Discrete-Event Simulation for Optimization and Planning of an Intersection

Mahdi Safa, PhD, MBA
Seokyon Hwang, PhD
Steven W. McCrary, PhD, PE
Lamar University
Beaumont, Texas

Arash Shahi, PhD, PE
Shahin Karimidorabati
University of Toronto
Toronto, ON

The growing number of vehicles in urban areas has continuously increased road traffic congestion in most major cities around the world, resulting in the increase of travel time. Traffic congestion also significantly contributes to economic loss as well as air and noise pollution. Meanwhile, traffic congestion, particularly in the case of urban intersections, can be significantly reduced through effective traffic management. This study investigates discrete-event simulation as an effective tool to model the traffic flow in vehicular traffic junctions. A common discrete-event simulation software package, Simul8, was used in this study. A prototype traffic flow model was developed by modeling an existing three-way signalized intersection. This model was verified and validated using actual traffic data provided by the Region of Waterloo, including but not limited to, Traffic Flow Diagrams, Intersection Collision Data Sheets, Signal Timings, Pedestrian Crossings, etc. This study concludes that discrete-event simulation can be effectively utilized for modelling traffic flow in intersection junctions. This capacity enables one to conduct a number of important planning actitivites, including the calculation of maximum junction capacity and the evaluation of future expansion alternatives.

Key Words: Discrete-event Simulation, Traffic Congestion, Optimization, Planning, Intersection

Introduction

Traffic congestion presents direct and indirect costs and implications to the road users and the local economy. These costs include air and noise pollution, gas consumption, and delay costs due to slow vehicle flow. Many governments have heavily invested in improving their roads and in investigating new traffic control strategies (Czogalla et al., 2002; Safa et al., 2015). While there are various solutions for mitigating traffic congestion problems, the most common solutions remain to be construction of new roads and extension or expansion of existing roads (Bullough, 2013). On the other hand, an alternative solution is to improve the traffic flow through better traffic light management (Wen, 2008). Simulation, in general, has been known to be a powerful technique for modeling complex real-world systems and has been widely adopted in various domains to support the decision-making process (Akhavian and Behzadan, 2014; Safa et al. 2014). Computer simulation has been proven to be an effective technique for modeling and simulation of traffic flow (Hwang, 2009; Heaslip et al., 2009). Numerous applications of computer simulation suggest that the technique can be effectively applied to model and simulate traffic flow in urban road junctions as well. Simul8, which is developed mainly for construction-related modelling, has been marketed as a simple, yet powerful simulation system (Behzadan and Kamat, 2009). However, the domain independence of Simul8 suggests its potential benefits for modelling real-world systems in the areas beyond construction.

This paper investigates the application of Simul8 as a tool for modelling and simulation of the traffic flow in a signalized traffic intersection. The authors acknowledge the limitations of the software as well as the complexities that have to be overcome when these software packages are first used in a new and a considerably different application. Therefore, this study serves as a stepping stone for future research in this area and aims at providing sound ideas and strong foundations that pave the way for the application of discrete modelling techniques in traffic related contexts. The model presented in this paper was developed based on an existing three-way signalized intersection in Waterloo, ON. The use of the developed traffic model provides opportunities to analyze, predict, and control the behaviour of the local traffic system. This model is also expected to enhance measurement of traffic performance, such as throughput, delay and fuel consumption. The proposed model is verified and validated using actual traffic data provided by the Region of Waterloo, including Traffic Flow Diagrams, Intersection Collision Data Sheets, Signal Timings, Pedestrian Crossings, etc.

In order to investigate the potential of discrete-event simulation for modelling and optimization of traffic flow in construction projects, an urban vehicular junction is analyzed. This decision was made in order to be able to validate the model with data from the municipality and in order to be able to draw meaningful conclusions based on statistical data. Once the model is validated using the data from this particular intersection, it can then be easily applied to similar situations in the construction domain. This paper presents the model for the intersection of Keats Way and University Ave. in Waterloo, ON (Figure 1). Keats Way hosts a number of condominium buildings, a large number of off-campus student housings, and Keats Way Elementary School, which result in rather busy rush hours during the morning and afternoon commute but slow traffic flow at other periods. Although the sensors in the intersection work very well during night times and allow traffic signal controls based on current demands, this intersection has long periods of fixed time operation, i.e., from 8:00 AM to 8:30 PM. This intersection has become a major bottleneck for the traffic going from Keats Way to University Ave. eastbound during both morning and afternoon 'rush hour' periods. The main objective of this paper is to conduct a feasibility analysis for using a discrete modelling program from the construction domain, Simul8, for simulating the traffic flow by using a three-way signalized intersection as a case study. The published literature is limited on this particular application of Simul8 and thus, no benchmarks exist to compare the results of this work. The second objective of this paper is to serve as the basis for future work in this field against which the future findings will can be compared and evaluated. In order to achieve the aforementioned main objectives, three secondary objectives were identified: (1) to accurately model the existing intersection using real data from the Region of Waterloo; (2) to validate the existing model using a minimum of three different traffic flows and signal timing configurations; and (3) to perform sensitivity analysis on the existing model and to provide solutions for improving the current average waiting time of the traffic going through this intersection.

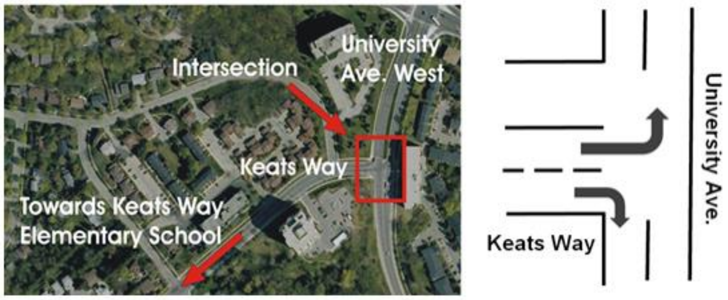


Figure1: Aerial view of the intersection

Research Methodology

In modelling this intersection, the following entities were observed: (1) buses, cars, and motorcycles driving through the intersection, which were considered as one type of vehicle, (2) the number of pedestrians crossing the intersection, which was very small and deemed negligible, (3) the data provided from Waterloo Region, which showed that the traffic rate in morning peak hour in the University Ave East Bound was considerably higher than that in the West Bound. However, this traffic rate switches from the East Bound to the West Bound in the afternoon peak hour. Figure 2 depicts the current traffic flow in the intersection modeled by Simul8.

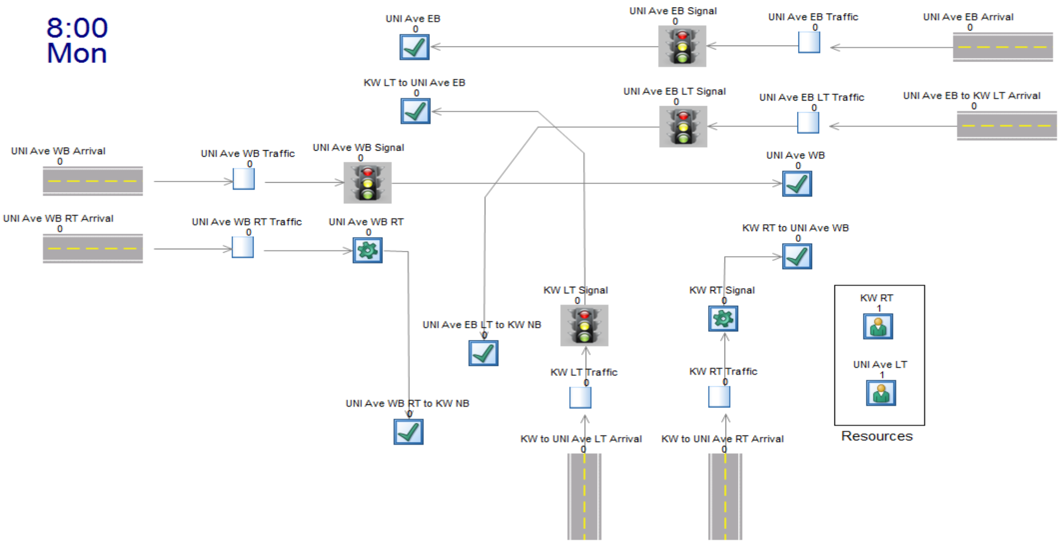


Figure 2: Current traffic flow modeled in Simul8

Data Collection

To properly develop the discrete-event simulation model of the University Avenue and Keats Way intersection, the following data is required: (1) Signal Timings, (2) Morning Peak Diagram, (3) Keats Way left-turn traffic signal service time, (4) Keats Way right-turn service time, (5) University Avenue East Bound and West Bound traffic signal service times, (6) University Avenue East Bound left-turn service time, (7) University Avenue West Bound right-turn service time, (8) Average maximum number of cars in the queue, and (9) Average waiting time. Signal timing in effect during the morning peak hour can be either collected by visually observing the intersection or using the signal timing data provided by Regional Municipality of Waterloo. Peak Diagrams are one of the best tools to calculate arrival rates at intersections. Daily traffics at intersections are often collected by municipalities' personnel to produce Peak Diagrams, Average Annual Daily Traffic (AADT), and annual traffic growth rates in different districts. In this study, the Morning Peak Diagram for the Keats Way and University Avenue intersection was provided by the Regional Municipality of Waterloo and used to calculate the arrival rates for different entry points at the intersection. In order to find out the peak hour, the municipality personnel collect data by counting the number of passing vehicles every 15 minutes. Next the personnel adds the 15-minute traffic counts from the beginning of the count period to find the one-hour traffic count. The process is repeated from the next 15-minute interval until the whole count period is covered. Then the largest one-hour traffic count delivers the peak hour. Figure 3 describes the data collection method.

Having the Morning Peak Diagram, the inter-arrival times (IAT) for different entry points at the intersection can be easily calculated. For instance, the IAT of vehicles intended to make a left turn at Keats Way to enter University Avenue East Bound can be calculated as follows: $IAT(\text{sec}) = 3{,}600/(No.of\ vehicles) = 3{,}600/393 = 9.16\ sec/veh$. Since the peak hour is equal to 3,600 seconds, 3,600 is divided by the number of vehicles arriving at the entry point, results in the IAT. The IATs are then used in the simulated work entry points with exponential distributions. If necessary the IAT can be categorized based on the type of vehicles. For instance, the arrival rate of heavy vehicles, trucks, and cars in the aforementioned entry point during the peak hour were 12, 7, and 374, respectively. To collect the data for traffic signals' service time, the research group visually monitored traffic lights and traffic flows at the intersection. After a considerable queue length was built up behind the red light, the effective green time upon turning to green for emptying the built-up queue was recorded.

One of the metrics for verifying the simulation model is the average maximum number of vehicles in the queue. In order to collect this data, the number of vehicles waiting behind the red light was counted for numerous cycles and its average is calculated. This average value is then compared with the simulation results to verify the model. For the verification purpose, it is possible to compare the average queue length rather than the average maximum queue length. However, collecting average queue length data is more difficult as compared to maximum queue length, because the average queue length data should be collected at random times during each cycle to avoid biased input data. In this study, the average maximum queue length is used as a metric for validation. Similar to the average number of vehicles in the queue, the average waiting time should be collected for random vehicles in the system. Accordingly, a random vehicle was selected and its waiting time was recorded. Next, the average waiting time was calculated. Two main challenges observed during the data collection period were as follows: (1) the influence of the date and weather condition on the data collected for the intersection and (2) incorporation of randomness during data collection. This intersection becomes more congested during the fall and winter time when both the local university and the Elementary school are open. Thus, collecting data in the summer time, when the volume of traffic is not high, was avoided in order to model the busiest times of the intersection. Also, in order to avoid biased input data, some of the required data, such as waiting times or average queue length, should be observed randomly.

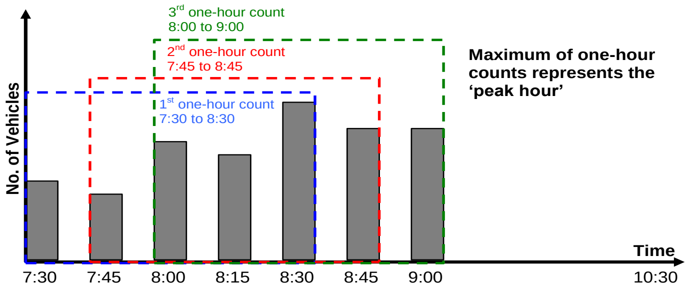


Figure 3: Peak hour traffic count and data collection method

Verification and Validation

The discrete-event simulation model of the University Ave. and Keats Way intersection involves two types of input data: inter-arrival times and service times. Since IAT represents the times between the arrivals from a large calling population (vehicles) who act independently of one another, IAT can be assumed to be 'exponential' and the arrival process to be Poisson. Figure 4 shows major events, flows, and the overall logic of the proposed simulation model. In order to verify the simulation model, simulation results for one-hour simulation time was compared to the morning peak hour traffic from the utilized Peak Diagram. Figure 5 presents some of the information that can be obtained from the animated model. Verification methods introduced in this section have been used to verify both system alternatives and their corresponding models. In addition, sensitivity analysis was conducted to check if the model behaves in the expected way. The sensitivity analysis showed that the addition of the second lane resulted in only an 8% improvement in the average wait time on Keats Way. However, it is important to note that the existing model assumes that all of the vehicles passing the intersection when the light turns green waited at the intersection for the full length of the red light preceding that green light. In reality that is not the case and, on average, vehicles wait only at the red light for approximately one third of its duration, because of the arrival distribution of vehicles ars at the intersection. Taking this into account, introducing the second lane, which does not have any significant implementation costs, reduces the average waiting time on Keats Way by approximately 25%. This is an example of the powerful capabilities of discrete modelling techniques in traffic management applications. Another important capability of the model offered in this paper is its ability to plan future traffic flow in the intersection. The number of cars that travel the intersection can be increased and the maximum number of cars than can get through the intersection, for example in one hour, can be calculated. Figure 6 shows the estimated 1,230 vehicles in total for 3,600 seconds (1 hr), indicating that under ideal conditions, this intersection can only accommodate 1230 cars per hour from Keats Way. The same method was applied for all three legs of the intersection, so as to estimate the theoretical maximum capacity values.

The model is also validated based on the average maximum queue length metric. The validation and statistic set includes comparing the system response, namely the average maximum queue length (MQL) and the model responses. Based on data collected at the intersection, the average maximum queue length at Keats Way left turn lane was equal to 6.76. Accordingly, a statistical test of the null hypothesis: $H_0: E(MQL) = 6.76$ versus $H_1: E(MQL) \neq 6.76$ can be conducted. If H_0 is not rejected, then, on the basis of this test, there is no reason to consider the model invalid. In order to perform this test, four replications are used. Since Simul8 does not give a direct output as the average maximum queue length, the average is derived from the queue graphs. For instance, as shown in Figure 7, all of the peak points represent the maximum queue length and the average. It also shows the results (tabulated) of four replications of the intersection model. In each replication, around 25 maximum points are observed and their average values are represented. Test statistics: $t_o = (Mean(E(MQL) - \mu\_0)/(S/\sqrt{n}) = (6.198 - 6.76)/(0.625/\sqrt{4}) = -1.74$. For the two-sided test (significance level of 0.05), $t_{\alpha/2,n-1} = t_{0.025,3} = 3.18$. Since $|t_0| = 1.74 > 3.18$, the null hypothesis is not rejected; thus, the model is valid for prediction of the behavior of the real system.

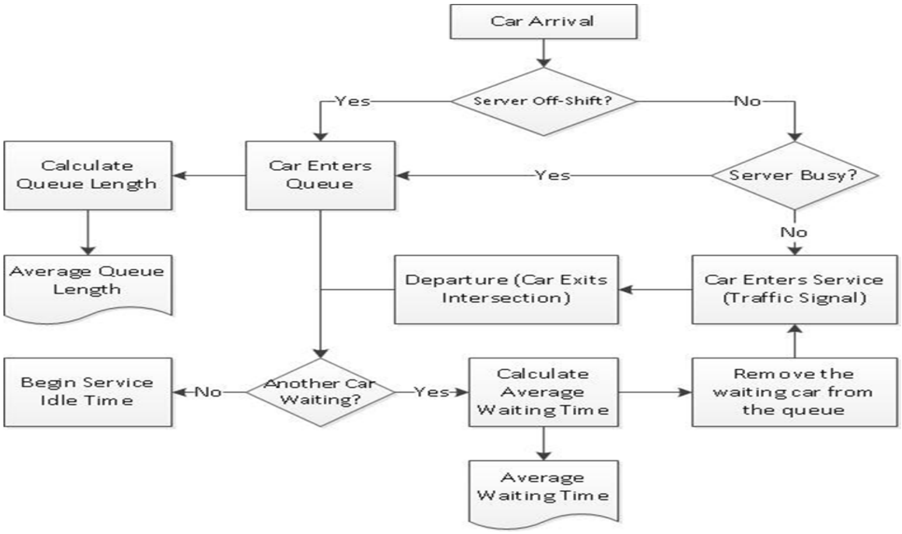


Figure 4: Conceptual flow diagram

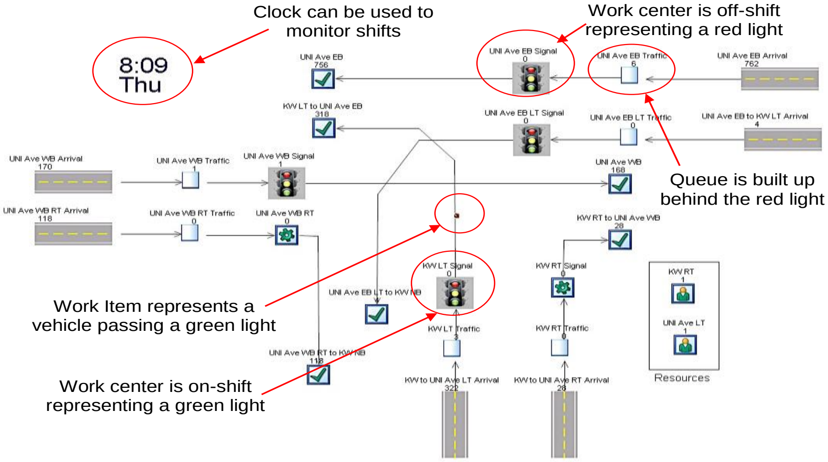


Figure 5: Model verification using animated simulation

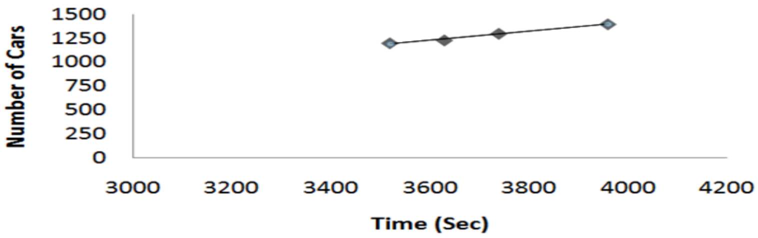
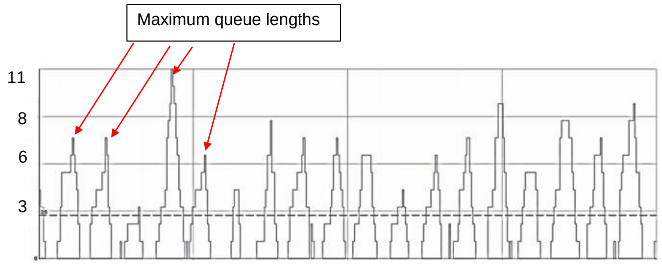


Figure 6: Maximum traffic capacity of Keats Way



Replication	E(MQL)
1	6.30
2	5.70
3	7.04
4	5.75
Mean	***6.198***
St.Dev	***0.625***

Figure 7: Collecting data on average maximum queue length from Simul8 and results of four replication of the intersection model (KW MLQ)

Discussions

The main objective of the simulation of University Ave. and Keats Way intersection is to compare the effect of using a new system alternative with two left turn lanes with the current system. In addition, effects of different signal timings are investigated in two alternatives. Alternative 1: Using the right-left shared lane in Keats Way. Alternative 2: Signal Timing Changes. Based on the available traffic information such as peak diagrams and average annual daily traffic (AADT) from previous years, and also with regards to population growth in the area of Waterloo, the annual traffic growth rate in the region is estimated to be about 2%. Using this annual traffic growth rate, the arrival rates for future years can be projected and performance of both system alternatives can be compared. Key Performance Indicators (KPIs) for this model are (1) Utilization Rate: Using the current traffic model, the capacity of Keats Way is 609 vehicles per hour and is expected to be reached by 2035. At that point the utilization rate of the Keats Way left turn would be around 99.47%. (2) Average Waiting Time: Another possible milestone for determining the capacity can be the level of service of the Keats Way traffic. A good KPI for serviceability is the average waiting time for cars in the queue. Accordingly, it can be assumed that the minimum level of service (LOS) for the KW is 50 seconds of average waiting time, and based on this KPI the current system reaches its maximum capacity, which is 563 vehicles, by year 2030.

Any of the above methods can be used to calculate the capacity and to determine the performance of the current system. Following figures show the expected values for average waiting time, average number of vehicles in the queue, and the utilization rates for KW left turn traffic using the current system. By using the alternative traffic model, the capacity is calculated and proved to increase significantly from 609 vehicles to around 1220 vehicles based on the first KPI (utilization rate), and from 563 to 1171 based on the second indicator. Using the second alternative also proved to be able to increase the service life of the system from 2035 to around 2070 (Figure 10). It is important to note that it is possible that KW reaches its maximum capacity much earlier than the dates presented here due to increasing growth of residents in this area. This study proves that allocating one lane for left turns and sharing the right lane for both left and right turn is a good approach to mitigate this problem at this time, specifically because there is no infrastructure related cost associated with this change. In addition, regional municipality of waterloo can add an exclusive right turn lane and allocate both existing lanes to left turn. However, this alternative seems to be much more costly. Following figures show simulation results for the second alternative and its influence on the system performance.

Investigating the effects of signal timings is another objective of this project. The project seeks to find an optimal timing for the green lights at the intersection, while keeping the cycle time unchanged (i.e., 110 seconds). This is to maintain the integrity of the road network, which is related to the cycle time. In addition, since clearance time is regulated by law, it cannot be changed and set to 6 seconds as before (2 sec for all red and 4 sec for amber). An optimum signal time is investigated for the current situation from two perspectives: First viewpoint defines the optimum signal timing as the timing that results in similar traffics in both University Ave. and Keats Way. In other words, this timing balances the traffic and avoids congestion in both roads. In order to investigate the signal timings, the shift times are changed in the model and required simulation outputs, such as average queue size, are recorded. Figure 11 shows the effect of different signal timings on University Ave. and Keats Way. All timings are added up to 110 seconds including clearance times or 98 seconds for green light. As seen in the figure, the optimum signal timing is found to be 36 seconds for Keats Way and 62 seconds for University Ave. (36/62). The second viewpoint, seeks an optimum timing that can be used in special conditions when the traffic in University Ave. becomes so heavy and nearly saturated. Such conditions can result from construction work in the adjacent thoroughfares, or collisions. In this case, an optimum timing is defined as a timing in which the utilization of Keats Way is at the highest possible point (occurs by decreasing KW's signal time) and the capacity of University Ave. is at its maximum (occurs by increasing the University Avenue signal time). In this case the best timing is 30 seconds for Keats Way and 68 seconds for University Ave. (30/62). Using this timing the capacity of University Ave. can be increased up to 35% from 948 to 1285. Using this timing, Keats Way utilization rate is around 97% and the capacity of University Ave. is maximized. It is important to note that the same procedure can be used to define an optimum timing while the traffic of Keats Way is so congested due to collision or construction work.

The authors refer to the following points as the lessons learned while simulating the project under consideration: (1) simulating a real project while considering every detail of it makes the simulating process extremely complicated. Thus, inconsequential data can be ignored without compromising the results. For instance, the pedestrians due to their very low rate of crossing, was found negligible; (2) accessibility to proper and accurate data is a vital artery for data input and leads to accurate output and result for the model. Research group benefited greatly from having access to the most recent empirical data of the intersection and accurately collected in-place data; (3) a clear definition of objectives and their level of practicality is of paramount importance at the proposal phase; (4) While working with this particular modelling environment was very effective, future research can compare its effectiveness with EZStrobe, another discrete modelling platform familiar to the construction industry.

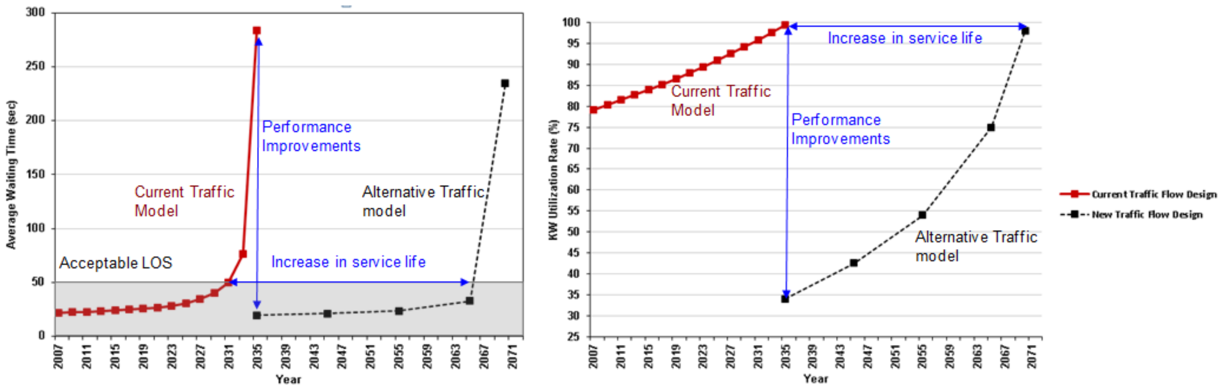


Figure 9: Improvements in average waiting times and utilization rate using the 2nd system alternative

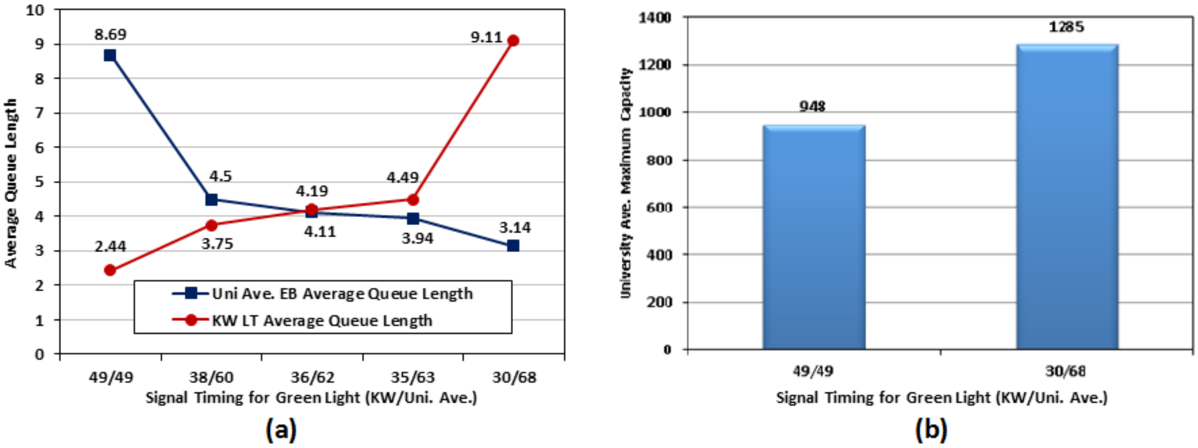


Figure 10: (a) Optimum signal timing by equating traffic congestion, (b) Maximizing the capacity of University Ave. by optimum signal timing of Keats Way

Conclusions

This paper investigated the use of a discrete modelling tool, Simul8, in modelling the traffic flow in a three-way signalized intersection. It was concluded that, although Simul8 is claimed to be domain independent, the underlying principles of the software are more compatible with construction or manufacturing related applications rather than traffic related situations. Despite its challenges, the model was successfully used for sensitivity analysis and for investigating what-if scenarios and simulated the intersection relatively accurately as demonstrated by the verifications performed. This study also investigated two system alternatives and their influence on the intersection performance. The first alternative, which changed the right lane at Keats Way to a "shared left and right" lane proved to be very effective and increased the capacity of Keats Way by approximately 100%. The second alternative, investigated the effect of signal timing changes on the model and showed that it was possible to obtain similar advances by changing the current timings to 36 and 62 second for KW and University Ave., respectively. It is also possible to maximize the capacity of University Ave. in special conditions such as collision or construction work by changing the current timings to 30 and 68 second for KW and University Ave. respectively. Although discrete modelling platforms are not commonly used for traffic studies, this study showed their effectiveness for modelling vehicular intersection crossings. Meanwhile, in order to draw a general conclusion regarding the applicability of discrete-event simulation for planning and optimizing an intersection, additional simulations at different intersections may be needed. For further validation of the approach, it needs to be compared with other existing methods to evaluate relative effectiveness of the approach. These two tasks are expected to be carried out in the future study.

References

Akhavian, R., & Behzadan, A. H. (2014). Evaluation of queuing systems for knowledge-based simulation of construction processes. *Automation in Construction*, 47, 37-49.

Behzadan, A. H., & Kamat, V. R. (2009). Automated generation of operations level construction animations in outdoor augmented reality. *Journal of Computing in Civil Engineering*, 23(6), 405-417.

Bullough, J. (2013). Development of a Guide for Replacement of Roadway Lighting with New Lighting Technologies. *Transportation Research Record: Journal of the Transportation Research Board* 2384, 95-101.

Czogalla O., Hoyer R., and Ulrich J. (2002). Modelling and Simulation of Controlled Road Traffic. *Lecture Notes in Control and Information Sciences*, Vol. 279, 419-436.

Heaslip, K., Kondyli, A., Arguea, D., Elefteriadou, L., Sullivan, F. (2009). Estimation of freeway work zone capacity using simulation and field data.Transportation Research Record 2130, 16–24.

Hwang, S. (2009). Dynamic Modeling Impact of Lane Closure on Traffic. *Proc. of the 26th Int. Symposium on Automation and Robotics in Construction (ISARC), Austin, Texas, June 24-27, 2009, 562-569.*

Safa, M., Sabet, A., Ghahremani, K., Haas, C., and Walbridge, S. (2015). Rail corrosion forensics using 3D imaging and finite element analysis. *International Journal of Rail Transportation*, (ahead-of-print), 1-15.

Safa, M., Shahi, A., Haas, C. T., & Hipel, K. W. (2014). Supplier selection process in an integrated construction materials management model. *Automation in Construction*, 48, 64-73.

Wen, W. (2008). A dynamic and automatic traffic light control expert system for solving the road congestion problem. *Expert Systems with Applications*, 34(4), 2370-2381.