ANALYZING POTENTIAL SOLUTIONS FOR TRAFFIC CONGESTION AT THE INTERSECTION OF FOREST AND SR-89A IN SEDONA, AZ USING TRAFFIC MODELING SOFTWARES

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Abstract: Gathering the necessary information required to tackle traffic congestion problems is generally time consuming and challenging but is an important part of city planners' work. The purpose of this paper is to describe the methodology used when analyzing potential solutions for the Arizona State Route 89A and Highway 179 roundabout in Sedona, Arizona; which is currently experiencing significant congestion. The oversaturated condition is typically applied to signalized intersections but its application to roundabouts requires further exploration for future management of similar transportation systems. The accompanying QESM (Quick Estimation and Simulation model) spreadsheet was calibrated using an iterative process to optimize its level of adaptability to various scenarios. This microsimulation modeling program can be used to predict the outcome of possible roadway improvements aimed at decreasing traffic congestion. The information provided in this paper helps users understand traffic system problems, as a primary to visual simulation programs.

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I. Introduction

A. Project Origin

Located at the intersection of Arizona State Route 89A and Highway 179, is a two-lane roundabout that causes significant congestion in Sedona, Arizona. The backup caused by drivers turning right from Highway 179 onto Arizona State Route 89A negatively affects the ability of travelers to easily navigate through Sedona on their way to popular hiking destinations such as Slide Rock State Park. This was the problem presented by the Arizona Department of Transportation engineer as expressed by the representatives from the City of Sedona requesting changes be made.

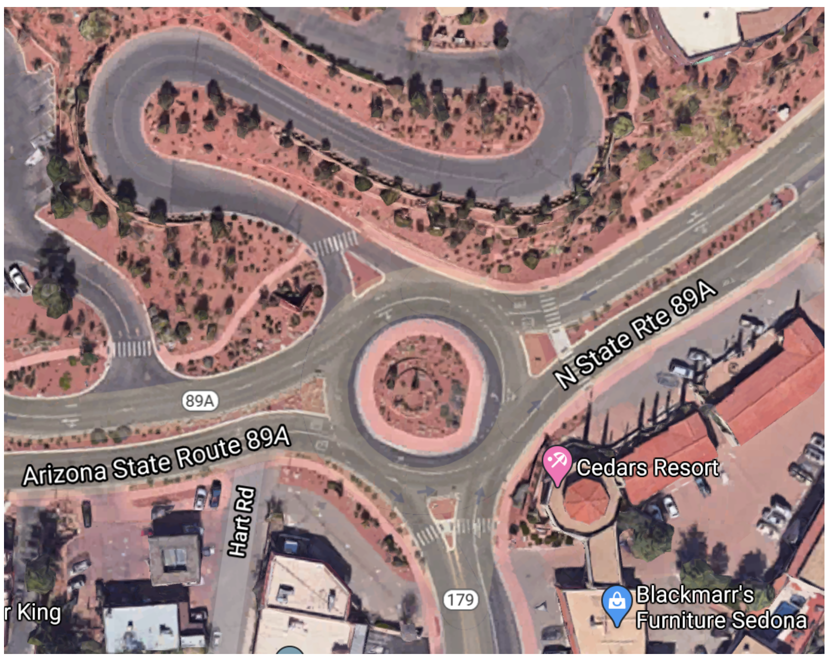


Figure 1: Vicinity Map (Source: Google Maps)

The City of Sedona is aware of the issue and is looking for ways to improve the roundabout without causing any adverse impacts to the businesses along SR-89A. This roundabout is heavily trafficked by tourists trying to reach Oak Creek Canyon, meaning that every person who wants to access those trails and its offered tourist attractions must travel through it. Since the traffic congestion in the City of Sedona does not closely resemble the normal peak travel times most cities in Arizona experience, it presents a unique opportunity to test the adaptability of traditional traffic generation software. The Arizona Department of Transportation has jurisdiction over the roundabout in question but is working closely with the city to formulate a solution to the problem.

B. Scope

The purpose of this report is to provide the Arizona Department of Transportation (ADOT) with the necessary background information for understanding how to accurately utilize the developed QESM (Quick Estimation and Simulation Model) spreadsheet in place of other time-consuming and costly traffic simulation software. The provided QESM spreadsheet offers users the opportunity to identify the problems caused by a particular intersection without having to exhaust resources on building a simulation and then altering it post-design to test its effectiveness. The goal is to increase the efficiency of solving oversaturated traffic flow problems by presenting ADOT with an alternative traffic generation software that can be used to analyze potential solutions with ease.

C. Significance

According to the Federal Highway Administration, roundabouts should be operating at 85% capacity (FHWA, p.86). The current roundabout geometry notably exceeds this limit, as does most of the transportation infrastructure in the Phoenix Metropolitan area. In 2018, Phoenix was named the fastest growing city in America, according to the United States Census, and currently stands at the fifth largest city in the United States. Since the City of Sedona is a popular tourist destination for both locals and visitors, this increase in population density has also negatively impacted their existing transportation infrastructure. The approach in implementing an analysis software should increase internal efficiency in evaluating the current state of various intersections, and allow the user to alter variables, based on the outcome of proposed improvements, in order to test their impact on limiting delays caused by congestion. The QESM spreadsheet is versatile enough that it can be calibrated and applied to evaluating roundabouts or signalized intersections for any city's peak travel time patterns.

II. Background Information

A. Roundabout Characteristics

The defining features of a roundabout are its circular structure and continuous flow pattern. According to the Federal Highway Administration, a roundabout has "channelized approaches, yield control on all entries, counterclockwise circulation of all vehicles around the central island, and appropriate geometric curvature to encourage slow travel speeds through the intersection" (FDHWA, 2010). The primary appeal of roundabouts is the uninterrupted movement drivers experience when operating under the maximum capacity. This results in shorter delays than those caused by signalized intersections because there is no mandated stopping period. Additionally, the center islands can be used to enhance the aesthetic appeal of the intersection, which is especially important in popular tourist areas like Sedona. The Federal Highway Administration also cites roundabouts as a common way to transition drivers "between high-speed rural and low-speed urban environments;" which is a large reason why the intersection in question is used as a transition between SR 89A and 179 (FHWA, 2010). However, there is a learning curve when it comes to roundabouts as many American drivers do not commonly encounter them during their day-to-day travels. This can cause unwanted stopping and occasionally accidents. Also, particularly in this case, on-street parking inhibits the constant flow causing unnecessary back-up because there is no time that exists where vehicles are not allowed to enter the intersection as they please. Applying alterations to an already existing roundabout is costly, which is why it is important to consider all possible solutions before committing to one.

B. Oversaturated Condition

The oversaturated condition is typically associated with signalized intersections, but the same principles can be applied to roundabouts. The National Academy of Science defines the oversaturated condition as any situation when approach movement "causes 'detrimental effects' to one or more of the other movements served by the approach" (NAS, p.17). Where, an "approach" is "a combination of compatible traffic movements that serve traffic in the same direction of travel" (NAS, p.17). The period before a queue begins formation is known as the loading period and the period when the queue begins to dissipate is known as the recovery period (see *Figure 2* below).

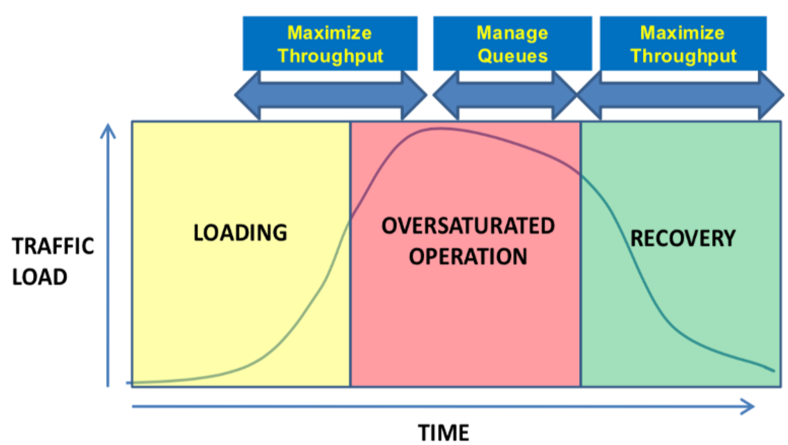


Figure 2: The Oversaturated Condition Diagram (Source: Figure 2 from *Operation of Traffic Signal Systems in Oversaturated Conditions,* FHWA pg. 12)

Oversaturated essentially implies that the traffic system is operating over its maximum capacity. This will inevitably result in some sort of overflow. Any congestion caused by this overflow will trickle into the downtown sector, making it a frustrating experience for both drivers and pedestrians trying to navigate Downtown Sedona. Overflow begins during loading and decreases during recovery. The oversaturated condition cannot simply be solved by increasing capacity. It is a unique challenge that requires creativity.

III. Methodology

A. QESM (Quick Estimation & Simulation Model)

The QESM spreadsheet is a microsimulation model that offers users a simple method for predicting the outcome of future transportation improvements. QESM is an extension of Dr. Zlatkovic & Dr. Zhou's signal timing estimation model known as the Quick Estimation Model (QEM). QESM is an extension of the work created by these two researchers in an effort to extend its application beyond signalized intersections. The QESM model is only evaluating the incoming and outgoing flow traveling through an intersection, it does not take into account yield or signalized time constraints because the approach method does not affect the output given by the spreadsheet. It is important to note that due to time sensitivity, the QESM spreadsheet is currently only operational for evaluation of a single approach. The upcoming calculations were all completed under the assumption that only one lane exists, even though the roundabout in question does have two lanes. This is because only one approach was being analyzed to develop a strong basis for future improvements to the QESM model given more time to research and expand its capabilities. Below is the core model, which defines the interaction of all the important variables used in the development of the simulation model.

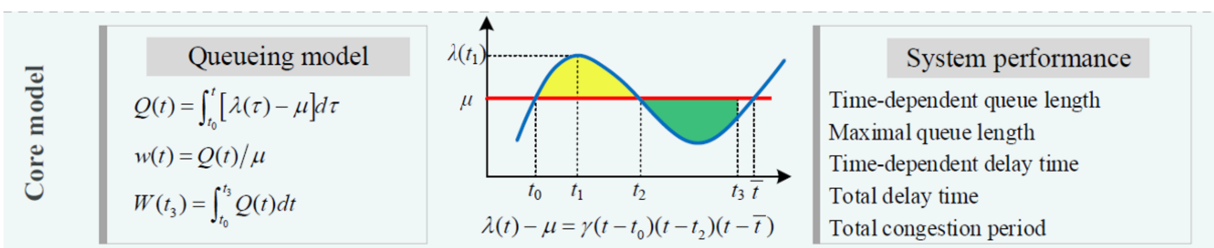


Figure 3: Core Model (Source: "A multiscale demand and supply model for oversaturated dynamic transportation queuing systems")

Although the methodology used when optimizing the QESM spreadsheet went through several variations before reaching its final form, the principles in *Figure 3* remained the same throughout the entire process. To evaluate system performance, time-dependent queue length, maximum queue length, time-dependent delay time, total delay time, and total congestion period were all analyzed (Cheng, Liu, & Zhou, 2020). The two factors that impact the system performance outcomes the most are the arrival rate, $\lambda(t)$, and the discharge rate, $\mu(t)$. The netflow traveling through the proposed area of interest is therefore:

$$Netflow = \lambda(t) - \mu(t) \tag{1}$$

The most significant events of the travel cycle occur at the locations where the arrival rate is equal to the discharge rate.

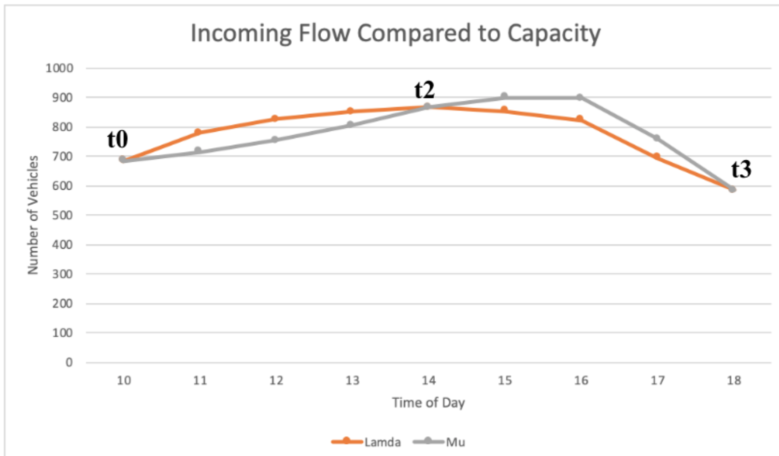


Figure 4: Inflow vs. Outflow

The time of day when the arrival rate is first equal to the discharge rate, and is headed towards exceeding maximum capacity, is defined as t_0.The second time when arrival rate is equal to discharge rate, t_2, marks the time of day when queue length is at its maximum. Lastly, $t_3$is the third and final time of the day when the number of incoming vehicles is equal to the number of outflowing vehicles. This is when the queue has dissipated. All time parameters, t_0, t_2, and $t_3$are to be defined by the user. When given reliable traffic counts, these values are easily identifiable and can be confirmed using historical traffic data. All primary variables used are defined in *Table 1* below:

Table 1: Parameters and Description

Parameter	**Description**
$\mu(t)$	Outflow (Discharge Rate)
$\lambda(t)$	Inflow (Arrival Rate)
Q(t)	Queue Length
w(t)	Waiting Time (Delay)
γ	shape parameter
t_0	Time at which queue begins formation
t_2	Time at which maximum queue occurs

t_3	Time are which queue dissipates

All variables were defined using both Google Maps, as seen in *Figure 5*, and the signal timing data provided by the ADOT for the intersection of SR89A & Forest Rd. The values given for t_1, t_2, and t_3 were chosen based on the historical congestion times and surveyance of all traffic counts.

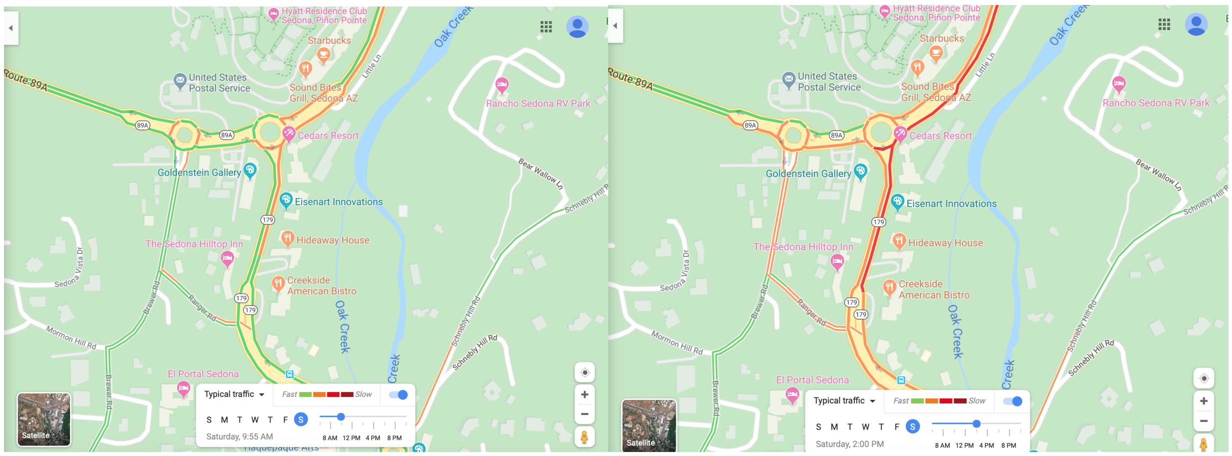


Figure 5: Google Maps Aerial Images (Sample traffic delay on a given date and time. The image above is a representative Sunday, May 4, 2018)

Ultimately, the times of day chosen as the peak times of interest are included in the table below:

Table 2: Significant Time Stamps

Variable	Description	Time of Day
t_0	$\lambda(t_0) = \mu(t_0)$	10:00
t_2	$\lambda(t_2) = \mu(t_2)$	14:00
t_3	$\lambda(t_3) = \mu(t_3)$	18:00

When deciding these times, the following information was considered:

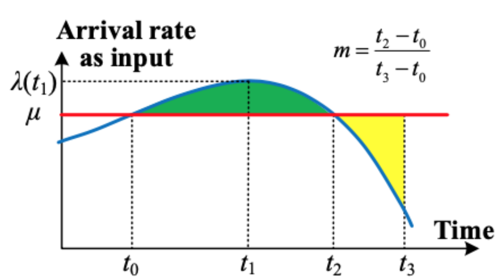


Figure 6: Arrival Rate as Input (Source: "A multiscale demand and supply model for oversaturated dynamic transportation queuing systems")

The time variables were chosen so that the parameter m was equal to 0.5. The value of 0.5 was chosen because the peak queue is located at the middle of the analysis period. Dr. Cheng, Dr. Liu, and Dr. Zhou in their paper “A Multiscale Demand and Supply Model for Oversaturated Dynamic Transportation Queuing Systems,” discuss the possible acceptable values that may be used for m based on their detailed research findings. Acceptable values for m include: 0.5, 0.66 and 0.72. The selected m value is dependent on what time of day the queue is the greatest.

The observed waiting time, $w(t)$, was calculated using the following equation, which was adapted from the equation used to estimate expected delays caused by work zones on freeways (Jiang, 2001).

$$w(t) = segment\ distance\left(\frac{1}{v_{congestion}} - \frac{1}{v_{freeflow}}\right) \qquad (2)$$

This value was used to evaluate error during the calibration process to ensure it was comparable to the approximated waiting time and simulated waiting time. This was only one method used to test for accuracy. For example, if the area of interest has a free-flow speed of 25 miles per hour, even though the roundabout in question has an advisory speed of 15 miles per hour, and the vehicles during peak traffic are forced to move at a congested speed of 5 miles per hour over a segment distance of a half mile, the observed waiting time would be 0.08 hours or 4.8 minutes. The congestion speed in the QESM Sedona model were assigned values based on the color given at a certain time of day as provided in the ADOT heat map traffic counts from the intersection of SR89A & Forest Rd.

The outflow rate, $\mu(t)$, also known as the capacity, was first assumed by averaging all provided traffic counts. Since the outflow rate is time-dependent just like the inflow rate, it was determined to not be a constant value. This conclusion took several iterations of the QESM spreadsheet to reach and was obtainable because of the City of Sedona’s abnormal traffic patterns. Originally, a constant capacity of 773 vehicles, the average of all incoming vehicles throughout the day, was assumed. However, after drawing a plotting the flow curves, there was a large deviation between t_0 and t_3, unlike the image shown in *Figure 3.* The assumption of μ being a constant value was switched to the assumption of it being a time-dependent variable, resulting in further exploration into the calibration and resulting simulation output of the QESM spreadsheet. The calibration steps taken will be explained later in *Significant Findings*. Time-dependent outflow, $\mu(t)$, is calculated using the following equation:

$$\lambda(t) - \mu(t) = \gamma(t - t_0)(t - t_2)(t - \underline{t}) \qquad (3)$$

The arrival rate approaching the congested area can be approximated by a polynomial function (Cheng, Liu, & Zhou, 2020). Using this value, the time-dependent delay can be calculated:

$$w(t) = \frac{1}{4\mu}\gamma(t - t_0)^2(t - t_3)^2 \quad (4)$$

The shape parameter γ, cannot be a negative value. This value is estimated and then optimized for the minimum value using the programs built-in solver feature. The time-dependent queue length can then be calculated as follows:

$$Q(t) = \frac{1}{4}\gamma(t - t_0)^2\,(t - t_3)^2 \quad (5)$$

Queue length is a function of the inflow minus the outflow integrated over the analysis period. The reflected value represents the area under the curve (see *Figure 7* below).

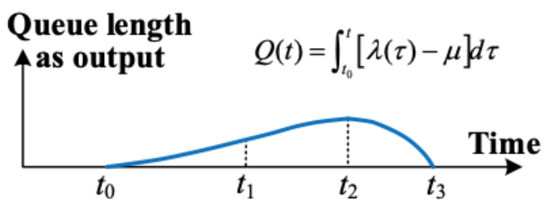


Figure 7: Queue Length as Output (Source: "A multiscale demand and supply model for oversaturated dynamic transportation queuing systems")

The figure above offers an additional alternative to verifying the accuracy of the selected analysis period.

Calibration was required to ensure versatility of the program when applied to different scenarios.

Step 1: Calibration based on continuous-time queueing model

Input: λ(t), Q(t), t_0, t_3

$$Q(t) = w(t) * \mu \quad (6)$$

Output: $\mu(t)$

Process:

1. Find shape parameter, γ, and back calculate the inflow rate, $\lambda(t)$ using equation 5 above.
2. Define the following equation:

$$X = \frac{1}{4}(t - t_0)^2\,(t - t_3)^2 \quad (7)$$

And Y as Q(t) for optimal linear regression,

$$Y = \gamma * X \quad (8)$$

To obtain γ.

3. Find $\mu(t)$ by defining equation 3 as "Netflow." As a result,

$$\lambda(t) = \mu(t) + Netflow(t) \qquad (9)$$

Step 2: Simulation and validation based on discrete-time queueing model

Process:

1. Simulate possible changes in queue length given changes to capacity using the following equation:

$$Q_s(t+1) = Q_s(t) + \lambda(t) - \mu(t)$$

(10)

2. Find time-dependent approximated waiting time:

$$w(t) = \frac{Q_s(t)}{\mu(t)} \qquad (11)$$

3. Compare calculated time-dependent queue length and discharge rate values:

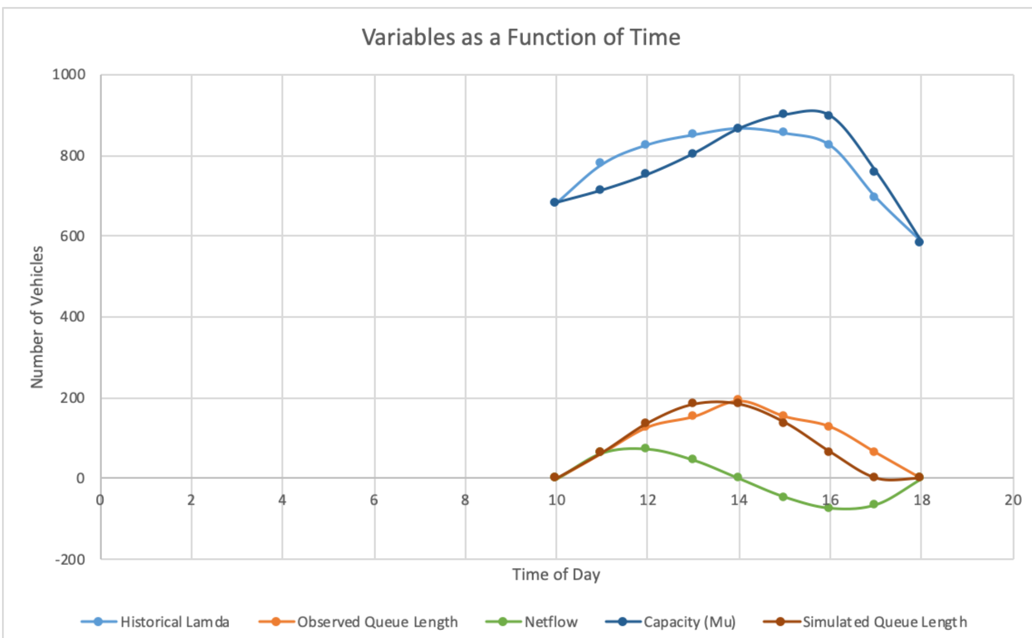


Figure 8: Q(t) & $\mu(t)$

Step 3: Simulation for new scenarios using discrete time model

Process:

1. Test different values for discharge rate to perform simulation runs and directly obtain the results.

2. Possible inputs: $\lambda(t), \mu(t), \Delta\mu(t)$
3. Obtainable outputs: $\mu_{new}(t), Q_{s_{new}}(t)$

Step 4: Set-up the macroscopic node-link model using GMNS format (See the section *Future Research* for more information).

Step 5: Set-up microscopic car simulation model. For example, SUMO.

As far as the QESM solving method goes, its implementation would be most appropriate given proper recording of incoming traffic. The recommended method of collecting traffic counts to be used is a 3 point sensor system to capture the number of cars entering and exiting the traffic system at the beginning, midpoint, and end of the area of interest to get the most accurate representation of how they are behaving with time. The primary obstacle is avoiding the midpoint sensor being treated as a discharge rate during congested periods of time, and an inflow rate during periods of free-flow travel. This is later discussed further in *Significant Findings*.

B. SUMO

SUMO is an open-source, continuous traffic simulation package design to handle road networks of various sizes. Both NetEdit and SumoGui were used in the beginning stages of this project in order to visualize the traffic count data given. The steps in creating a network are outlined in Appendix A. It was quickly realized that an iterative process was needed to accurately model the network to match data given. Instead, the analytical model shown previously was switched to in order to interpret the data given to have a representative time-based system that could identify queue lengths. In this respect, the SUMO program was not able to analyze a system for queuing, only to generate it. By switching to the analytical model above, we were able to first identify important queue lengths and times to later be implemented into a model. If time had permitted during this project, SUMO could have been revisited as a simulation package that would have worked to support traffic congestion models. More than supporting findings found for traffic congestion, the program can also be used as a way to visualize overall traffic queues.

C. Google Geo Charts

Further analysis of the project can be extended to incorporate Google Maps' geographic cell information. An open-sourced project run by Sidewalk Labs aims to reproduce S2 cells generated by Google. Cells of varying sizes, of 30 levels, are blanketed over the globe and depending on the level observed, range from within an intersection on the highest level to across an ocean on the smallest.

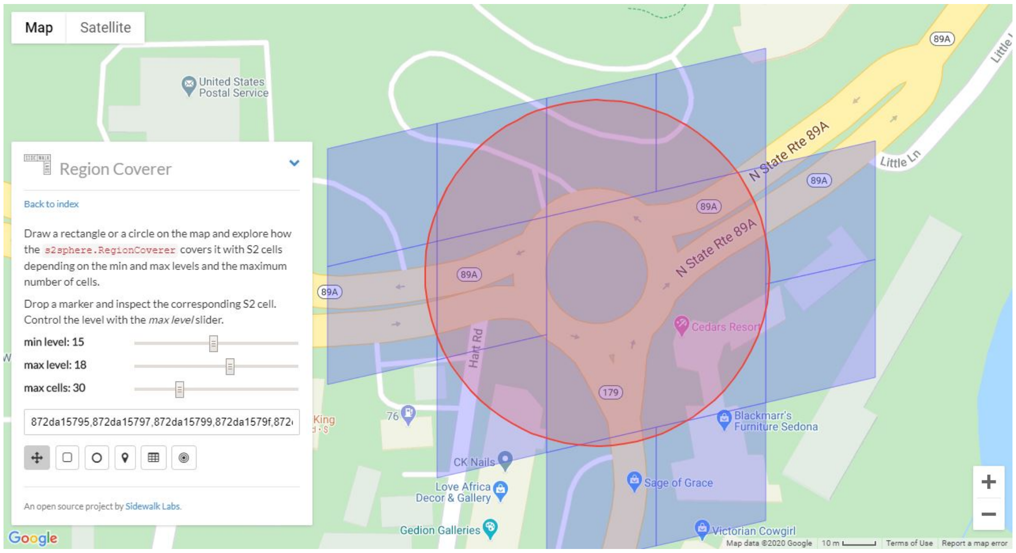


Figure 9: *Region Coverer* (Source: Sidewalk Labs)

Such information and technology have already been implemented in augmented reality games where players can interact with their environment based on their location and that position's relation to the surrounding area. This can easily be extended to the analysis of traffic flow and something that can be modeled as inflow/ outflow out of cells. An area of any size can be selected by location of interest, shape, size, or area of travel. Cell "codes" are given in level and cell location and can accurately describe any region selected on any macroscopic scale. In fact, many ride-share services already use this technology to varying degrees. Each system is run internally however, and "cell" information can vary from one intellectual property to another. Such things as shape chosen (rectangular here, but such shapes as hexagonal, triangular, or trapezoidal have been used) and level definition can inhibit cross-platform information sharing. A universal cell coding system could be defined to more easily share such things as flow information, queue lengths, etc. Current observational technology is already in place, it is the data processing that will inhibit future incorporation of traffic flow information. Future processes including automated driving, real-time traffic analysis, etc. could benefit from the traffic analysis methodology studied here and the incorporation of it to a cell-based grid system.

IV. Summary of Results

A. Calibration and Verification

One verification that the system accurately modeled for the data and roadway chosen was the constant shape factor seen in *Table 3*. The shape factor is representative of the roadway design of the intersection and is independent of the in- and outflow rate through it. The model utilizes back calculation of the arrival rate to find the value of γ. Since all scenarios tested yielded a constant γ for each season and all seasons together, it can be concluded that this value is accurate. Recommendations for reductions in the shape factor γ are given in the *Recommendations* section of this report, as ways to decrease overall queue length.

Table 3: Calibration Results Extracted from Design

Scenario	Outflow Rate	Shape Factor	Oversaturated Factor
-	$\mu\ (veh/ln/hr)$	γ	m
All Seasons	774	3.05	0.5
Spring	867	3.05	0.5
Summer	805	3.05	0.5
Winter	648	3.05	0.5

Another important parameter that was assumed early on is the oversaturated factor, m, which was chosen to be 0.5. This value represents the time of day at which peak congestion occurs. In this case, peak traffic is during the middle of the day, which is why 0.5 was chosen. The figure below verifies the accuracy of this assumption because t_2, the time at which the queue is the longest, is located at 14:00, the center of the curve. Other acceptable values for m include 0.66 and 0.72. For all scenarios, t_2 is at the same time of day. In *Figure 10*, $\lambda(t)$ is shown in blue and mu $\mu(t)$ is shown in orange for all scenarios.

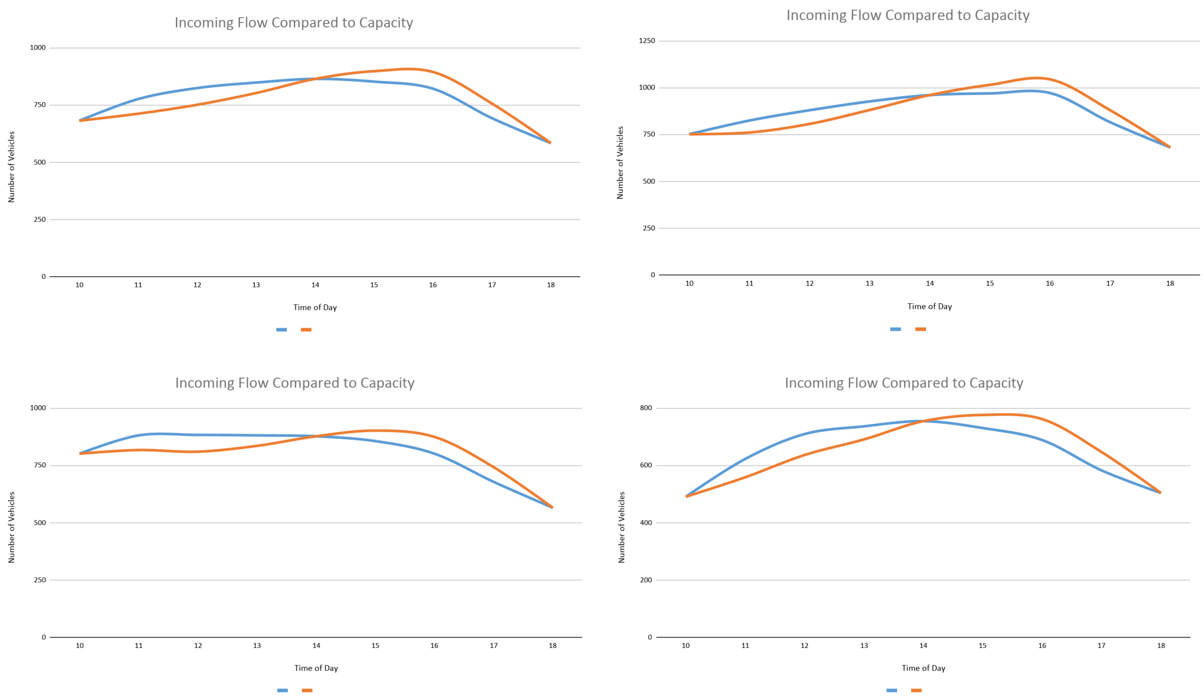
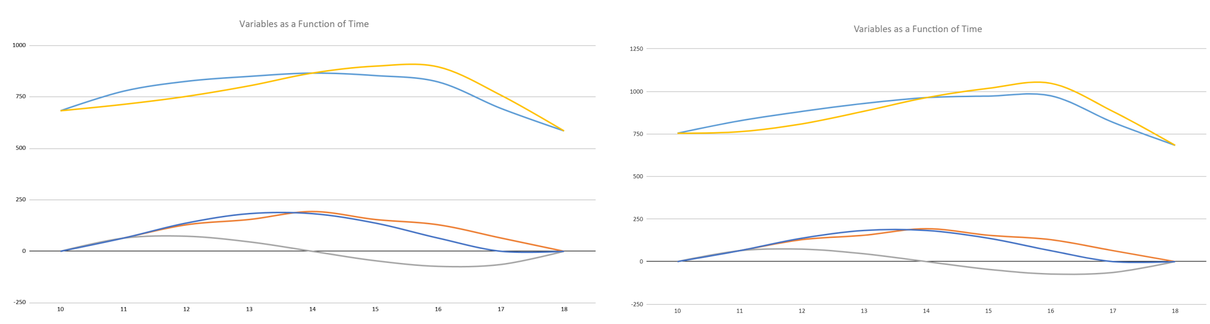


Figure 10: Verification of m=0.5

(Subsets from top-left to bottom-right: All-Seasons, Spring, Summer, and Winter)

The plots given in *Figure 10* above validates the QESM spreadsheets accuracy. To test its flexibility using different traffic counts, the all-season model used for the primary analysis was broken down by season to ensure all the output plots and values were appropriately updating. The value for time-dependent outflow and inflow is populating accurately at the desired points of interest, t_0, t_2, and t_3.



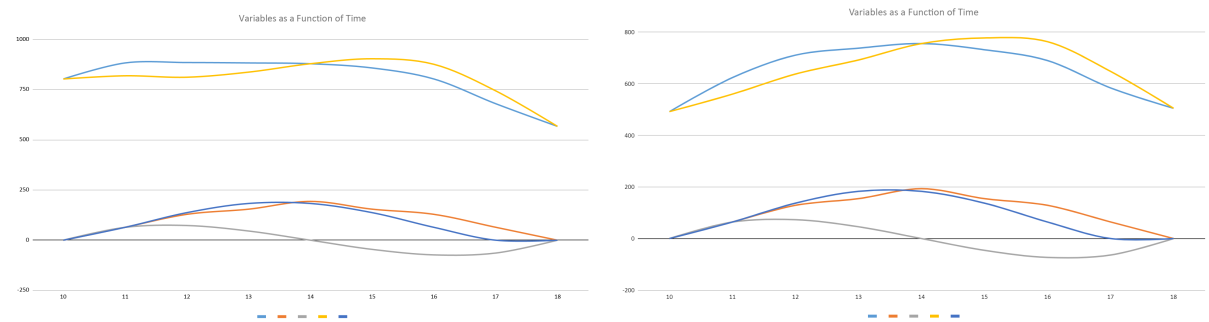


Figure 11: Variables as a Function of Time
(Subsets from top-left to bottom-right: All-Seasons, Spring, Summer, and Winter)

In *Figure 11*, the two lines in the upper bounds represent $\lambda(t)$, shown in blue, and $\mu(t)$, shown as in yellow. In each subplot, the observed queue is shown orange, the simulated queue is shown in blue, and net flow is shown in grey. Important things to note in *Figure 11,* the close approximation of simulated to observe queue and the relation of max queue at t_2. The net flow is also seen to be centered around t_2, which is another way of verification for both m and queue formation. *Figures 10* and *11* are presented as continuous functions conducted using discrete data points. This does not change the interpretation of the data, but it does make it easier for the user to visualize what is happening throughout the time analysis period.

B. Time-Dependent Output

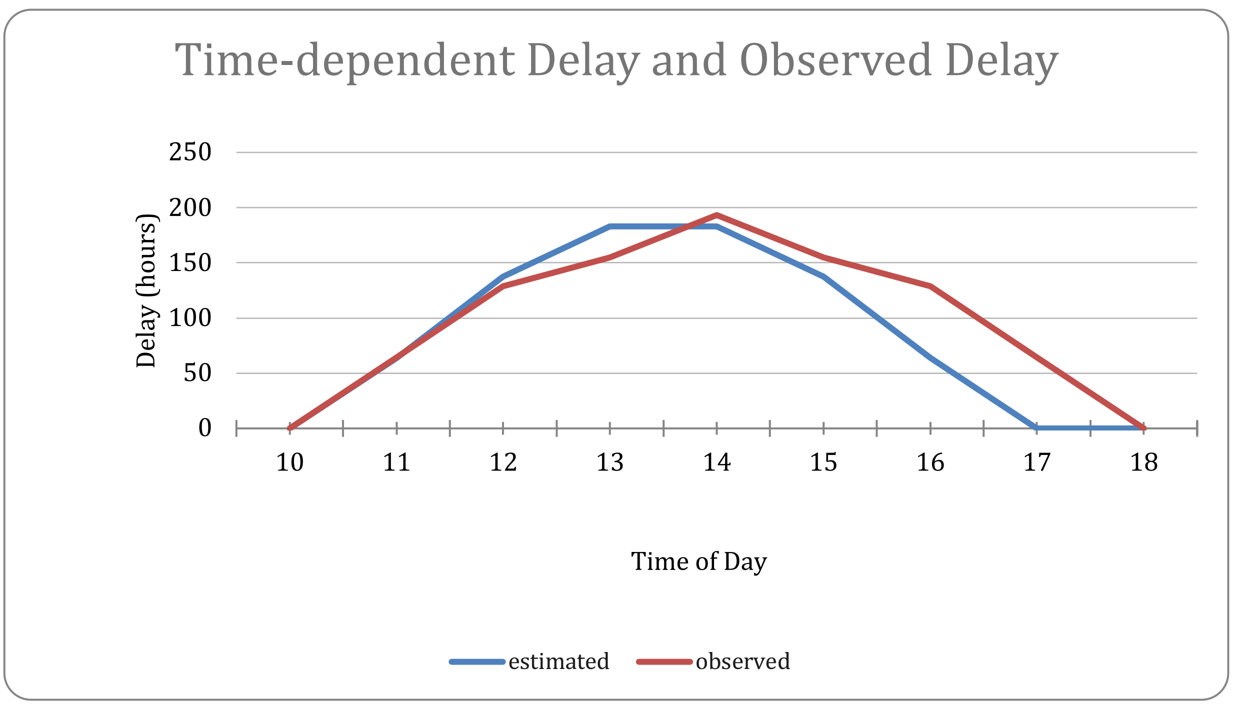


Figure 12: Observed Queue and Waiting Time (All-Seasons Scenario)

Figure 12 shows the relationship between observed queue time and waiting-time (per-vehicle) in for the All-Seasons scenario. This relationship was defined further in the *Methodology* section but is shown here to be true for the dataset observed.

C. Simulated Analysis

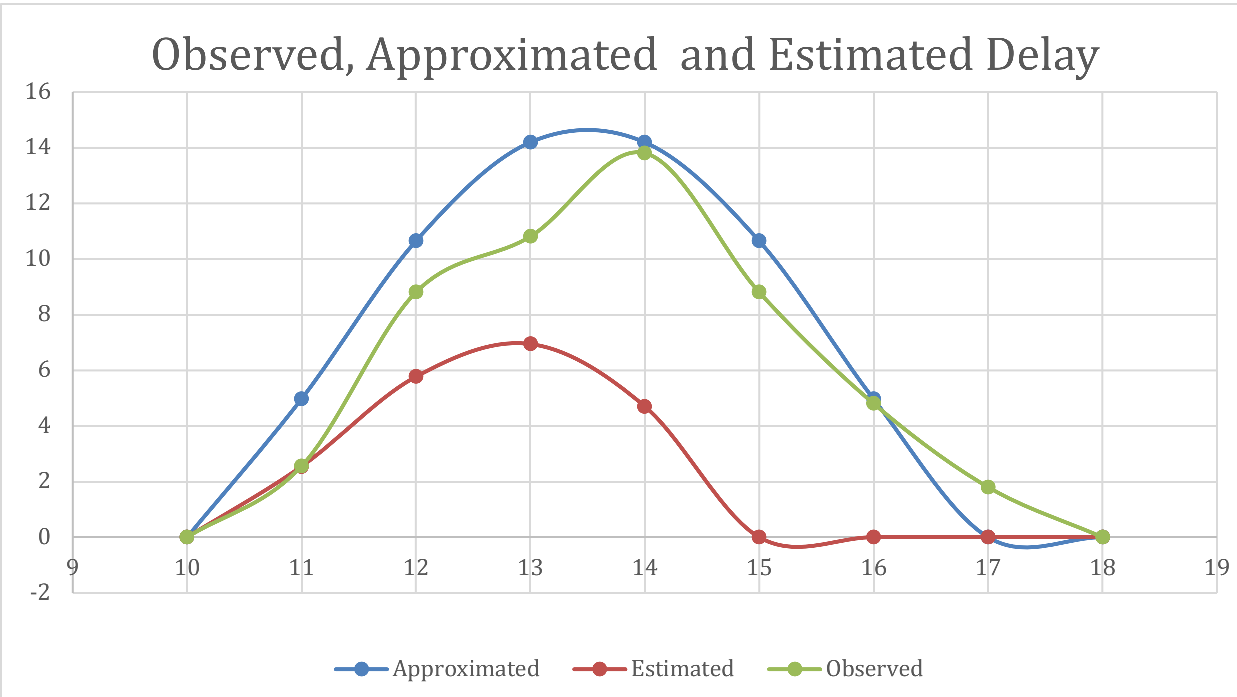


Figure 13: Effect of Increasing Capacity (All-Seasons Scenario)

Figure 13 demonstrates the impact of increasing capacity on the total wait time for the all-seasons scenario. This was done easily by increasing $\mu(t)$ by 30 vehicles per lane per hour. This increase in the capacity impacts the outflow rate and can arise from any situation that would potentially increase throughput and ease dissipation. Some recommendations for this are given in the *Recommendations* section, however the results from the above figure illustrates how the analysis output adjusts easily as a result of changing a single input parameter.

D. Limitations

The Quick Estimation and Simulation Model does have some limitations, and are based on those discovered in Dr. Cheng's, Dr. Liu's, and Dr. Zhou's working paper "A multiscale demand and supply model for oversaturated dynamic transportation queuing systems," and through the iterative process used to develop the QESM method . These go as follows:

1. Reliability issues related to the user's ability to estimate and predict underlying demand $\lambda(t)$ and supply $\mu(t)$ as part of observable qualification tasks, such as defining m.

2. Limited user understanding of how to appropriately assign the t_0, t_2, and t_3 values.

3. To what extent the user proactively controls the demand inflow curves $\lambda(t)$ and supplied capacity μ at different scales as part of the controllable qualification tasks for determining limitation 2.

4. Possible inaccuracy while attempting to appropriately estimate the observed waiting time, w(t).

5. The need for manual calibration by the user.

These were the observed limitations gathered during the research and development period of the QESM method. It is entirely possible that additional limitations will arise and be identified in the future.

V. Summary of Conclusions

A. Significant Findings

When looking over the data, it was discovered that the traffic count was taken as the midblock volume count and not from either the start or tail end of a queue. It was unclear whether to take this count to be the inflow $\lambda(t)$ or the outflow $\mu(t)$ as in the case of an input/ output detector. It was assumed that during congestion this count was most nearly $\mu(t)$, which changed the formulation for queue $Q(t)$ and is reflected in the latest version of the QESM spreadsheet. Conversely, the midblock-flow sensor could be treated as part of the inflow free-speed pattern during non-congested regions of time. Knowing what the midblock volume represented significantly affected the approximation of both t_0 and t_3, and something that had to be reworked with the assumptions made above.

Another significant change made to the analysis tool was changing $\mu(t)$ from an average, constant value to a time-dependent variable ($\mu_{ave} \rightarrow \mu(t)$). This was done after seeing how there was a large deviation from t_0 to t_3 when μ_{ave} was assumed to be a constant. The previous model did not match the initial estimate that $\lambda(t_0) = \mu(t_0)$and $\lambda(t_2) = \mu(t_2)$ for the data analyzed. This worked to complicate the analysis, as traditionally there were only 3 peak hours to observe. But with the change, 8 values needed to be checked to further enable the resulting calibration and simulation.

The following cubic function as a regression model was finalized to include the time-dependent variable $\mu(t)$ with the already established parameter γ and the three roots associated with $t_{0,}$ t_2, and t_3 as discussed in *Methodology*:

$$\lambda(t) - \mu(t) = \gamma(t - t_0)(t - t_2)(t - t_3) \tag{12}$$

From here, the calibration process based on the continuous-time queuing model above can be used to find the correct shape parameter and to back calculate inflow $\lambda(t)$. If the right-side of the above equation is simply treated as the net-flow of traffic conditions, inflow is simply $\lambda(t) = net\ flow - \mu(t)$. Similarly, $\mu(t)$ can be found as an output with $\lambda(t), t_0$, and t_3 as inputs.

Similarly, queue length was finalized with the time-dependent $\mu(t)$ and wait time W(t) as $Q(t) = W(t) * \mu(t)$. By relating queue length and the above model, a relationship between $Q(t)$ and γcan be derived for optimal linear regression: $Q(t) = \gamma X$, where X are all time roots associated with the model.

From these derivations, a final discrete time simulation queueing model was created:

$$Q_s(t + 1) = Q_s(t) + \lambda(t) - [\mu(t) + \Delta\mu] \tag{13}$$

$$W(t) = \frac{Q(t)}{\underline{\mu_t} + \Delta\mu} \tag{14}$$

With this discrete-time model, simulations were run for differing scenarios of discharge rates with $\lambda(t), \mu(t)$, and $\Delta\mu$ as inputs to find new $\mu_1(t)$ and $Q_{s,1}(t)$. $\Delta\mu$ is the difference in the outflow rate given assumed changes in traffic flow. For example, when calculating using the historical inflow traffic counts, an assumed outflow value is calculated, to simulate a new scenario, the change this outflow rate is assumed to test how this increase or decrease in capacity will affect the overall traffic flow. If an additional lane was added to the network that was capable of transporting 100 additional vehicles, $\Delta\mu$ would be equal to 100 vehicles per lane per hour, and if it decreases the capacity by 100 vehicles, $\Delta\mu$ would be input as a negative value.
This can be seen in the final results found above.

B. Future Research

Future research can include the above methodology of using SUMO for simulation confirmation and incorporating Google Geo Charts for information sharing. Another program that was considered during the late stage of this project was using NeXTA for network visualization. Different from SUMO which simulates a created intersection, NeXTA would work by opening a pre-existing data set (including geographic information system- GIS data) and running a network configuration through it. By changing network data and using the time-dependent results found from this study, the analysis features in the program can be run and output a network-related display. By providing the open-data format information generated and running NeXTA, outputs such as an Origin-Destination (OD) matrix, measures of effectiveness (MOE) for links, and time-dependent simulation results can be generated; all of which are common-place in the regular analyses conducted by civil engineering firms and agencies in this field.

C. Recommendations

"In the analysis of active demand scenarios such as demand spreading, the changes of arrival rates can be characterized by the shape parameter γ which directly impacts the total delay and maximum queue length. On the other hand, the supply capacity enhancement in terms of μ could be effective if it leads to a reduction of congested period $(t_3 - t_0)$, but in many cases induced traffic could have an unintended consequence on demand that makes the congestion period unchanged or even worse. Thus, careful planning of congestion mitigation strategies calls for integrated sensitivity analysis for all control factors including t_0, t_1, t_2, t_3 and the shape factor γ" (Cheng, Liu, & Zhou, 2020).

As seen in the *Results* section of this report, the shape factor γ was a constant value of 3.05 regardless of season analyzed. As outlined in *Results*, this speaks more to the design of the roadway that can contribute to total congestion. The shape factor γ and the time parameters $t_0 - t_3$ are the most important control measures for oversaturated dynamic queueing systems, and the change in these variables will help to reduce overall congestion. Some recommendations for doing so are as follows:

1. Decrease the arrival rate from the demand-side, to allow the congestion to occur later and dissipate earlier (move t_0 to the right and t_3 to the left)
2. Increase the discharge rate μ from the supply-side, to again allow the congestion to occur later and dissipate earlier
3. Coordinate with travel agencies in managing queueing systems through pricing, incentives or slot reservations, so as to shift the peak of the queue model (changing the shape of the γ parameter)
4. Designing appropriate capacity management strategies, e.g. traffic signal timing, transit scheduling, or other forms of metering for the traffic system to effectively enhance the system-level discharge rate μ

These recommendations can be incorporated to the specific case study of the Sedona intersection studied in the next section.

D. Conclusion

The City of Sedona is currently working on a proposed signal timing in the intersection that will be in place in the months succeeding the writing of this report (City of Sedona (n.d.). *Uptown*

Roadway Improvements Project). As part of the Sedona in Motion (SIM) program, the City of Sedona is conducting a combination of street, hardscape, and landscape improvements in the affected areas of the project. The goal of the project is to improve traffic flow and safety, decrease delays, and create more opportunities for pedestrians to access Uptown businesses. Beginning in June of 2019 and slated to finish by Spring of 2020, the improvement project will work to include:

- An additional southbound lane along SR-89A
- A new connector road between 89A and free parking along Schnebly Road
- Two roundabouts, one at Jordan Road and one at the new Schnebly Road Connector
- Landscaped, decorative median along 89A through Uptown
- Decorative median and extended sidewalk on the north side of Forest Road, between 89A and Van Deren Road

Under the Uptown Roadway Improvements project headed by Eagle Mountain Construction as lead contractor, the crosswalk on the south side of the intersection would be eliminated to allow the pedestrian crossing of SR 89A on the north side of the intersection to happen in conjunction with the northbound left turns onto Forest.

If changes were made to the capacity of the system that change can be incorporated into the analytical model with minimal effort to easily simulate what impact it would have on the discharge rate as a function of time. This shows the robustness of the system in accommodating such changes in the design space. The simulation model similarly can be changed dynamically as just a change of the total input/ output of the segments in a network.

VI. References

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Appendices

Appendix A - SUMO Simulation Steps

Part I Simulation of an Intersection

Step 1: Create the intersection in NETEDIT

Output Filename chosen: intersection.met.xml*[1]

Step 2: Modify the flow file

The flow file saves the demands for simulation.

Filename chosen: input_flows.flows.xml†

Arguments	Notes
flow id	Id of the flow
from	Id of the edge where the flow is loaded to network
begin	Begin time (second)
end	End time (second)
number	Total number of vehicles loaded to the edge from 'begin' to 'end'
departLane	How vehicles choose their lanes when they are loaded to the first edge

Step 3: Modify the turning ratio file

The turning ratio file allows users to define the choice probabilities of downstream edges in any diverge points.

Filename chosen: input_turns.turns.xml†

Arguments	Notes
Interval being	Begin time (second)

[1] The .xml file extension is for Extensible Markup Language (XML) file, in which the files are plain text files with custom tags to describe the structure and other features of the document.

end	End time (second)
fromEdge id	Id of the approach
toEdge id	Id of the downstream edge
probability	From 0 to 1

Step 4: Modify the route generation configuration file

Filename chosen: route_generation_configuration.jtrrcfg†[2]

Arguments	Notes
net-file	Name of the network file (intersection.net.xml)
flow-file	Name of the flow file (input_flows.flows.xml)
turn-ratio-files	Name of turning ratio file (input_turns.turns.xml)
Sink-edges	Ids of edge where vehicles will finish their trip as soon as they leave it.

Step 5: Create the route file

The route file saves the route for each vehicle.

Conduct “jtrrouter -c ***” command in cmd dialog[3], where *** is the name of the route generation file (in this case “jtrrouter -c route_generation_configuration.jtrcrfg”)

Step 6: Modify the simulation configuration file

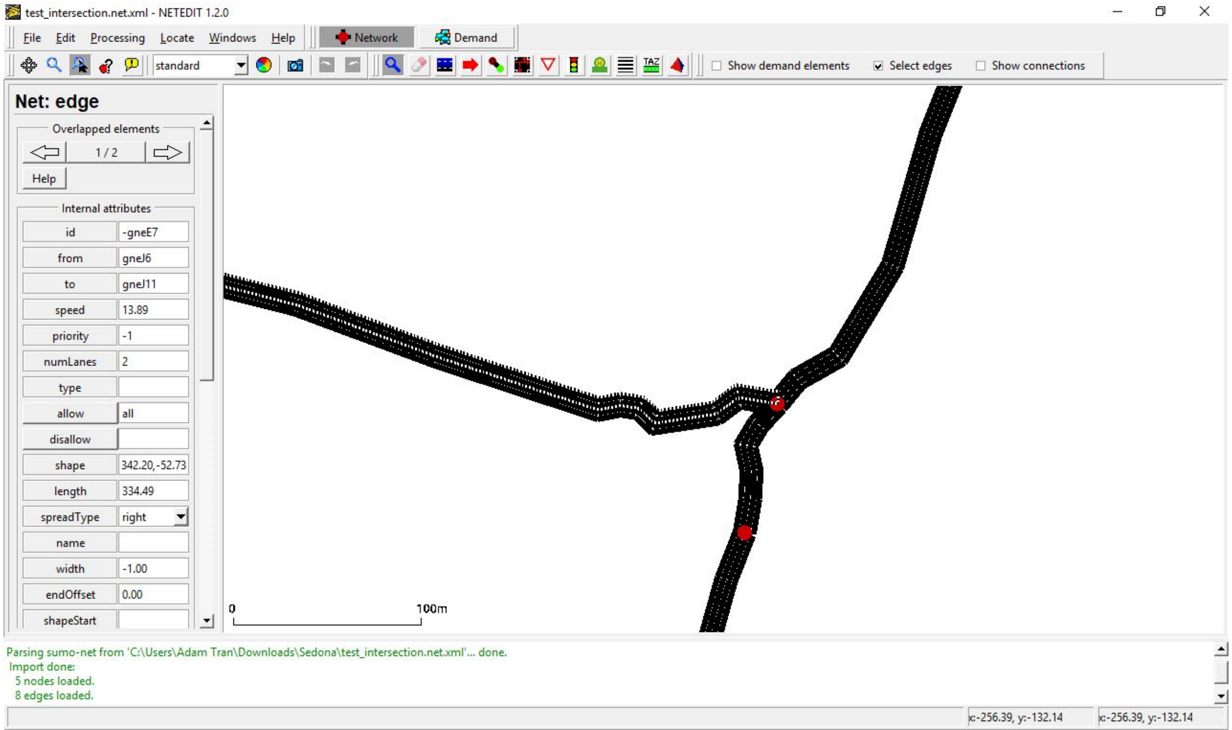
Filename chosen: intersection.sumocfg*[4]

Arguments	Notes
net-file	Name of network file (intersection.net.xml)
route-file	Name of the route file
begin	Begin time (second)
end	End time (second)

[2] The .jtrcrfg file extension is ran by the command prompt found in Step 5 of Part I of creating an intersection.

[3] Done through command prompt window.

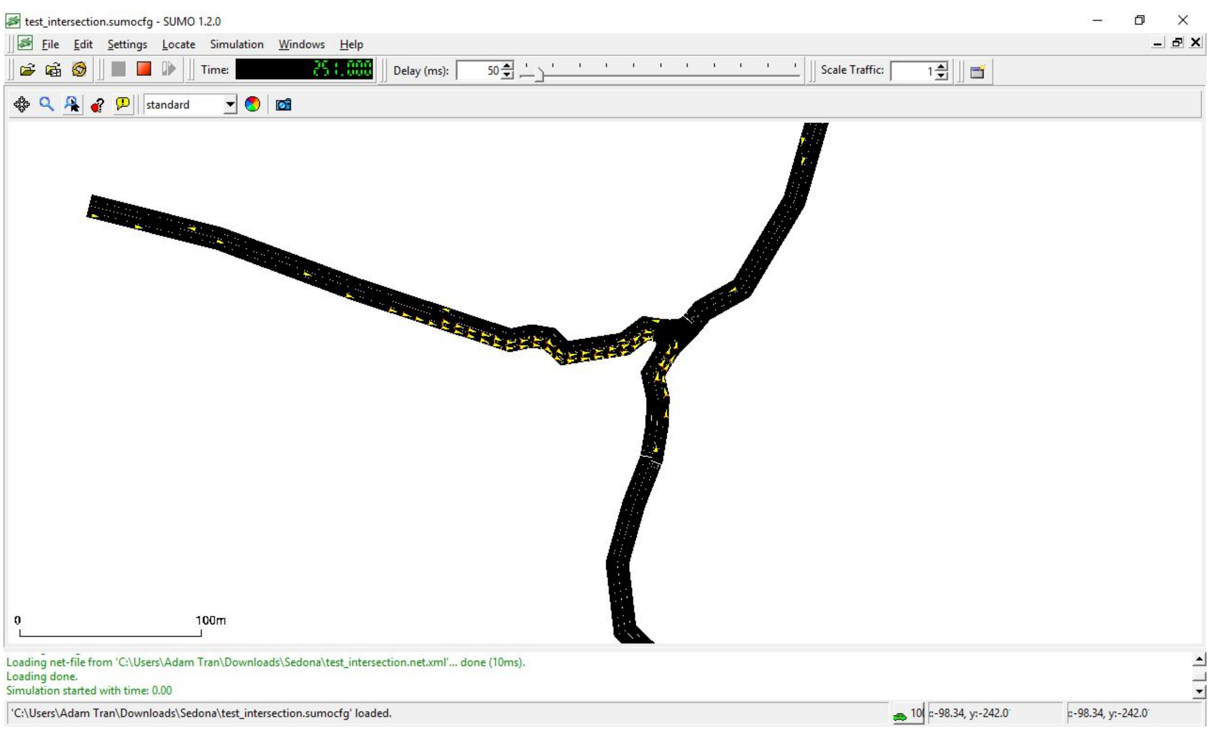
[4] Executed through SUMO program.



Step 7: Simulate in SUMOGui

File →Open Simulation, select simulation configuration file (intersection.sumocfg)

Start simulation.



* File can be of any name

† File can be of any name, but must be referenced by that name

Part II Signal Control Plan

SUMO is robust enough to have included a signalled intersection into the model created. This was something that could have been included as outlined in the Recommendations section in support of analytical models done if time permitted.

Part III Output Simulation Results

Available outputs include vehicle positions, trip information, vehicle routes information, simulation state statistics, etc.). These outputs are generated using command line options; others have to be defined within additional files. Refer to the SUMO User Documentation[5] for details. The following steps can be used to output edge data, emission data, and queue data.

Step 1: Modify the additional file

Write the measures interested into .add.xml file.

Step 2: Modify the simulation configuration file

Add additional file in the input section.

Step 3: Simulate in SUMOGui

If all parameters are set correctly, output files will be generated after the simulation.

Step 4: Simulate using command line

Some measures can only be executed by calling SUMO simulation using a command line (e.g. queue data). For example: use command “sumo -c demon_intersection.sumocfg -queue-output output_queue .xml” to conduct a simulation and output queue data to “output_queue.xml”.

Notes:

- These steps are done before the simulation is run.
- Use command “cd” to change the current working directory to the folder where the network files were saved.
- By calling SUMO using a command line, SUMO can output all available measures, including measures defined in the command line and any additional files.
- Output data will be kept in memory until SUMOGui is closed. To view simulation output as a .xml file, SUMOGui must be closed after the simulation is finished.

[5] https://sumo.dlr.de/docs/Simulation/Output.html as of January 24, 2020.

Appendix B - BPR-X Guide

Step 1:

1. Assume the arrival rate is a polynomial function of time, and discharge rate is a constant
2. Rewrite the net flow rate as a factor form ($Net\,flow\,rate = Arrival\,rate - discharge\,rate$)
3. Derive the time-dependent queue length, time-dependent delay, total delay, and average delay.
4. For cubic inflow rate, net flow rates may have three different roots (i.e. t_0, t_2, and $\underline{t}$). Since $\underline{t}$ is unobservable, the queue dissipation ratio parameter m is introduced to eliminate the unobservable parameter $\underline{t}$.

Step 2:

For a fixed m factor, approximations are made to generate analytically driven equations:

Different γ analyzed for different ranges of m

1. When $\gamma > 0$ and $m = \frac{1}{2}$, $t_{bar} = t_3$. Case 1 is obtained below.

Case 1: $\gamma > 0, m = \frac{1}{2}$

The arrival rate function is symmetric around the point (t_2, μ), and $\underline{t} = t_3$. We then obtain the time-dependent queue length

$$Q(t) = \frac{1}{4}\gamma(t - t_0)^2(t - t_3)^2 \tag{E.1}$$

The time-dependent delay

$$w(t) = \frac{1}{4\mu}\gamma(t - t_0)^2(t - t_3)^2 \tag{E.2}$$

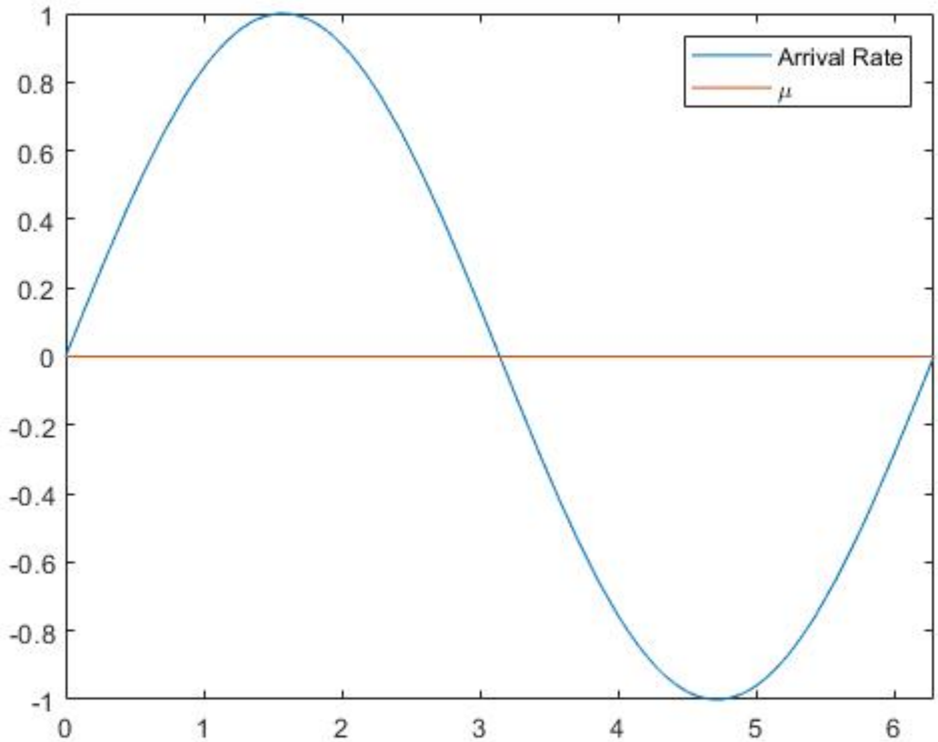
The total delay from t_0 to t_3

$$W(t_3) = \frac{1}{120}\gamma(\frac{D}{\mu})^5 \tag{E.3}$$

and the average delay

$$w = \frac{\gamma}{120\mu}(\frac{D}{\mu})^4 \tag{E.4}$$

To get the time-dependent queue length, time-dependent delay, total delay, average delay, it is recommended that $\gamma > 0$ and $m\epsilon[\frac{1}{2}, \frac{2}{3}]$. If μ is calibrated first, all terms are only related to γ.



A spreadsheet was used to create the time-dependent queue profile to verify the formulation of the relationship shown above.

Appendix C - QESM Spreadsheet Output

The QESM Spreadsheet for All Seasons is given in this Appendix. The spreadsheet ran for the other seasons analyzed in this report (i.e. Spring, Summer, and Winter) are done with similar analyses and the same model with their respective traffic counts.

Overview:

Instructions: Input raw data on this sheet. Include time and traffic counts. (Adjust according to time analysis period)

Data origin: All traffic counts in current spreadsheet provided by ADOT as heat map data taken from the Forest Avenue intersection in Sedona Arizona.

Intersection/Roundabout Information:
Location: SR 89A & 179 in Sedona, AZ
No. lanes: 1
Speed limit: 25 mph
Distance: 0.5 mi

Traffic Counts:

Winter

7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00
115	271	329	492	624	711	738	756	732	690	584	505	445	244	170	113

Spring

7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00
164	337	541	754	827	882	929	963	972	974	818	683	595	493	279	173

Summer

7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00
206	385	614	803	883	885	883	879	858	803	680	567	490	420	314	179

Average

7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00
162	331	495	683	778	826	850	866	854	823	694	585	510	386	255	155

Final Traffic Counts (account for No. lanes):

7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00
162	331	495	683	778	826	850	866	854	823	694	585	510	386	255	155

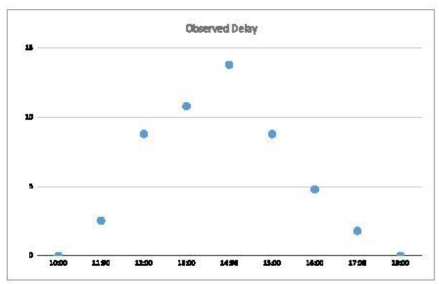
Assume mu:

mu	774

Observed Delay (Hand Calculate) (in hours):

	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00
	0	0	0	0	2.5500	8.8000	10.8000	13.8000	8.8000	4.80000	1.8000	0	0	0	0	0
				0	0.043	0.147	0.180	0.230	0.147	0.080	0.030	0.000				
Queue = w*mu				0	32.895	113.520	139.320	178.020	113.520	61.920	23.220	0.000				

How to Calculate Observed Delay:



Instructions: Data interpretation using information given in Sheet 1. Adjust according to analysis period.

Given:

Queue formation	t0	10	(Queue appears)
Max Queue length	t2	14	(Peak Queue)
Queue dissipates	t3	18	(Queue dissipates)
Eqn 1.1	m	0.5	∈[0.5,0.66,0.72]
constant mu	mu	774	

Solve 1st:

Step 1: find Gamma

	Description of Variable	Symbol	1	2	3	4	5	6	7	8	9	10 (t0)	11	12	13	14 (t2)	15	16	17	18 (t3)	19	20	21	22	23	24
Given	Historical Traffic Flow	lambda(t)							162	331	495	683	778	826	850	866	854	823	694	585	510	386	255	155		
Given	Observed Queue (hr)	Q_obs(t) as Y							0	0	0	0	64.4167	128.833	154.600	193.250	154.600	128.833	64.4167	0	0	0	0	0		
Derived	estimated X	X										0	12.25	36	56.25	64	56.25	36	12.25	0						

Step 2: find mu(t)

Gamma to be estimated 3.050010952 0

		Description of Variable	Symbol	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Eqn 2.5	Calculate	Netflow(t)=lambda(t)-mu(t)											0	64.050229	73.200262	45.750164	0	-45.75016	-73.20026	-64.05022	0						
Eqn 2.1	Calculate	mu (t)=lambda(t)-netflow(t)	mu(t)										683	713.94977	752.79973	804.24983	866	899.75016	896.20026	758.05023	585						
Eqn 2.4	Calculate	Simulated Queue Length Q_s(t+1)= Q_s(t)+lambda(t)-Mu(t)	Q_S(t)									0	0	64.050229	137.25049	183.00065	183.00065	137.25049	64.050229	0	0	0					
Eqn 2.3	Calculate	Time-dependent approximated Waiting Time= Queue(t)/mu(t)	w(t)										0	4.9651341	10.639573	14.186097	14.186097	10.639573	4.9651341	0	0						

Simulated scenario:

Assume: mu difference: 30

Solve 2nd:

		Description of Variable	Symbol	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
	Given	Historical Traffic Flow	lambda(t)							162	331	495	683	778	826	850	866	854	823	694	585	510	386	255			
	Assume	mu (t)	mu_new(t)										713	743.94977	782.79973	834.24983	896	929.75016	926.20026	788.05023	615	30	30	30	30		
Eqn 2.4	Calculate	Simulated Queue Length Q_s(t+1)= Q_s(t)+lambda(t)-Mu(t)	Q_simu_new(t)									0	0	34.050229	77.250492	93.000657	63.000657	0	0	0	0						
Eqn 2.3	Calculate	Time-dependent approximated Waiting Time= Queue(t)/avg mu	w(t)										0	2.5410619	5.7649621	6.9403475	4.7015415	0	0	0	0						

Reference Equations:

Eqn 1.1

$$m = \frac{t_2 - t_0}{t_3 - t_0},\ 0 < m < 1$$

Eqn 2.1

Cubic form	$\lambda(t) = \gamma(t - t_0)(t - t_2)(t - \bar{T}) + \mu$

Eqn 2.2 When $\gamma > 0$, $m = 1/2$, the arrival rate function is symmetric around the point (t_2, μ), and $\bar{T} = t_3$. Then, we can obtain the time-dependent queue length

$$Q(t) = \frac{1}{4}\gamma(t - t_0)^2(t - t_3)^2 \quad (S.31)$$

The time-dependent delay

Eqn 2.3

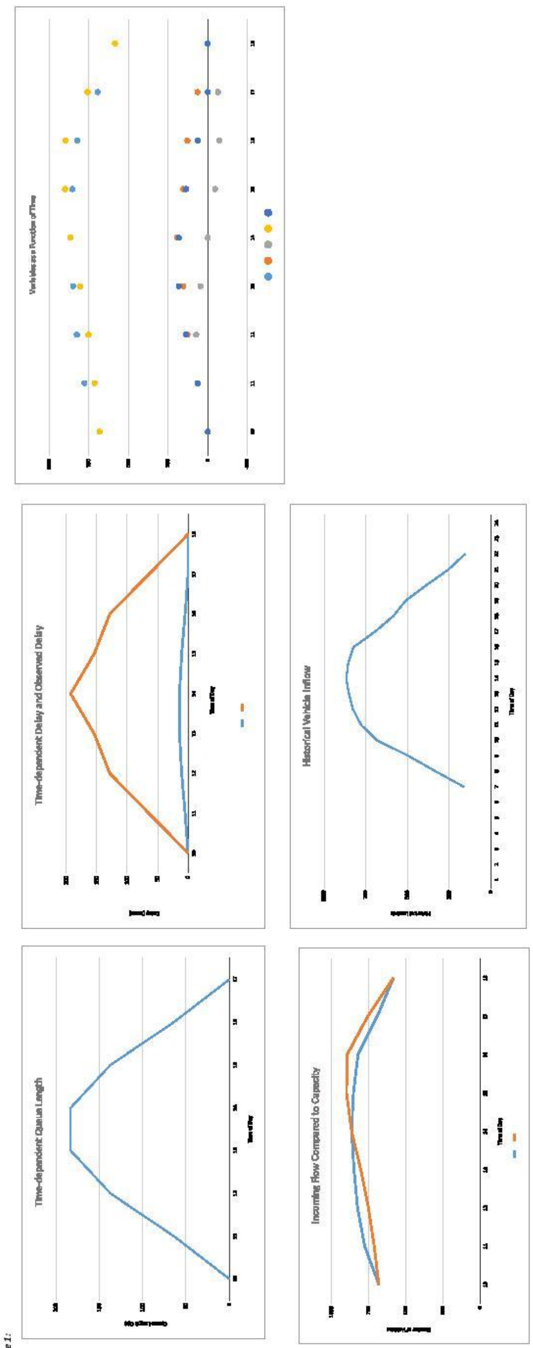
$$w(t) = \frac{1}{4\mu}\gamma(t - t_0)^2(t - t_3)^2 \quad (S.32)$$

Eqn 2.4

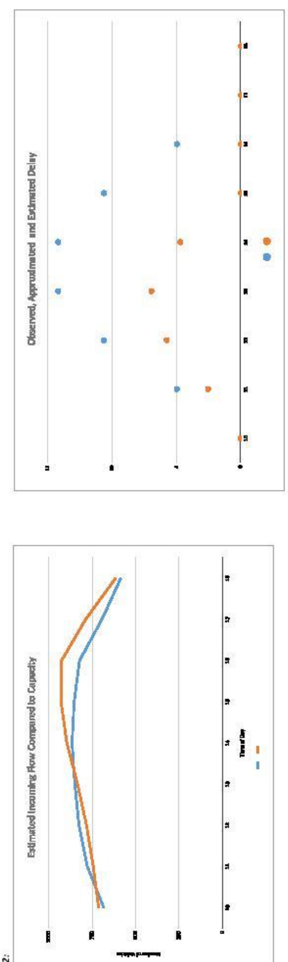
Q(t+1)=Q(t)+lamobda(t)-mu(t)

Eqn 2.5

Solve 1:



Solve 2:



Results Extracted from Design:

Calibration Results

Inflow Rate	Outflow Rate	Oversaturate Factor
mu	gamma	m
774	3.050010952	0.5

Instructions: Use Google Maps geographic cell information to interprete results of spreadsheet.

Website: http://s2.sidewalklabs.com/regioncoverer/ (open source project provided by Sidewalk Labs)

How to Use:

Step 1: Visit website above and pan to location of interest: 

Step 2: Pin location of interest by clicking this icon: 

Step 3: Min level must equal max level for cells to be uniform in size.

Step 4: Highlight area of travel using either of these icons (rectangular or circular selection):  or 

Step 5: Copy cell "codes" that correspond with area of interest.