Sensors, client simulators, and servers all communicate via "last hop" wireless links, i.e., all communications require transmission over a wireless link, forwarding over the wired infrastructure, and then a final wireless link to reach the destination. Client terminals were placed in the same locations for both communication and simulation experiments as shown in Figure 2.

Figure 2: Node locations within the test region. The server locations are denoted by squares and the client locations, that may represent a simulator, sensor, or some other terminal node by circles.

The field terminals and server were implemented on DELL Latitude 630 laptops utilizing built-in wireless cards. The commercial transportation simulation program VISSIM was chosen to simulate the testbed area (PTV 2007). This program handles vehicle movement through a region along with speed distribution, signal timing plans, and the addition of new vehicles into the network. VISSIM was selected not only due to its wide use and accepted reliability, but for its ability to interact with other programs through a COM interface (PTV 2008). It was this functionality that allowed the VISSIM simulation to be integrated with the other distributed components through the TRTI.

Thus the implemented testbed includes the following components:

- STM server, storing observed flow rates provided by sensors and predicted future flow rates produced by client simulators
- VISSIM wireless simulation client with a model of the 5th Street corridor
- Traffic flow rate sensors
- TRTI publish/subscribe communication middleware
- 802.11g wireless and wired communications infrastructure

4 COMMUNICATION PERFORMANCE

The impact of communication performance on the effectiveness of online distributed transportation simulations is an open question. Excessive message latency or loss could limit the ability of the logical processes to provide reliable predictions of future traffic conditions. Experimental evaluations of wireless communication performance in the context of intelligent transportation systems have been studied by several other researchers, e.g., see (Moske et al. 2004; Ott and Kutscher 2004; Singh et al. 2002). Wireless communications in urban environments creates specific challenges due to the "urban canyons" that are often created by buildings and other obstructions lying adjacent to streets and sidewalks. The testbed area includes a mix of residential areas in the portion of the testbed to the west of the dividing highway (see Figure 2) and terrain more like that of a downtown area in the portion to the east of the highway. We believe the testbed terrain to be representative of environments encountered in many urban areas.

Client nodes in the testbed physically residing on the street communicate via a wireless link to a base station mounted in a building that in turn communicate through the wired network infrastructure to another base station at the STM location, which then communicates with the final destination through another wireless link. Several experiments were run in order to validate the usability and performance of the WiFi network. All communication experiments took place either during the same time of day as the traffic monitoring experiments or when a similar load was present.

To establish a base case, several communication trials were run with varying message sizes. In each experiment, several client terminals within each experimental region on 5th Street (the regions marked with circles in Figure 2) sent messages to a remote server in site 1, (the square in the center, and near the southern or bottom edge shown in Figure 2). In each trial, 100 messages were successively sent to the server using Window's ping functionality. Figure 3 shows the frequency at which different latencies were observed.

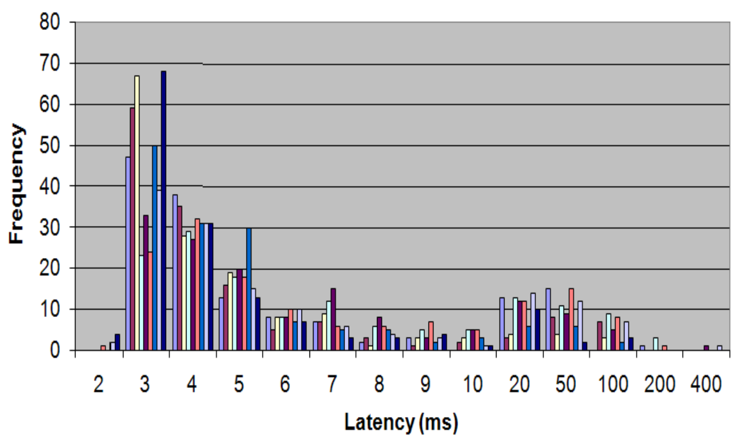

Figure 3: Frequency of latency observance for 100 byte pings. Each color represents a separate trial of 100 messages.

The average latency varied by location between 50.75 and 123.75 ms. However, most messages were received within 3 to 5 milliseconds, with occasional outliers of up to 3713 ms greatly increasing the overall average. The fraction of messages lost varied from 3% to 18% depending on sensor location.

These measurements illustrate that stationary systems utilizing a wireless network can be expected to experience large variability in message delay. Thus, any simulation structure must be resilient against severe variation in latency. Software must allow for occasional delays in addition to any processing overhead when setting time limits. The simulation framework should be constructed with allowances for such behaviors in the underlying communications infrastructure.

After establishing baseline message latency, several tests using the TRTI system and clients were completed. In the first trial, three of the clients sent a roundtrip message to a server at site 2 (the western or leftmost box in Figure 1). The message was parsed by the server and returned to the client. These experiments used the UDP communication protocol.

A high variability in latency was again observed. While the minimum latency was consistently around 240 ms, the maximum latency experienced by a terminal varied from 800 to 2400 ms. The frequency of outlier occurrences agreed with the ping testing, but the magnitude was significantly higher. Notably, the average latency, 429 ms, was higher than twice the original one-way trials that used TCP. To isolate the cause of the latency increase, the trials were modified. The messages were sent through TRTI to the server and returned without being parsed by the server. Figure 4 shows the distribution of round trip message latencies. The average latency was significantly reduced with fewer outliers.

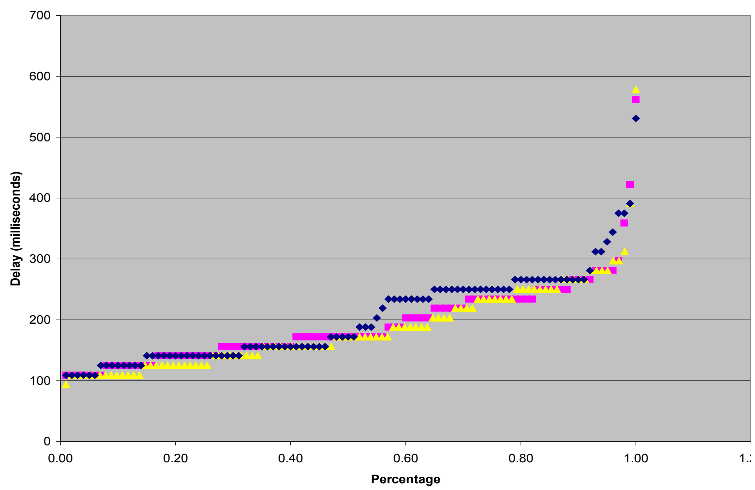

Figure 4: Message latency at east sensor location. Each curve corresponds to a different client.

This reduction in latency indicates the server adds a significant amount of time for message processing. If the server is utilized for routing decisions, message latency is effectively doubled, possibly limiting the simulations' forward progression. The server was implemented using Visual Basic due to constraints associated with the VISSIM COM interface.

The highly variable latency that was observed indicates that a tightly synchronized simulation may not be possible in this environment, suggesting the use of more loosely synchronized distributed simulation approaches. Since message latency is often sporadic and unpredictable, message order or reception is not guaranteed. Overall, despite the high and variable latency, the network characteristics proved acceptable for our initial traffic experimentation and were within expected tolerance of the simulations that were used for these tests.

5 ON-LINE SIMULATION EXPERIMENTS

The initial field experiments were designed to test the ability of the VISSIM simulation to accurately model traffic in the testbed region (5th street, see Figure 5). This section is representative of a small-scale area that might be modeled by a simulation client. In order to successfully implement an online distributed simulation, each client must be able to successfully simulate its local area much faster than wallclock time.

5.1 Model Area and Data

Sensors were placed at three locations within the region, indicated by circles in Figure 2. In these experiments, each sensor was composed of a Visual Basic GUI with inputs provided by the experimenter. Sensor data was generated manually based on roadside observation. Currently, video cameras with image processing software are being added to automate this process. The sensors utilized the TRTI for message routing and provided their readings to the STM.

Real-time traffic flow rates were recorded by the sensors. The volume of eastbound vehicles passing each sensor was obtained every 10 seconds. This value was converted into a flow rate and submitted to the STM. Instead of treating the observed flow rates as real-time measurements of traffic flow, this experiment used these flow rates as historically collected flow rate estimations. In this manner, the flow rates collected form a predictive model that the simulation uses as it simulates forward in time. In the envisioned deployed system these flow rates in the STM would be aggregates of historical data, predictions from other clients, and real time sensor data. For the purposes of validating the predictions made by the simulator, using only the observed flow rates makes it possible to compare the simulator output to the observed travel times.

The ten second flow rates at the west most sensor provide the real world field data used during the simulation trials for generating vehicle arrivals at the west boundary of the model area. As VISSIM simulates individual vehicles the VISSIM client performed a decomposition function on the flow rate values, spreading the vehicle generation evenly over the simulation period to obtain the same average flow rate.

The cross street and westbound traffic is generated by the VISSIM model based on historical probabilities. In the several weeks prior to the experiment we gathered representative field data at these boundary points. The model was also programmed to have turning ratios similar to observed trends. Additionally, vehicular speed detection was used to establish appropriate speed variations within the simulation. Finally, signal control data is based on estimates derived from field observations. The envisioned system would utilize signal timing output from the signal controllers themselves, however, this functionality has not yet been incorporated into the testbed.

After the trials, collected data were post-processed to calculate the travel time of individual vehicles through the testbed area in order to assess the accuracy of simulation predictions. This was accomplished by recording the time each vehicle entered and exited the test area, using license plate numbers to identify individual vehicles. Since the data were collected simultaneously with the flow rates used for the predictive model, it is assumed that the observed flow rates should directly give rise to these observed travel times. Therefore, the observed travel times were compared to the predictions made by the simulator as a measure of accuracy. The first 30 minutes of collected travel time data (4:30 to 5:00 pm) was use to calibrate the simulation model in addition to the comparative analysis to be presented.

The VISSIM model representing 5th street covered the area shown in Figure 5. For later analysis this area is considered to be divided into two regions, divided by Spring St., a major (4 lane) Southbound cross street. The sensor locations fall on the vertical lines of the outlined regions.

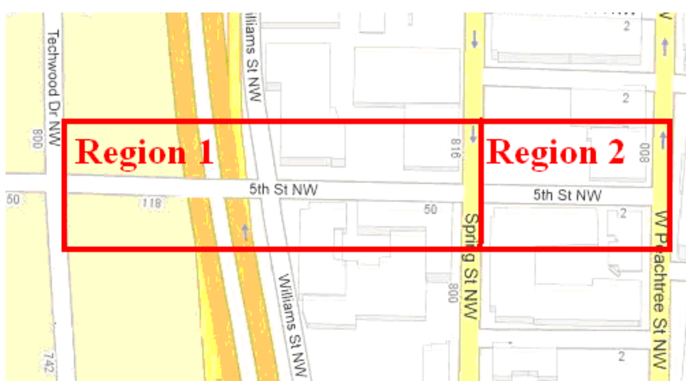

Figure 5: Map of VISSIM simulated area of 5th Street

Travel times were processed only for vehicles entering the western border of Region 1 and proceeding east through both regions. Vehicular volumes and travel times were observed from 4:30 to 5:30 pm and 6:30 to 7:30 pm on July 8th, 2008 along 5th Street. Observed volumes, as shown in Figure 6, were typically between 0 and 4 vehicles every 10 seconds. Figure 6 shows the number of vehicles passing the west most sensor. As expected, entering vehicle flow rates were reduced later in the evening, as shown in Figure 7.

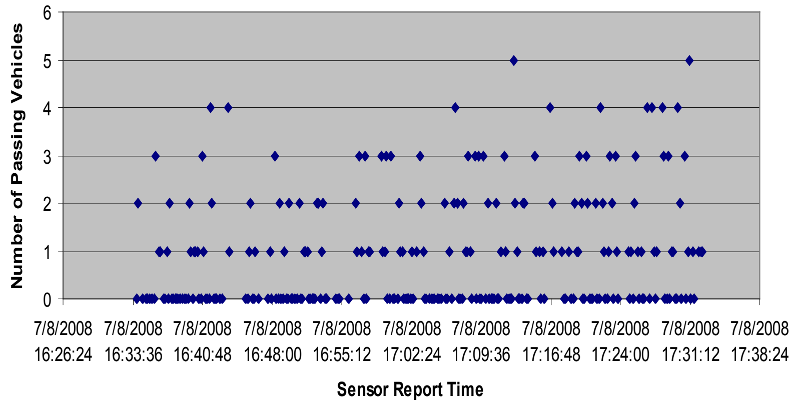

Figure 6: Number of vehicles observed at from 4:30 to 5:30pm from Techwood Ave. to Spring Street

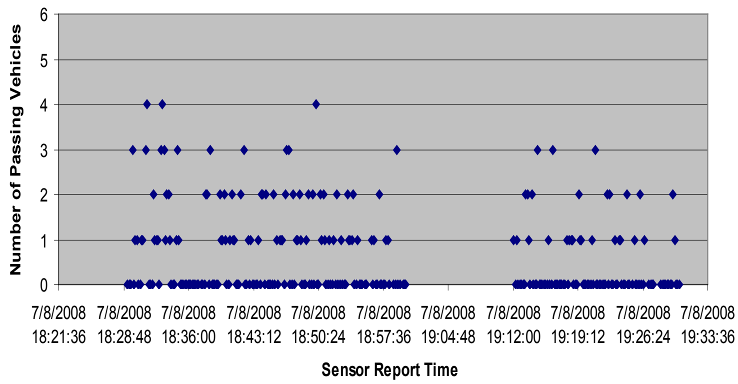

Figure 7: Number of vehicles observed from 6:30 to 7:30pm from Techwood Ave. to Spring Street.

Messages were lost from the period 19:00:17 to 19:12:07 due to losses in the communication network. The travel time of vehicles through region 1 during the 4:30 to 5:30 pm experiment are shown in Figure 8. As seen in this figure travel times exhibited a significant amount of variation. A distribution of observed travel times from 4:30 to 5:30 pm is shown in Figure 9.

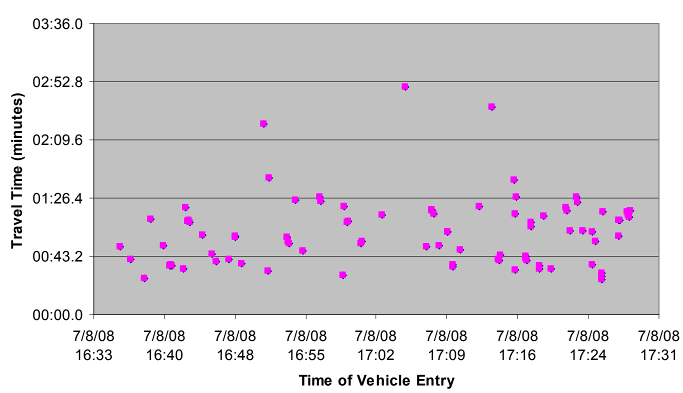

Figure 8: The travel time of entering vehicle for region 1 during the first trial.

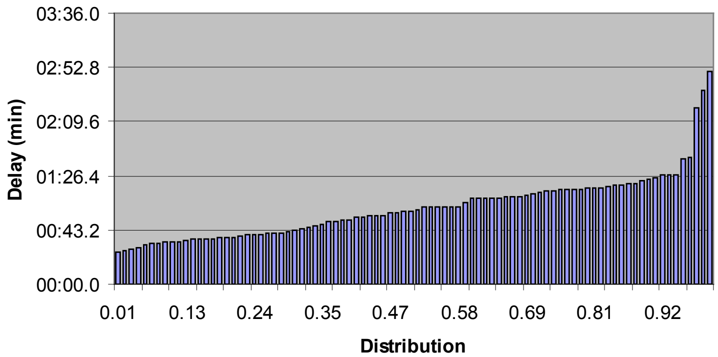

Figure 9: Distribution of observed travel times during first period in first simulation region.

5.2 Simulation Trials

Each trial represents predictions one hour into the future. During each ten second period in the simulation experiment the simulation client requested the observed or predicted flow rate from the STM at that simulated time for the 5th Street west boundary arrivals. The simulation then progressed forward for 10 seconds, submitting predicted travel times and flow rates to the STM server, and requested the flow rate for the next 10 seconds. After the experiment was completed, the travel times predicted by the simulator were compared against the actual measured travel times experienced by vehicles traveling through the testbed region when the flow rates were collected.

Five experimental trials were run using the flow rates observed during the field study. Figure 10 shows the relative frequency of eastbound travel times through Region 1 from 4:30 to 5:30 pm for the observed field data and the simulation trials. The simulation predictions reasonably predicted the actual average travel time. The field data indicated an average travel time of 61seconds, while the five simulation predictions ranged from 60 to 80 seconds. However, as seen in Figure 10 the distribution of the actual travel time is strongly bimodal while the simulated trials do not capture this effect. We believe this difference is largely due to the simulation model not including synchronization among traffic signals and the lack of local buses (a shuttle bus service) along Fifth Street in the simulation model. Other sources of error include message losses and approximations associated with simulation parameters such as turning probabilities, as noted earlier. These factors contribute to different simulation predictions from one trial to the next.

Region 2 eastbound travel times (Figure 11) yielded results that provide a better match of the distribution of the travel time data however there is a slight shifting to the right of the simulation predictions compared to the field data. This is again likely due to a lack of accurate signal data in the model. The impact of buses is less pronounced because there are fewer shuttle bus routes in this portion of the testbed area compared to Region 1.

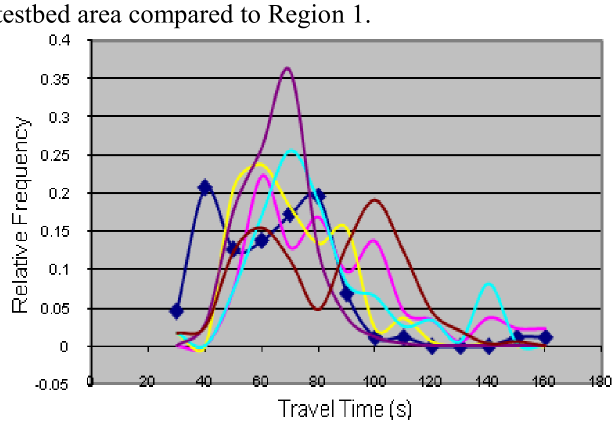

Figure 10: Relative frequency of vehicle eastbound travel times in the Region 1. The line with diamond markers represents the observed travel time. The other five lines show the five trials.

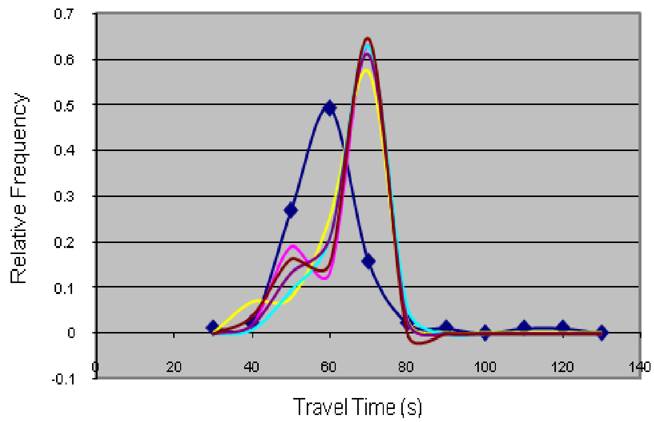

Figure 11: Relative frequency of vehicle eastbound travel times in the Region 2. The line with diamond markers represents the observed travel time. The other five lines show the five trials. Outliers above 3 minutes have been removed for clarification.

The experiment was repeated using data from 6:30 to 7:30pm on the same day. The same model was used from the earlier experiment without modification. Due to the late nature of the day, the observed flow rates were significantly reduced. As expected the lower flow rates resulted in reduced travel times. Figure 12 shows the data from the Region 1 and Figure 13 the data from the Region 2.

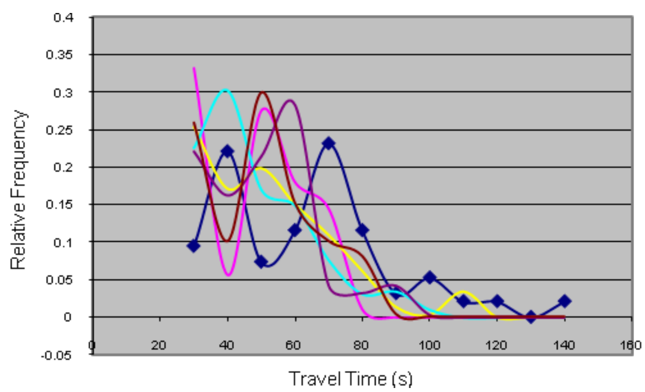

Figure 12: Relative frequency of vehicle eastbound travel times in the Region 1 during the second experimental period. The line with diamond markers represents the observed travel time. The other five lines show the five trials.

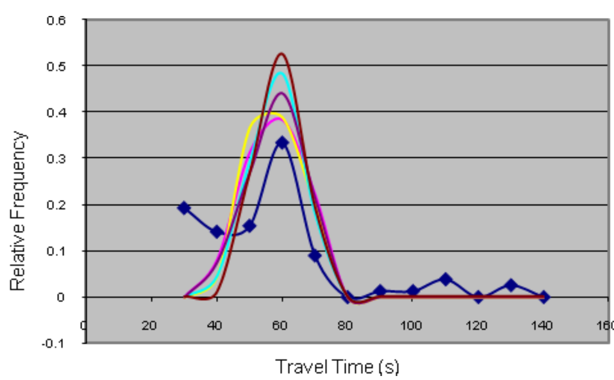

Figure 13: Relative frequency of vehicle eastbound travel times in the first Region 2 during the second experimental period. The line with diamond markers represents the observed travel time. The other five lines show the five trials.

For this time period the simulation of Region 1 overestimated travel time, as was the case for the 4:30 to 5:30 pm period discussed earlier. The travel time distribution results are qualitatively similar to those reported earlier. The Region 2 simulation trials seem to reasonably predict observed data.

The latencies as observed in the communications experiment proved to be inconsequential for all of the online simulation trials from a performance perspective, as expected. The simulation could potentially slow as it waits for values from the STM, but all hour long simulation runs were completed in five minutes or less, far surpassing a real time rate. Minor data loss was also experienced and may have contributed to the error in the simulated times.

Overall VISSIM's simulation capabilities provided average travel time results that were sufficiently similar to observed travel times to warrant future use and experimentation. Although, of key interest is that in an arterial system traffic flow data alone is likely insufficient to allow for a highly accurate real time simulation, particularly where traffic responsive control is utilized. An ability to stream timing parameters will also be critical to data driven simulations in this environment.

6 CONCLUSION AND FUTURE WORK

These experiments suggest a online simulation approach can reasonably predict average travel times for vehicles in the region covered by the testbed, holding promise for online distributed implementations. The experiments also shed light on what data is necessary to produce accurate distributions of travel time. VISSIM was shown to produce reasonable travel time estimations when utilizing obtained flow rates from the modeled region. Communications experiments revealed high variability in message latencies, suggesting that an on-line simulation must be robust to such variation in the performance of the communication structure, even under "normal" operating conditions. The technical challenges regarding VISSIM and STM integration were proven surmountable during this implementation.

These experiments highlight some of the requirements for on-line transportation simulations to provide reliable predictions. As with all simulation programs, predictive capability is dependent upon model fit and input scope. Not surprisingly, the simulation was accurate when assumed flow rates were similar to actual conditions. Presumably, greater accuracy could have been obtained if all entering flow rates were observed and utilized during the period. In addition, the incorporation of real time signal control parameters and light synchronization will greatly enhance the simulation's ability to reflect field conditions. Another result was establishing the effectiveness of the space-time memory in that flow rates were shown to be an appropriate aggregate representation of regional state.

A particular focus was given to proving the viability of the online simulation implementation. Experimental results indicate that this approach offers some potential. While the simulation experiments were conducted using trace data to provide historical flow rates, the message structure was such that historical references may be supplemented with on-line readings or client predictions.

Evaluation of online distributed simulations for traffic management is in its infancy. Future experiments are needed that span a much broader range of traffic conditions, and larger areas of investigation. Further additional work is required to investigate larger scale implementations with many client simulators, as well as mobile clients. Infrastructureless implementations using peer-to-peer architectures are under consideration. Such a wide scale implementation might require use of cellular phones for communication rather than, or in addition to WiFi.

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