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# DEVELOPMENT AND VALIDATION OF A FLEXIBLE, OPEN ARCHITECTURE, TRANSPORTATION SIMULATION

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## ABSTRACT

Simulation has been utilized in the planning and development of almost all sectors of the transportation field. The practicing transportation community primarily relies on simulation packages, as opposed to "ground up" simulation development. Unfortunately, the use of these simulation packages has several disadvantages, most notably the "black box" phenomenon and reduced modeling flexibility. The simulation approach described in this paper lays the foundation for a transportation simulation approach that minimizes the "black box" problem and increases modeling flexibility, while still providing an easy to use package in which highly capable models may be quickly and accurately built. This simulation approach utilizes SIMAN and ARENA. This paper includes a brief discussion of the simulation approach, a comparison of the proposed simulation and CORSIM simulation results for an intersection and an arterial, and a comparison of the proposed simulation control delay to delays collected for a twelve intersection grid north of downtown Chicago.

## 1 INTRODUCTION

Simulation is vital in the planning and development of almost all transportation sectors. Isolated intersections, entire networks, airport landside and airside operations, freight movement, and passenger terminals: all of these features of a transportation system may be analyzed through simulation. List and Troutbeck (1999) describe four basic paradigms for simulation development: program code, flowcharts, pseudo code, and worksheets; although in practice simulation development usually involves a combination of two or more of these approaches. In these paradigms simulations are constructed from the ground up, addressing issues such as event-based vs. time-based simulation, distribution selection and implementation, underlying vehicle movement (i.e. car-following equations, Newtonian mechanics, acceleration / deceleration parameters, etc.), and selection of a programming language. Such simulation development contains several significant disadvantages, particularly extensive training requirements and excessive development time and costs. To alleviate these disadvantages the practicing transportation community primarily relies on simulation packages. A few (of the many) examples of transportation simulation packages available include CORSIM, WATSim, INTEGRATION, VISSIM, and TEXAS. When a practitioner uses a simulation package, the simulation development effort has already been completed. With the inclusion of graphical user interfaces, models are approaching "plug and play" capabilities, in which models may be quickly and economically constructed.

While overcoming the advantages of simulation development these packages have disadvantages, most notably the "black box" phenomenon and reduced modeling flexibility. An end user can enter data and receive results with little understanding of how the simulation operates and limited knowledge of the inherent assumptions. Also, a user is bound by the methods and assumptions of the given simulation package. It is virtually impossible for an end user to conceptualize, design, and develop a simulation for a situation beyond the bounds set by the simulation package developer.

## 2 PROPOSED SIMULATION MODELING APPROACH OBJECTIVES

The model described in this paper lays the foundation for a transportation simulation approach that minimizes the black box problem and increases modeling flexibility while still providing an easy to use package in which highly capable models may be quickly and accurately built. For this simulation modeling approach, SIMAN (Pedgen, Shannon, and Sadowski 1995), a general-purpose simulation language, and ARENA (Kelton, Sadowski, and Sadowski 1998), a hierarchical simulation-modeling tool that automates the creation of SIMAN, were used. With SIMAN and ARENA as the foundation, the development of a flexible, open, efficient approach to transportation simulation with the following properties is undertaken: hierarchical, event-based, object-oriented, and stochastic.

### 2.1 Hierarchical

This simulation approach consists of three tiers of blocks (objects). The tier 1 blocks are most functionally robust and may be readily combined to create an intersection, arterial, or network simulation model. Each of these tier 1 blocks is constructed from hierarchy tier 2 and tier 3 blocks. Tier 3 blocks (the lowest tier) are the basic SIMAN building blocks. Tier 2 blocks are intermediary blocks, constructed from tier 3 blocks with the intent of simplifying the construction and complexity of tier 1 blocks. For example, the APPROACH block is a tier 2 block that models the vehicle queue and stop bar departure on a single lane approach. The tier 1 PRETIMED block ties together APPROACH blocks with a pre-timed signal logic, capturing the operation of a pre-timed intersection in a single tier 1 block.

Utilizing tier 1 blocks greatly reduces the complexity of model construction. For example, the single intersection model in the validation discussion was constructed using twenty-one tier one blocks. If this same model was constructed directly from tier 3 blocks (i.e. constructed with only SIMAN basic building blocks) nearly 900 blocks would be required. By utilizing the hierarchical object-oriented approach the task is greatly streamlined, allowing for efficient model development.

### 2.2 Event-Based

Currently the proposed simulation is event-based. Once all actions have been completed at a simulation time the simulation clock is advanced to the next scheduled event, regardless of the amount of time between events.

### 2.3 Object-Oriented

Roughly stated, object-oriented programming is a programming approach where one first considers the software in terms of objects and how those objects interact with each other. By utilizing a simulation approach where the transportation system is seen as a collection of interacting objects, creation of an open simulation architecture becomes a simpler and more straightforward task. This approach enables contributions by a wide array of developers and users.

### 2.4 Stochastic

In current tier 1 blocks, a user may introduce randomness. Aspects that may include randomness include the creation (i.e. vehicle enter) interval, aggressiveness factor (which affects speeds, headways, and intersection start-up lost times), and turning movements. The stochasticity of the creation interval and aggressiveness factor may be set to follow many different distributions.

### 2.5 Summary

Currently the proposed simulation only models vehicle traffic on signalized networks. This is accomplished through 10 tier 1 blocks: ENTER, EXIT, QUEUECHANGE, TURNBAY, LANEADD, LANEDROP, PRETIMED, PRETIMED8P, ACTUATED8P, and SIGNAL. Through these blocks, vehicles enter and exit the network, change queues and select turn movements, lanes are added and dropped in the network, pre-timed, actuated and adaptive signal control is modeled, vehicles travel along links, and both vehicle and network statistics are collected.

## 3 MODEL VALIDATION

Validation of a simulation can be a difficult process, difficult even to precisely define. In a general sense the goal of validation is to gain confidence in the ability of the model to reasonably reflect real world conditions. Validation includes testing for reasonableness, adequacy of the model structure, and model behavior against the referent system (Pedgen, Shannon, and Sadowski 1995). The focus of this discussion is on the comparison of proposed model behavior to that of several transportation networks. For additional information on the model reasonableness and structure the reader is referred to Hunter (2003). It must be noted that neither this discussion nor the referenced document should be considered the final statement on the validity of the proposed simulation approach. Validation is a continual process, only over time and through use may wide-ranging confidence be gained. The intent of this study is to provide initial confidence in the simulation approach.

Ideally, a transportation simulation validation study includes comparisons of simulated results against real world data. Unfortunately, an acute problem in transportation is the lack of sufficient data sets to vigorously validate a simulation. To overcome the limited data available a combination approach to validation was undertaken, comparing the developed simulation against CORSIM, a highly regarded transportation simulation package, and against a real-world data set.

This approach has several notable drawbacks. Firstly, CORSIM errors are introduced into the validation process. In a comparison to CORSIM it is only possible to state how well the proposed model reflects the performance of CORSIM, not the real world. Secondly, the determination of the quality of the proposed simulation results is subjective. The following discussions rely on engineering judgment to gauge the quality of the proposed simulation versus CORSIM and the real world data. Future research will delve into developing formal methods by which transportation simulation results may be gauged.

### 3.1 CORSIM Validation Scenarios

Two different geometric scenarios were studied for initial model validation: an isolated intersection and a three intersection arterial. These scenarios were chosen as they capture the fundamental aspects of most traffic networks: operations at an intersection and the interaction between intersections. Characteristics similar to intersections in both validation scenarios include three phase signal timing (leading East-West lefts), protected only left turns, no right turns on red, 2.4 second start-up lost time, 2.0 second departure headways, and turn movements from turn bays only (i.e. no shared lanes). In the isolated intersection scenarios the East-West approaches include three through lanes while in the arterial scenarios there are two through lanes. The distance between arterial intersections (from stop bar to stop bar) is set at 1320 ft with a 30 mph average free flow speed. In all scenarios the North-South approaches are comprised of a single right turn bay and a single through lane. Also, vehicle queue changing probabilities in the simulation were set to achieve a similar queue changing frequency of that observed in CORSIM. Due to space constraints, only a synopsis of the validation study against CORSIM is presented. For a complete discussion the reader is encouraged to refer to Hunter (2003).

#### 3.1.1 Validation – Isolated Intersection

For the isolated intersection, comparisons were made under low to over-saturated traffic conditions through fifteen different volume / cycle length scenarios. Five replicate runs were performed for each scenario, for a total of 75 runs of each simulation model. Figure 1 shows the average eastbound through volumes, delays, speeds and queues determined in both models. Similar results were developed for the westbound, northbound, and southbound approaches.

Overall CORSIM and the proposed simulation were found to exhibit similar values and trends for several measures of effectiveness (volumes processed, average vehicle delay, average queues, and average speed) in non-congested situations. In over-congested situations both models identified intersection performance problems although absolute differences between the measures of effectiveness values produced by the two models could be significant. The proposed simulation approach typically had greater delays, most likely resulting from the vertical queuing model. A vertical queue fails to limit the queue length by the approach link length, inflating the link delays. In a network the upstream intersection delay would also be effectively lowed, since vehicles would be allowed to enter a downstream link even when the downstream queue length exceeds the link length. Also, upstream crossing movements would not be blocked by spillback.

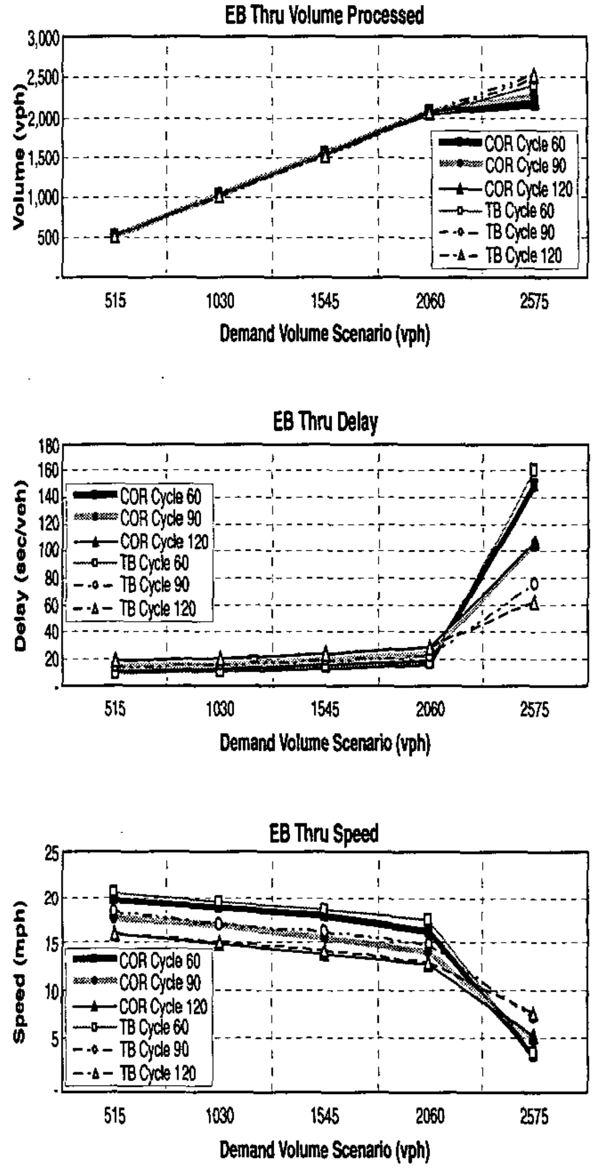


Figure 1: Eastbound Thru Delay, Volume, and Speeds for CORSIM (COR) and the Proposed Simulation (TB) Under Different Isolated Intersection Demand Volume / Cycle Length Scenarios

Another area of disagreement is left turn movements, particularly when demand approaches or exceeds capacity. CORSIM consistently processes more vehicles and has a lower delay than the proposed simulation. The CORSIM congested left turn behavior is the more aggressive, allowing for a higher capacity. Left turn behavior is an area in which additional study is required.

### 3.1.2 Validation – Arterial

The arterial validation study is primarily concerned with the operation of intersection approaches where there is a modeled upstream intersection, as other approaches will operate in a manner similar to that of the isolated intersection. Thus results discussed are for the eastbound and westbound directions. Northbound and southbound operations behave as seen in the isolated intersection discussion.

Based on the isolated intersection comparisons a single cycle length and volume demand scenario was selected for the arterial study. A thru volume demand of approximately 85% of capacity (85% green time utilization) was selected and a common cycle of 90 seconds was chosen. The effect of the offset is the variable of most interest in the arterial study. Thus six different offset scenarios were modeled. Listed as (Intersection 1, Intersection 2, Intersection 3) offsets in seconds, these six cases are (0,0,0), (0,15,30), (0,30,60), (0,45,0), (0,60,30), and (0,75,60).

Figure 2 presents the proposed simulation and CORSIM average delays, queues, and speeds for the eastbound and westbound approaches of the test arterial. For the un-congested volume scenario tested the proposed simulation and CORSIM demonstrate excellent agreement in the captured absolute MOE values and trends, as signal offsets changed. In both the eastbound and westbound directions both simulations process similar through, left, and right turn volumes. The approach delays vary according to the offset scenarios with both simulation models exhibiting similar trends in delays over the offset scenarios. The calculated delays from both models were found to be similar, typically within five or fewer seconds.

Also, for the given offset scenarios there are no significant differences between queues modeled by the two simulations. The queue differences are always within two vehicles and typically within one vehicle or less. In addition, both absolute speeds and speed trends simulated by both models are similar.

### 3.2 Comparison to Chicago Data

The utilized data set was part of a RT-TRACS (Real-Time Traffic Adaptive Control System) field test. This test was a field evaluation of RTACL (Real-Time Adaptive Control Logic) on a twelve-intersection network just north of downtown Chicago. The adaptive control field test involved numerous participants: FHWA, Chicago Department of Transportation, Chicago Bureau of Electricity, PB Farrradyne, and ITT Systems (ITT 2001). ITT Systems, who was responsible for performing the field evaluations, was the primary contact for obtaining the field data utilized in this validation effort.

As part of the RTACL evaluation, before and after conditions were measured in the field. The before condition field measurements provided the data required for a comparison to the simulation. The performance measure utilized for comparison in this simulation study is control delay.

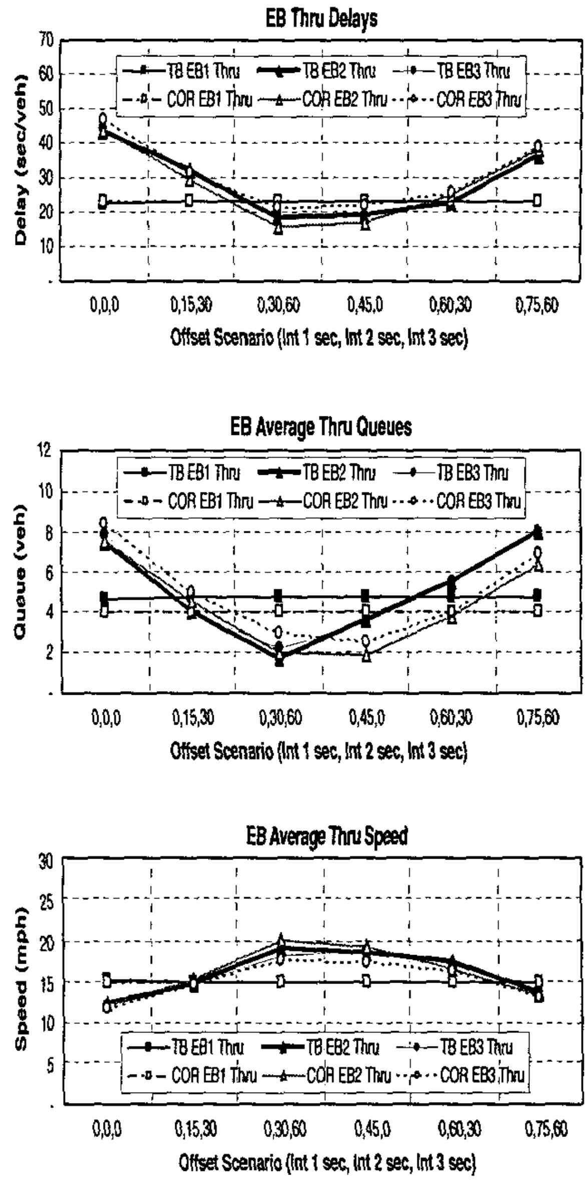


Figure 2: Eastbound Thru Delay, Queues, and Speeds for CORSIM (COR) and the Proposed Simulation (TB) Under Different Offset Scenarios

### 3.2.1 Site Description and Data Collection

Figure 3 provides an overview of the twelve intersections (numbered 1 through 12) for which data was collected. This twelve-intersection grid is bounded by West Ontario on the North, West Grand on the South, North LaSalle on the East, and North Orleans on the West. Signal control data were also known for the neighboring intersections on

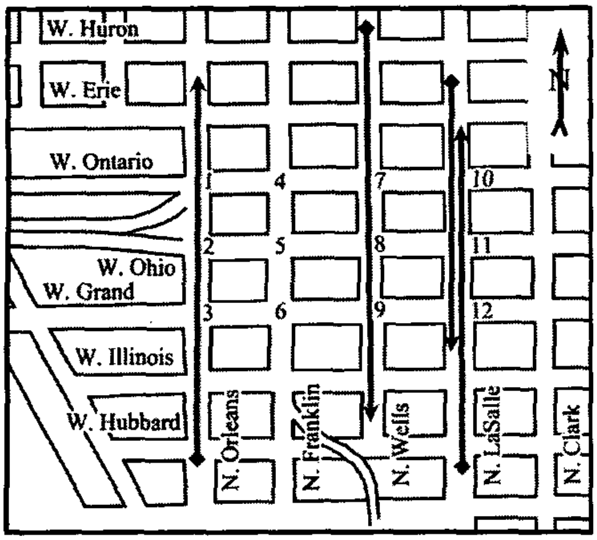

Figure 3: North – South Probe Vehicle Route

West Erie (North), West Illinois (South), and North Clark (East). These intersections were included in the simulation model (for a total of 23 simulated intersections), allowing for nearly all approaches on the twelve primary intersections to have simulated arrival patterns more consistent with those found in the field. Only the eastbound intersection approach arrivals on North Orleans do not account for the impact of upstream intersections. The network consists of both one-way and two-way streets, with average block length of 300' to 400' and speed limits of 30 to 35 mph. Detailed descriptions of the network geometry may be found in the ITT report (2001).

A drawback to this data set is limited traffic volume data. Volumes are based on 15-minute counts performed at each intersection during 1999 and 2000. The signal timings are all pre-timed with a 75 second background cycle. Timing plans were two or three phase. As part of the adaptive control evaluation, the intersection offsets for the before conditions were optimized (ITT 2001).

Travel time runs utilizing probe vehicles instrumented with Starlink GPS antennas and receivers were utilized to gather performance measures. Five probe vehicles were utilized during the peak hours over a three-day period in late October 2000. The probe vehicles followed specific routes. Figure 3 shows the north-south routes, similar east-west routes through the network were also included in the probe vehicle runs. Routes involving I-90 access were determined to be critical and were therefore assigned two probe vehicles, all other routes were assigned a single probe vehicle (ITT 2001). Over the peak periods, the probe vehicles were able to obtain 10 to 95 observations for each route, with most approaches receiving 30 to 60 observations. From this data, travel time and control delay information was determined for most of the twelve intersections. All reduction of raw data was performed by ITT Systems as part of the RT-TRACS field evaluation with the published results being utilized for this validation effort. For raw data and summarized results the reader is referred to the RT-TRACS field study report (ITT 2001).

### 3.2.2 Comparison of Simulated and Measured Control Delays

A simulation model was constructed for the twenty-three intersection network for which data were collected. Figures 4 and 5 contain the simulated and field measured control delays for the AM and PM peak periods, respectively. As all probe vehicle routes are straight through the network the probe vehicle delays are for the through movements only. Thus, for a consistent comparison the simulated delays are also for through movements only. Also, in this presentation, evaluation of agreement between model and probe vehicle data is that of practical rather than statistical difference, based on traffic engineering expertise and judgment. Hunter (2003) further explores the use of statistical significance in the evaluation of the proposed simulation model.

#### 3.2.2.1 AM Peak Period Control Delay

Overall, the AM peak period simulated versus probe vehicle control delays demonstrate reasonable agreement. For example, the critical I-90 access route, West Ohio Eastbound, the simulated versus probe vehicle control delays are (all in sec/veh) 7.1 vs 3.2, 11.9 vs 13.0, and 16.0 vs 10.7 for the intersections with North Franklin, North Wells, and North LaSalle, respectively. Both the probe vehicle and simulated delays indicate similar traffic conditions. A review of Figure 4 leads to the same conclusion of similar probe vehicle and simulated traffic conditions for West Ontario westbound, North LaSalle northbound and southbound, and North Wells southbound.

Further review of Figure 4 does however show that not all probe vehicle and simulated control delays indicate similar operating conditions. A prime example of disagreement is the northbound approach at the North Orleans and West Ontario intersection. The probe vehicle delay is 1.2 sec/veh while the simulated delay is 21.9 sec/veh. A 1.2 sec/veh control delay (probe vehicle measured delay) implies that nearly all of the probe vehicles passed through the intersection unimpeded by the traffic signal. The 21.9 sec/veh control delay (simulated delay) implies that at least a fraction of the vehicles are hindered by the signal control. The probe vehicle and simulation would seem to indicate different operating conditions.

A review of the data collection methodology reveals how the simulation and probe vehicles may be reflecting different aspects of the real-world operation. From Figure 3 it is seen that the probe vehicle route that includes this approach from which the control delay is measured begins south of West Hubbard on North Orleans, traveling northbound on North Orleans thru West Hubbard, West

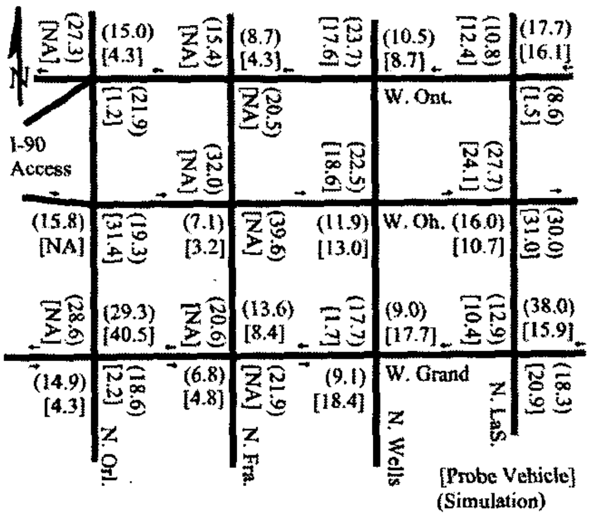


Figure 4: Chicago Simulation and Probe Vehicle Control Delay (sec/veh) - AM Peak (not-to-scale)

Grand, West Ohio, and finally West Ontario. Platoons of vehicles travel along this route, falling within a green band, are not hindered by an intersection's signal control. The majority of probe vehicles will fall within these platoons, incurring little delay, as measured in the field.

In contrast the simulated control delay is not calculated from a sampling of probe vehicles but from all vehicles that travel northbound through the intersection of North Orleans and West Ontario. In this instance, this is a significantly different vehicle population than that captured by the probe vehicles. The intersection of North Orleans and West Ohio provides access to the network from I-90. The North Orleans and West Ohio intersection west approach's left turn movement (i.e traffic from I-90 turning northbound onto North Orleans) is significant, at approximately 950 veh/hr, nearly double the northbound traffic from the south approach. These vehicles are not within a green band and are hindered by the North Orleans and West Ontario signal control.

Thus, the simulation is capturing a major movement (from I-90 to northbound on North Orleans) not reflected in the probe vehicle measurements. The probe vehicle measurements dramatically fail to capture the overall performance of the approach, underestimating the through movement control delay. Wherever an upstream turning movement feeds a substantial portion of an approach's through movement, a system of probe vehicle routes such as those utilized is likely to fail to accurately reflect the approach's operation. The intersection of North Wells and West Grand southbound approach is another example of this effect. The right turn movement onto North Wells from West Ohio is a significant movement that is not captured by the probe vehicles. Again this leads to a significant skewing of the probe vehicle control delay.

#### 3.2.2.2 PM Peak Period Control Delay

The PM peak period simulated versus probe vehicle control delays may be found in Figure 5. These delays do not demonstrate the same level of agreement as the AM peak period. While there are still examples of agreement, such as the West Ohio westbound traffic flow there are significant areas of disagreement. Areas of particular concern are the West Ontario and West Grand eastbound and the intersections of West Ontario and West Grand with North LaSalle.

Significant upstream turning movements do not readily explain these control delay differences; two possible explanations follow. The first is the possibility of inaccurate volume and signal timing data. The volumes were collected up to a year prior to the conducting of the probe vehicle runs. Also, during the probe vehicle study a bridge providing access out of downtown Chicago was closed, leading to a significant increase in the northbound traffic on LaSalle during the PM peak (ITT 2001). This detour is not reflected in the volume counts. The possibility exists that the data given for the before conditions does not match the field conditions during the probe vehicle measurements.

A second possibility is that the simulation has accurate initial data and does not adequately reflect real-world operation. It is possible to gain some additional insight into this possibility. As part of the adaptive control study ITT Systems developed CORSIM models of the before conditions. The CORSIM results have a closer correlation to the proposed simulation results than the probe vehicle measurements. While both the proposed simulation and CORSIM may be incorrect it appears reasonable that the discrepancies result from inaccurate input data. At this time the PM comparison must be considered inconclusive in gauging the validity of the proposed solution.

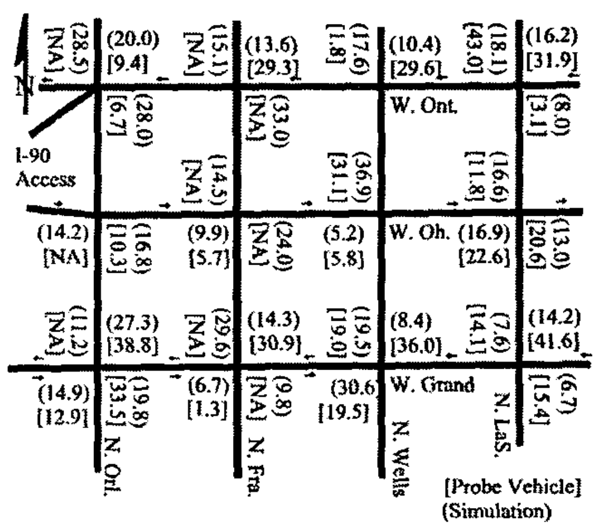


Figure 5: Chicago Simulation and Probe Vehicle Control Delay (sec/veh) - PM Peak (not-to-scale)

## 4 CONCLUSION

This approach to simulation has potential advantages over current widely utilized transportation simulation packages. While currently limited to intersection/arterial/network traffic analysis it is readily expandable to other aspects of the transportation system. Much of this expansion potential is a result of the hierarchical, object-oriented structure. When a user wishes to model a transportation system feature other than those directly accounted for, such as a toll plaza, such development may be done in-house or by third-party developers. All other current blocks may be used with the new toll plaza block(s). This "open architecture" approach frees a user from a dependence on the original developers.

The hierarchical nature of the model also allows for a minimal learning curve to initial model construction. One may quickly become efficient with tier 1 blocks, learning as little or as much as desired about the underlying logic, and still be able to construct realistic, highly capable models. As users desire to expand beyond the default tier 1 blocks they can learn and experiment with tier 2 and 3 blocks, performing more unique analyses.

Finally, the object-oriented approach to modeling represents a more "common sense" approach to simulation. From an individual's earliest experiences one typically views the world in terms of objects and how they interact with each other; from a toaster's interaction with bread, to a key's interaction with a lock, to a car's interaction with a traffic signal. Utilizing existing human mechanisms for viewing surroundings increases the likelihood of creating a more intuitive, understandable, efficient, and accurate simulation software package (Brown 1997).

Importantly, initial confidence may be placed in this simulation approach. The Chicago AM measured performance matches well with those simulated while the PM results are inconclusive. Combined with the CORSIM comparison results, a reasonable level of confidence in this modeling approach is warranted.

### 4.1 Limitations

While these initial efforts into this open architecture, object oriented approach to simulation are promising, there are limitations. These may be categorized into real-world traffic operations not captured and general limitations to the simulation approach. Traffic operations not yet captured include permissive phasing, vehicle lane changing to overtake slower vehicles, horizontal queuing, and freeway simulation. Many of these limitations may be overcome through the continued development of simulation objects, although some will be difficult to capture due to the more general limitations.

Possibly the most daunting general limitation is the underlying event-based nature of this approach. While event-based simulation is well suited to modeling signal control it is not nearly as apt at capturing some of the interaction of traffic flow. This weakness will become particularly constraining when attempting to model freeways. The event-based nature is the underlying reason for the current use of vertical queuing rather than horizontal queuing. Future effort on this simulation approach will include the incorporation of time-based simulation. Initial efforts will center on incorporating time-based modeling into the current ARENA platform although if this is not possible it will be necessary to move the hierarchical, object-oriented constructs to a alternative platform, if the simulation approach is to be further advanced.

Also, while this approach attempts to open the "black box" by allowing the user to add to and alter the underlying objects, it must not be assumed that this will be a simple task. To fully understand the model constructs, the user will have to devote time and effort into gaining an understanding of general simulation development and the underlying SIMAN language. Without this effort a user may still construct complex models using the tier 1 blocks, but the model will be no less a "black box" than the other available simulation packages.

As a last point this validation effort also highlighted the lack of availability of quality, real world data. There is a clear need for field studies with the express goal of developing data collection guidelines and obtaining data sets for the validation of transportation analytical and simulation models. This would not only be useful for validation of the proposed simulation model but also would provide a means for direct validation of the many other simulations that are used in practice today.

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