Estimating Vehicle Stops at Under-Saturated and Over-Saturated Fixed-Time Signalized Intersections

by

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ABSTRACT

This paper first reviews state-of-practice models for estimating vehicle stops at signalized intersections and then introduces two approaches for computing vehicle stops at under-saturated and over-saturated signalized intersections. The first approach that is introduced is a microscopic model that computes instantaneous partial and full stops for under-saturated and over-saturated conditions using second-by-second speed measurements. This model, in particular, has been introduced in the INTEGRATION traffic simulation software. The second model that is introduced is an analytical formulation derived from the proposed microscopic model that computes the number of vehicle stops for over-saturated approaches over a given analysis period. Finally, comparisons of the stop estimates produced by the two proposed models to estimates obtained from current state-of-practice analytical models demonstrate both their validity in their respective domains of application.

INTRODUCTION

The measurement of the level of performance of signalized intersections has been an area of interest for traffic engineers since the birth of the profession. For many years, this interest has primarily focused solely on vehicle delay. Besides delay, other performance measures such as the number of vehicle stops and the spatial extent of queues on intersection approaches have also been found to play an important role in the evaluation of signalized intersections. These measures not only relate to the level of service that is provided to the drivers, but also to the level of fuel consumption and air pollution that is generated by the vehicles traversing the signalized intersections. In particular, while vehicle stop estimates play an important role in determining vehicle fuel consumption and emissions on intersection approaches, queue length estimates are important not only for the design of pocket lanes, but also to ensure that traffic signal operations do not result in vehicle queues that spillback onto upstream intersections.

Background

Numerous researchers have dealt with the problem of estimating vehicle stops at signalized intersections. An important early contribution is attributed to Webster (*1*), who generated stop and delay relationships by simulating uniform traffic flows on a single-lane approach to an isolated intersection. These relationships have been fundamental to traffic signal setting procedures since their development. Later, Webster and Cobbe (*2*) developed a formula for estimating vehicle stops at under-saturated intersections assuming random vehicle arrivals. In another effort, Catling (*3*) adapted equations of classical queuing theory to over-saturated traffic conditions and developed a comprehensive queue length estimation procedure that captured the time-dependent nature of queues and that can be applied to both under-saturated and over-saturated conditions. In a last effort, Cronje (*4-7*) developed stop and delay equations by treating traffic flow through a fixed-time signal as a Markov process. The approach assumed that the number of queued vehicles at the beginning of a cycle could be expressed by a geometric distribution.

Although a number of stop estimation models have been developed, the majority of these models have not been designed to account for the partial stops that vehicles may incur on intersection approaches. Furthermore, the models that currently account for partial stops do not estimate them for over-saturated conditions. In many instances, it has been observed that vehicles approaching an over-saturated intersection incur a series of partial stops as they gradually approach intersection stop line and not only complete stops. Finally, the stop estimation models that were developed for over-saturated conditions have not been demonstrated to be valid.

Research Objectives

The research effort presented in this paper addresses two objectives. The first objective is to develop and validate a microscopic stop estimation model that accounts for both partial and full vehicle stops and can be applied to the analysis of both under-saturated and over-saturated signalized intersections. This model, which has been incorporated in the INTEGRATION simulation model, is microscopic in the sense that it utilizes a vehicle's instantaneous speed as an independent variable for estimating instantaneous vehicle stops. The second objective is to utilize the microscopic model to develop and validate an analytical procedure for estimating the number of vehicle stops at over-saturated signalized intersections without the need for analyzing individual vehicle speed profiles.

Paper Layout

In addressing the identified research objectives, the paper first describes the current state-of-practice for estimating vehicle stops at signalized intersections. Following this review, the paper describes the proposed microscopic stop estimation approach and subsequently uses this approach for developing an analytical model for estimating vehicle stops for over-saturated conditions. These models are then validated by comparing their stop estimates to state-of—the-art models for a number of test scenarios. Finally, the main conclusions of the paper are presented after review of the evaluation results.

CURRENT STATE-OF-THE-ART ANALYTICAL STOP ESTIMATION MODELS

This section describes three state-of-the-art models that estimate the number of vehicle stops at signalized intersections. These models include an analytical model based on queuing theory, the model proposed in the 1995 Canadian Capacity Guide (*8*), and the model proposed by Cronje *(2)*.

Queuing Theory Model

In queuing theory, Equation 1 is used to calculate the average number of stops incurred by vehicles approaching a signalized intersection. This equation is valid for both uniform and random arrivals for under-saturated conditions. For under-saturated conditions, the equation expresses the exact number of stops that vehicles will incur at the intersection. For over-saturated conditions, however, the equation expresses only the expected number of stops that vehicles may incur at the intersection.

$$N_{QT} = \frac{s}{(s-q)} \cdot \frac{r}{C} \qquad [1]$$

where:

N_{QT} = Average number of stops per vehicle (stops/vehicle),
s = Average saturation flow rate (vehicles/second),
q = Average arrival flow rate (vehicles/seconds),
C = Cycle time (seconds),
r = Effective red interval (seconds).

When applying queuing theory to signalized intersections, three major assumptions are made. The first assumption assumes that vehicles queue vertically at the stop line, which means that vehicles only stop when they reach the intersection. The second and third assumptions assume that vehicles decelerate instantaneously to a complete stop and then accelerate instantaneously back to their original speed.

Canadian Capacity Guide Model

The 1995 Canadian Capacity Guide utilizes a stop model based on random arrivals that was originally developed by Webster and Cobbe. This model estimates the number of vehicles that are stopped at least once by the operation of traffic signals during an evaluation period using Equations 2, 3 and 4.

$$N_{CCG} = \frac{k_f \; t_e \; q_h \; (C-g)}{3600 \; C \; (1-y)} \qquad [2]$$

with:

$$N_{CCG} \le \frac{t_e \; q_h}{3600} \qquad [3]$$

$$y = \frac{q_h}{s_h} \le 0.99 \qquad [4]$$

where:

N_{CCG} = Average number of passenger car units stopped at least once during the evaluation period (passenger car units),
k_f = Adjustment factor for the effect of the quality of progression,
t_e = Evaluation period (seconds),
q_h = Hourly average arrival flow rate (passenger car units/hour),
s_h = Hourly saturation flow rate (passenger car units/hour).
C = Cycle time (seconds),
g = Effective green interval (seconds),

As indicated by Equation 3, the number of vehicle stops that are estimated by the model is constrained to not exceed the number of vehicle arrivals during any given evaluation period. This means that the model assumes that all vehicles only stop once before crossing an intersection. As expressed by Equation 4, this assumption thus precludes the use of the model to evaluate the number of stops at over-saturated intersections, as vehicles at these intersections may go through a series of stop-and-go cycles before being able to cross the intersection.

Another important element is the adjustment factor k, which is used to approximate the effect of signal coordination and progressive movement of vehicles through the intersection. Correct use of this factor is essential when the number of stops is to be used to determine vehicle fuel consumption and emissions. Depending on the level of progression, the number of stops calculated by Equations 2 may range from 0, under excellent progression conditions, to 2.6 times greater than the number of stops calculated for random arrivals.

Cronje Model

Cronje developed equations for estimating the number of stops at isolated intersections by treating the traffic flow as a Markov process. For under-saturated conditions, Cronje found after comparing various models to simulation results that Equation 5, in combination with Equations 6, 7 and 8, which was developed by Newell (*9*), is most accurate for estimating vehicle stops under steady-state traffic conditions.

For over-saturated conditions, Cronje developed equations for estimating the expected number of stops per cycle based on the expected queue size at the beginning of the analysis period. Assuming that the queue size is distributed according to a geometric distribution, Cronje then applied the properties of the distribution to obtain simpler equations. Further modifications finally yielded Equations 9 and 10.

$$N_{CR} = Q_0 + q\left[\frac{qr + Q_0}{s - q} + r\right] \qquad [5]$$

$$Q_0 = I \cdot e^{-(\mu+\mu^2/2)} \cdot \frac{x}{2}(1-x) \qquad [6]$$

$$\mu = (1 - x)\sqrt{s \cdot g} \qquad [7]$$

$$x = \frac{qC}{gs} \qquad [8]$$

$$N_{CR} = Q_B + qC + \sum_{sg} P(sg) \sum_{qC=0}^{sg-1} P(qC)\left(\frac{q}{s - q}\right)\left[Q_B\,(1 - f^{\,sg-qC}) + qC - sg\right] \qquad [9]$$

$$f = \frac{Q_B}{1 + Q_B} \qquad [10]$$

where:

q = Average arrival flow rate (vehicles/second),
s = Saturation flow rate (vehicles/second),
x = Volume to capacity ratio,
C = Cycle time (seconds),
r = Effective red interval (seconds),
g = Effective green interval (seconds),
I = Ratio of variance to the average arrival rate per cycle (1.0 for a Poisson distribution),
N_{CR} = Expected number of vehicle stops per cycle (stops/cycle),
Q_B = Expected queue size at beginning of cycle (vehicles),
$P(k)$ = Probability of having a queue of size k (set to 1.0 for $x \geq 1.0009$),
f = Probability of having a queue at the start of the cycle.

PROPOSED PARTIAL STOP MICROSCOPIC MODEL

Current state-of-the-art analytical approaches for estimating vehicle stops typically base their estimates on the number of vehicle arrivals when a queue exists at the stop line (during the red interval and the green interval when the queue is being served). Since all arriving vehicles are assumed to cross the intersection within a single cycle, these models are only valid for under-saturated conditions. Consequently, since the models only record a single stop for each arrival, they under-estimate the number of stops that are typically observed at over-saturated signalized intersections. Contrarily, Multiple stops are often made by vehicles attempting to cross an over-saturated intersection because these vehicles experience a series of stop-and-go cycles as they approach the intersection stop line.

Figure 1 illustrates the simulated speed profiles of a series of vehicles approaching an over-saturated intersection. In the first profile, it is observed that Vehicle 1 makes a single stop before crossing the intersection. In this case, the vehicle stops fairly close to the stop line, only to wait for the return of the green interval. In the second profile, Vehicle 13 decelerates to almost a full stop before accelerating back to its original speed. This vehicle does not have to make a full stop as it reaches the back of the queue that has formed during the previous red interval while all vehicles in the queue have already started to move. Later in the simulation, it is observed that Vehicle 19 makes a single partial stop before coming to a complete stop, while Vehicles 43, 85, 169, 241 and 334 make an increasing number of partial stops before finally coming to a full stop near the stop line.

In Figure 1, each deceleration/acceleration event corresponds to the discharge of a number of vehicles through the intersection during a green interval. In particular, the smaller oscillations that are observed in the figure for the vehicles arriving later within the simulation express a phenomenon that is often observed in congested areas. Because the acceleration of a vehicle is constrained by vehicle characteristics and the acceleration of other vehicles in front of it, the successive waves of moving vehicles created by the signal operations tend to merge as they move upstream the intersection approach, creating a situation where approaching vehicles travel at slow speeds until they get close to the intersection.

In the INTEGRATION model, the total number of stops experienced by a vehicle on a link is computed as the sum of the partial stops incurred every second by the vehicle while traveling along the link. As indicated by Equation 11, these partial stops are calculated for each vehicle as the ratio of the vehicle's instantaneous speed reduction over a one-second interval to the link free-speed. As an example, a reduction in speed from the free-speed to a speed of zero would be evaluated as a complete stop, while a reduction in speed from half the free-speed to a speed equal to one quarter the free-speed would constitute a quarter of a stop.

To illustrate the application of Equation 11, Figure 2 presents the speed profile of a vehicle approaching an under-saturated intersection. This profile, which was generated using the INTEGRATION model, illustrates a typical partial stop. The profile indicates that the vehicle starts to decelerate at time 935 and continues to do so until it decelerates to a speed of 10 km/h at time 942. Then, the vehicle accelerates back to its original speed. For this scenario, partial stops are computed by INTEGRATION using Equation 11 for each one-second interval between time 935 and time 942. The table shown in the figure indicates the results of the calculations. After summing the partial stops incurred during the entire deceleration movement, the model estimates that the vehicle made 0.848 stop.

Figure 3 illustrates the speed profile of a vehicle approaching an over-saturated intersection. Similar to Figure 2, this profile was generated using the INTEGRATION model. In this case, it is observed that the vehicle makes a series of decelerations and accelerations while approaching the intersection. For this scenario, the table shown in the figure presents the results of the partial stop estimations for each deceleration/acceleration event of Figure 3 using Equation 11. In this case, it is determined by summing the partial stops that constitute seven decelerations that the vehicle makes an equivalent of 2.24 full stops while attempting to cross the intersection.

$$S_i = \frac{u_{i-1} - u_i}{u_f} \qquad \forall\ i, \qquad \ni u_i < u_{i-1} \qquad [11]$$

where:

S_i = Estimated partial stops at time I,
u_i = Instantaneous speed of vehicle at time I,
u_f = Free-speed of roadway section.

PROPOSED ANALYTICAL MODEL FOR OVER-SATURATED CONDITIONS

Current state-of-the-art analytical stop estimation models assume that all vehicles joining a queue during a red interval are able to cross the intersection before the next red interval. However, this assumption is not necessarily valid in heavy flow conditions, as vehicles may be forced to stop more than once before being able to cross an intersection. When such conditions exist, it becomes almost impossible to find general equations for estimating the number of vehicle stops on intersection approaches using traditional queuing analysis approaches, particularly when considering stochastic arrivals.

This section presents the results of a research effort that lead to the generation of a stop estimation model for over-saturated conditions through the establishment of an upper bound for the number of vehicle stops in over-saturated conditions. The section briefly describes both the derivation of the equation for estimating the upper bound number of vehicle stops and the process that was utilized to generate an analytical model for estimating vehicle stops in over-saturated conditions using the upper bound stop estimates.

Upper Bound Number of Stops

If vehicles were assumed to incur a single stop at an over-saturated signalized approach then the total number of stops would be equal to the product of the arrival rate and the analysis period ($q.t_e$). This assumption of a single stop per vehicle represents a lower bound for the number of vehicle stops. On the other end, an upper bound for vehicle stops can be derived by assuming that vehicles caught in a queue incur an additional full stop for each cycle that the vehicle is not served. The derivation of this upper bound for the number of vehicle stops at signalized intersections can then be computed using queue length estimation equations. Specifically, the maximum number of vehicle stops can be computed as the number of vehicle arrivals while a queue exists at the intersection plus the overflow of vehicles that are not served during previous cycles assuming that vehicles always incur a full stop.

To illustrate the calculations, Figure 4 shows the first two cycles of a traffic signal operation at an over-saturated signalized approach with uniform arrivals. In this diagram, the maximum number of stops for the second cycle is equal to the sum of all arrivals during the second cycle, plus the demand that did not discharge during the previous cycle. The volume that is not served in the first cycle is computed as the difference between the cumulative arrivals and departures. Similarly, the maximum number of stops for the third cycle is computed using the cumulative arrivals during the analysis period plus the number of vehicles that remain to be served at the end of the second cycle. By generalizing the calculation process, Equation 12 is finally derived for computing an upper bound for the maximum number of stops at over-saturated signalized approaches over a given evaluation period (t_e).

$$N_{ub} = \frac{q \cdot t_e + \sum_{i=1}^{n-1} i \cdot (qC - sg)}{q \cdot t_e} \quad [12]$$

where:

N_{ub} = Upper bound average number of vehicle stops (stops/cycle),
q = Average arrival rate (vehicles/second),
s = Saturation flow rate (vehicles/second),
C = Cycle time (seconds),
g = Effective green time (seconds),
t_e = Evaluation period (seconds), and
n = Number of cycle lengths in analysis period (t_e/C).

Proposed Model for Over-saturated Conditions

Using stop estimates produced by the microscopic model of Equation 11, an adjustment factor as a function of the volume-to-capacity (v/c) ratio was developed to scale the upper bound vehicle stop estimates of Equation 12 to an actual estimate of stops. Specifically, the adjustment factor was developed using regression with the v/c ratio as the model's independent variable, as demonstrated in Equation 13 further down.

Figure 5 illustrates the fit of the adjustment factor to the ratio of the upper bound stop estimates (Equation 12) to the estimated number of vehicle stops (Equation 11) for v/c ratios that range from 1.0 to 2.0. The figure clearly demonstrates a good agreement between the adjustment factor regression curve and the estimated stop ratios as confirmed by the high coefficient of determination ($R^2 = 0.993$). The results also demonstrate that all chosen variables, the v/c ratio and the squared v/c ratio, are significant at a 95% confidence level. The figure further indicates that the adjustment model produces a correction factor that ranges from 1.0 at a v/c ratio of 1.0 to 0.5 at a v/c ratio of 2.0. This means that the adjustment model assumes that all the stops that are determined by the upper bound model are actual stops at a v/c ratio of 1.0, when traffic conditions are just saturated, and that only half the stops that are determined by the upper bound model are actual stops at a v/c ratio of 2.0.

Using the adjustment factor model of Equation 13, the model of Equation 14 was finally proposed to compute the average number of vehicle stops at over-saturated signalized approaches.

$$AF = 2.352 - 1.731x + 0.405x^2 \quad [13]$$

$$N_s = N_{ub} \times AF \quad [14]$$

where:

x = Volume to capacity ratio,
N_s = Average number of vehicle stops (stops/vehicle),
N_{ub} = Upper bound for average number of vehicle stops, computed using Equation 12 (stops/vehicle),
AF = Upper bound adjustment factor.

TEST SCENARIOS

To validate the models proposed in this paper, the number of stops incurred by vehicles on an approach to a signalized intersection was first estimated using the simulation model of Figure 6. Parallel to this estimation, the number of vehicle stops was also computed for the same approach using queuing theory, the Canadian Capacity Guide, and the Cronje model, as well as the proposed microscopic and analytical models. Two sets of test scenarios were also developed to validate the proposed models in both the under-saturated and over-saturated regimes.

In the first set of scenarios, stop estimates were obtained for a series of v/c ratios ranging from 0.1 to 1.0 at an increment of 0.1. In the second set, evaluations were carried out for v/c ratios between 1.0 and 2.0, again at an increment of 0.1. Within each set, calculations were also made assuming uniform and random arrivals. For the under-saturated scenarios, the proposed analytical model was not considered as this model was developed only for over-saturated conditions. For the over-saturated scenarios, all models were evaluated, except for the Canadian Capacity Guide model, which was designed only for application to under-saturated conditions.

For each scenario, stop estimates from the queuing theory, Canadian Capacity Guide and Cronje models were obtained by applying Equations 1, 2, 5 and 9. Similarly, Equation 14 was used to determine the stop estimates for the proposed analytical model for over-saturated conditions. For the proposed microscopic model, evaluations were made with the INTEGRATION software after Equation 11 had been coded into the software to allow it to report directly the estimated number of stops at the end of each simulation run. In order to ensure consistency in the stop units, the results of each calculation were converted to express an average number of stops per vehicle.

To account for the stochastic variability in the simulation runs and to ensure valid comparisons with other models, ten replications were made for each scenario that was evaluated with the INTEGRATION model. For the under-saturated scenarios, stop evaluations were conducted over a 15-minute simulation period that covered 15 traffic signal cycles. For the over-saturated scenarios, an additional 30-minute was simulated with no new traffic demand added to the test network in order to clear the network of any queues.

Comparison of Stop Estimates for Under-Saturated Conditions

Figures 8 and 9 illustrate the results of the evaluations for under-saturated conditions. When comparing both figures, it is observed that the queuing theory, Canadian Capacity Guide and Cronje models produce identical stop estimates for both uniform and random arrivals. Such results were expected given that these models were all derived assuming random arrivals and steady state conditions. As explained earlier, the main difference between the results from the uniform and random a arrival scenarios is that the stop estimates for the random scenarios express an average number of stops that may be incurred, while the estimates for the uniform arrival scenario express an exact number of stops that are incurred. In this case, it can be noted that considering uniform or random arrivals lead to the attribution of the same values to the parameters used in Equations 1, 2 and 5. It can also be observed that Equation 2 can be converted into Equation 1 if both sides of the equation are divided by the arrival flow rate q, if random arrivals (k_f =1.0) and a one-hour evaluation period (t_e = 60) are assumed, and if it is assumed that all arriving traffic are passenger cars (passenger car units of 1.0 for every vehicle).

In Figure 7, it is further observed that the microscopic model that was coded into INTEGRATION produces slightly lower stop estimates than the queuing theory, Canadian Capacity Guide and Cronje models when considering uniform arrivals. This difference is attributed to two primary factors. First, the INTEGRATION model considers only discrete vehicle departures while the theoretical models consider average hourly flows that may yield fractional number of vehicle arrivals within a traffic signal cycle. This difference in vehicle arrival modeling particularly explains the stepwise behavior the proposed microscopic model. Second, the car-following logic used by the INTEGRATION model allows vehicles to decelerate when they approach a queue of vehicles. In the theoretical models, vehicles only stop when they reach the back of the queue and instantaneously decelerate to a full stop. Consequently, these models always assume that vehicles make a complete stop when reaching a queue. In reality, some vehicles may only experience partial stops. For instance, partial stops would occur when vehicles intentiallu decelerate while approaching a queue so that they would reach the back of the queue shortly after the last queued vehicles would have started to move. As a result, it can be expected that the microscopic stop estimation model would typically produces slightly lower estimates than the other models.

Despite the above differences, it is generally observed that the estimates for the proposed microscopic model are consistent with those from the theoretical models. Figure 8, in particular, indicates a general agreement between the various models for the scenarios considering random arrivals. In this case, the proposed microscopic model produced stop estimates that generally follow those from the queuing theory, Canadian Capacity Guide, and Cronje models, especially for v/c ratios of less than 0.9. As traffic demand approaches saturation (v/c ratio of 1.0), it is also observed that a general disagreement appears between the proposed microscopic model and the three theoretical models. This is explained by differences in the stochastic processes used by the INTEGRATION model to simulate traffic behavior and the random processes from which the theoretical models are derived.

Comparison of Stop Estimates for Over-Saturated Conditions

Figure 9 and 10 illustrate the results of the evaluations for over-saturated conditions. When comparing both figures it is observed that there are general disagreements between the various models. On one hand, both the queuing theory and Cronje models produce stop estimates that reach infinity at a v/c ratio of 2.0 and exceed the upper bound of Equation 12 for v/c ratios above 1.7. On the other hand, the estimates produced by the proposed microscopic model remain within a relatively narrow range. For this model, the estimates did not exceed a value of 2.27 stops per vehicle in the presence of uniform arrivals, and 2.30 in the presence of random arrivals.

The asymptotic behavior of the queuing theory and Cronje models is attributed to the fact that these models were developed assuming steady-state conditions. While such assumptions are valid for under-saturated conditions, steady-state conditions rarely exist for an extended period in the over-saturation domain. In reality, any peak period of traffic ends at a point in time. At the end of the period, the arrival rate diminishes, allowing the queues that have formed to gradually dissipate. In both the queuing theory and Cronje models, the assumption of steady-state conditions results in a constant demand hypothesis, which leads to a situation in which the queues are assumed to never cease to grow.

For the proposed microscopic model, the maximum of 2.27 and 2.30 stops per vehicles for uniform and random arrivals is explained by typical traffic behavior. Referring back to Figure 1, it is observed that vehicles arriving later in time at an over-saturated intersection often do not stop until they get close to the stop line. Furthermore, most vehicles do not accelerate to full free-speed, which by definition results in vehicles incurring only partial stops. These constraints, which are considered by the INTEGRATION simulation model, thus leads the proposed microscopic model to estimate numbers of vehicle stops on over-saturated approaches that are less than the number of cycles taken by individual vehicles to reach the intersection stop line.

In Figures 10 and 11, it is further observed that the stop estimates for the scenarios involving uniform and random arrivals are generally similar. This similarity is explained by the fact that the introduction of randomness in the arrival pattern has very little impact on the simulation results due to the presence of a large number of queued vehicles on the intersection approach. While vehicles arrive randomly at the back of the queue, the signal operations tend to release vehicles at a uniform rate, thus reducing the randomness in traffic behavior.

In general, it is observed that there is consistency between the proposed microscopic model and the proposed analytical model in over-saturated conditions for both the uniform and random scenarios. In particular, it is observed that the estimates from the two models never exceed the proposed upper bound and appear to follow a trend similar to the upper bound. The results, as well as the comparisons with the theoretical models, thus generally confirm the validity of the two proposed models and their applicability to the evaluation of the number of stops incurred by vehicles at signalized intersections.

CONCLUSIONS

The paper presents two approaches for estimating vehicle stops at signalized intersections. The first model computes and sums up the instantaneous partial vehicle stops in real-time to compute trip-wide stop estimates. This model is ideal for usage within a microscopic simulation environment and in real-time or off-line to Global Positioning System (GPS) field speed measurements. The paper also proposes an analytical model for estimating vehicle stops at over-saturated intersections. The model uses the signal timings, approach arrival rate, approach saturation flow rate, and analysis period as independent variables for estimating vehicle stops. Such a model is ideal for estimating stops in the field when data are not available on vehicle speed profiles.

Validation of the microscopic instantaneous model demonstrated consistency with current state-of-practice stop estimation models for under-saturated signalized approaches. Because current state-of-practice stop estimation models are generally inaccurate when signalized intersection approaches experience over-saturation, the over-saturation validation effort only involved comparing the microscopic and proposed analytical models.

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LIST OF FIGURES

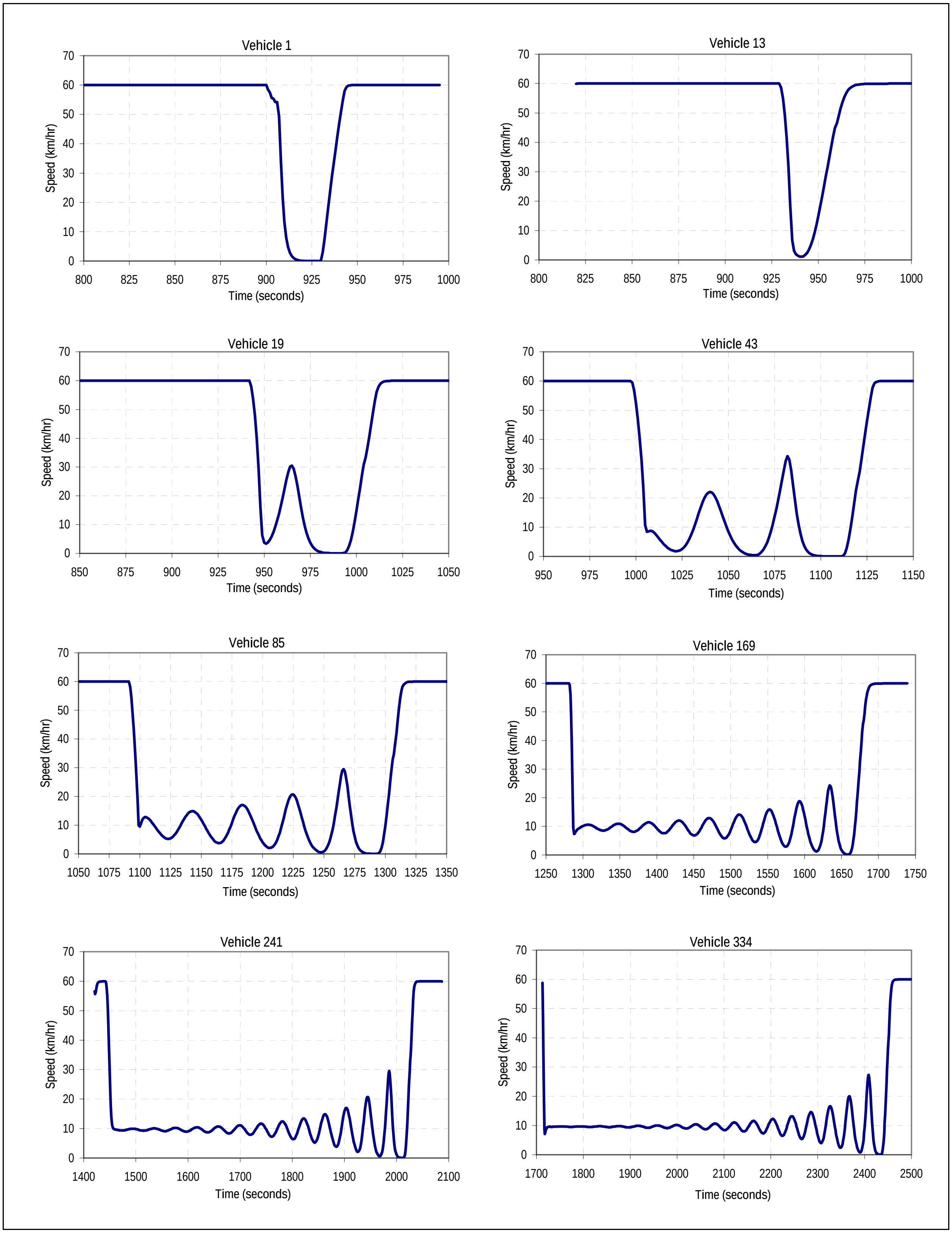
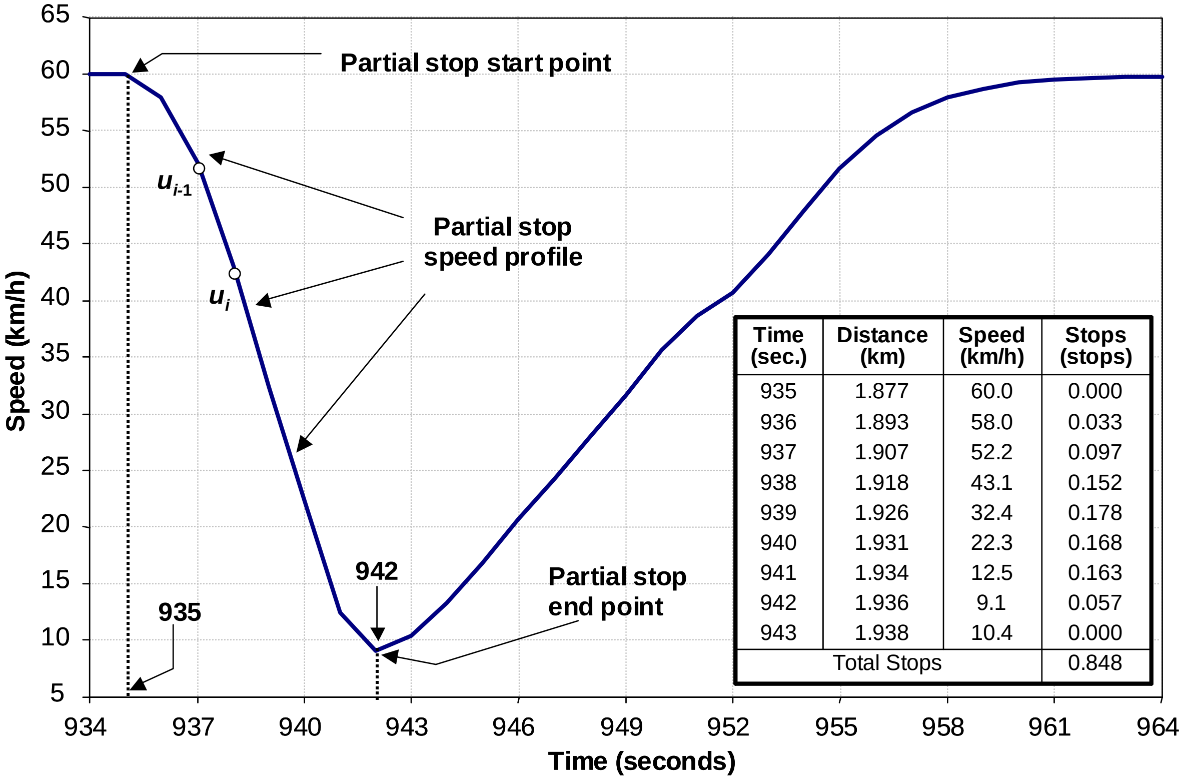
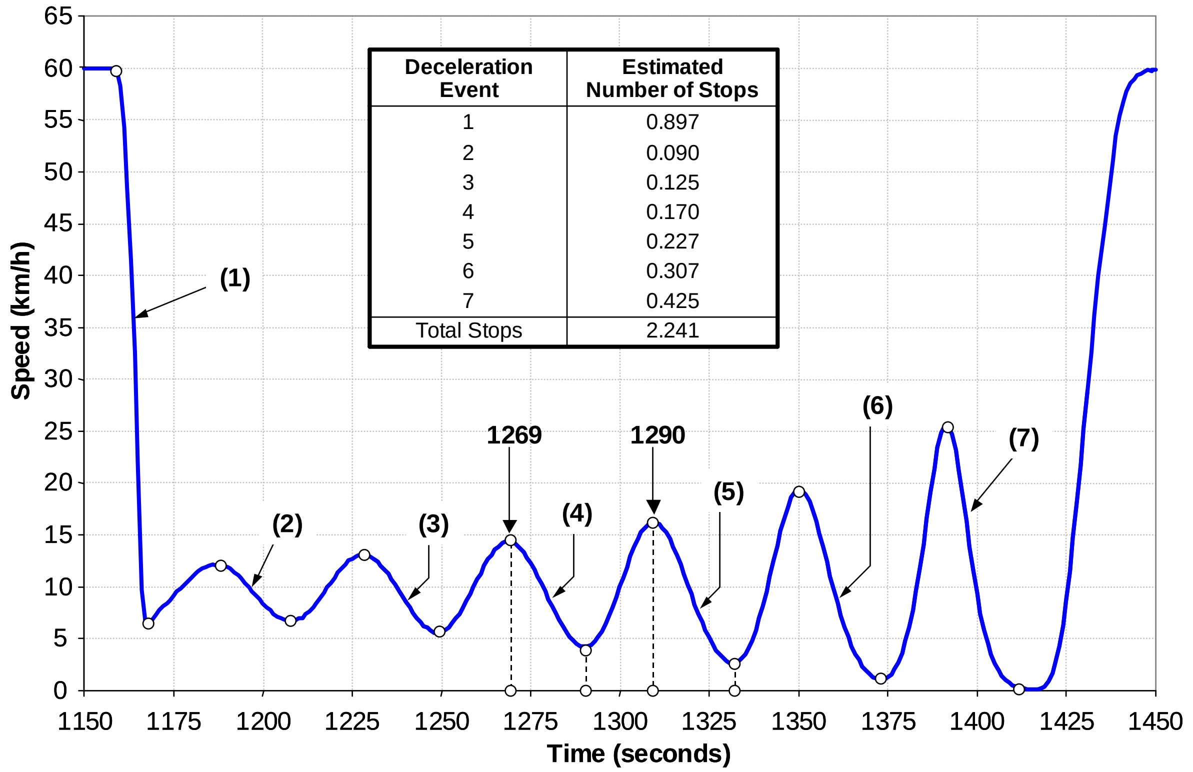


FIGURE 1: Simulated Speed Profile of Selected Vehicles in INTEGRATION



Time (sec.)	Distance (km)	Speed (km/h)	Stops (stops)
935	1.877	60.0	0.000
936	1.893	58.0	0.033
937	1.907	52.2	0.097
938	1.918	43.1	0.152
939	1.926	32.4	0.178
940	1.931	22.3	0.168
941	1.934	12.5	0.163
942	1.936	9.1	0.057
943	1.938	10.4	0.000
Total Stops			0.848

FIGURE 2: Partial Stop on an Under-saturated Intersection Approach



Deceleration Event	Estimated Number of Stops
1	0.897
2	0.090
3	0.125
4	0.170
5	0.227
6	0.307
7	0.425
Total Stops	2.241

FIGURE 3: Sequence of Partial Stops on an Over-saturated Intersection Approach

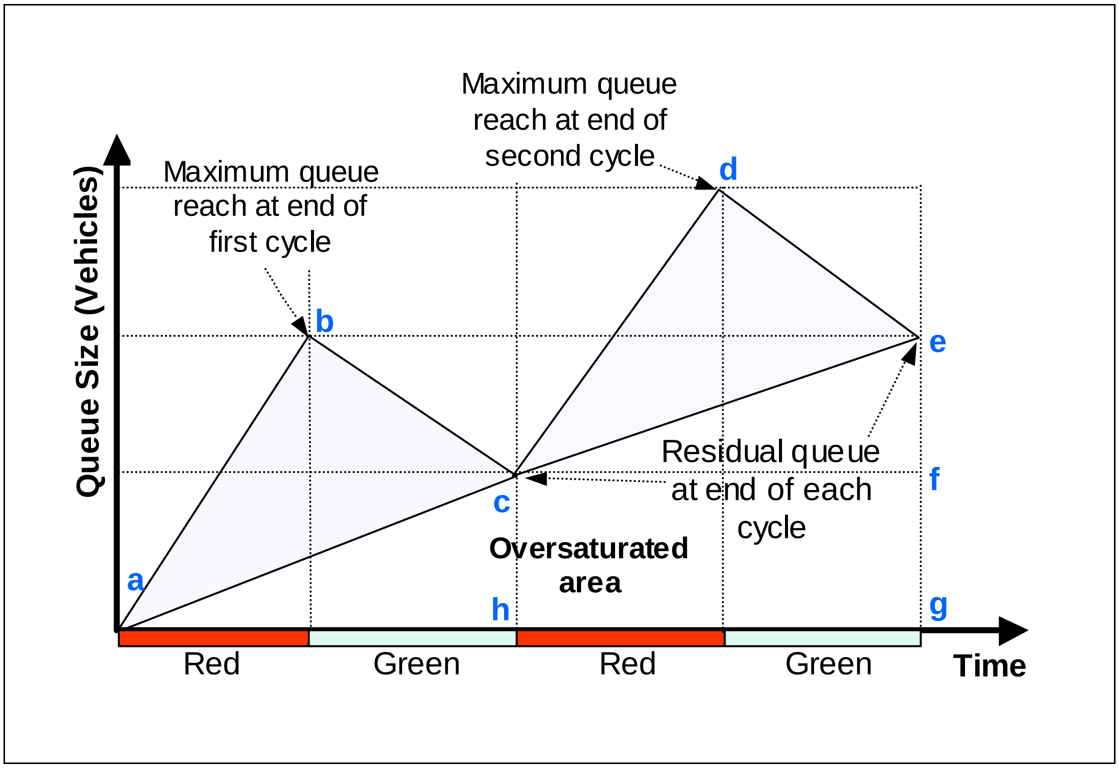
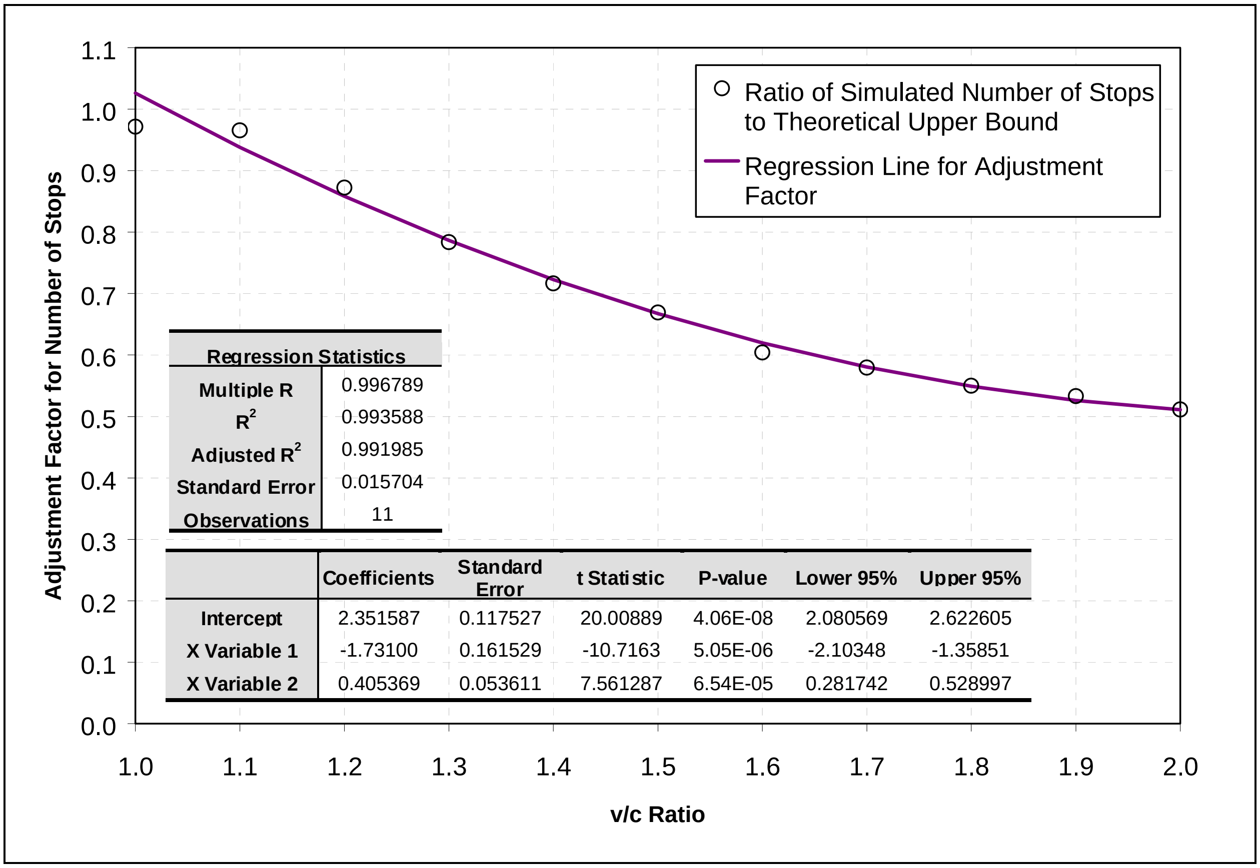


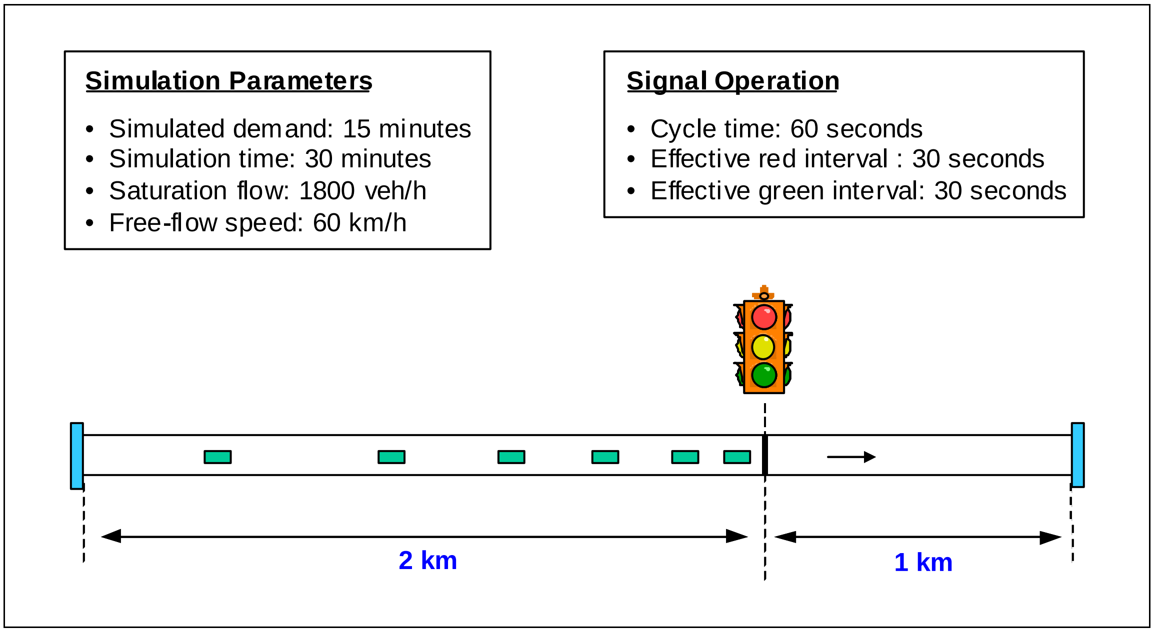
FIGURE 4: Queuing Diagram Analysis for Over-Saturated Conditions



Regression Statistics	
Multiple R	0.996789
R^2	0.993588
Adjusted R^2	0.991985
Standard Error	0.015704
Observations	11

	Coefficients	Standard Error	t Statistic	P-value	Lower 95%	Upper 95%
Intercept	2.351587	0.117527	20.00889	4.06E-08	2.080569	2.622605
X Variable 1	-1.73100	0.161529	-10.7163	5.05E-06	-2.10348	-1.35851
X Variable 2	0.405369	0.053611	7.561287	6.54E-05	0.281742	0.528997

FIGURE 5: Comparison of Simulated Stop Ratio and Stop Adjustment Factor



Simulation Parameters

- Simulated demand: 15 minutes
- Simulation time: 30 minutes
- Saturation flow: 1800 veh/h
- Free-flow speed: 60 km/h

Signal Operation

- Cycle time: 60 seconds
- Effective red interval : 30 seconds
- Effective green interval: 30 seconds

FIGURE 6. Evaluation Scenarios

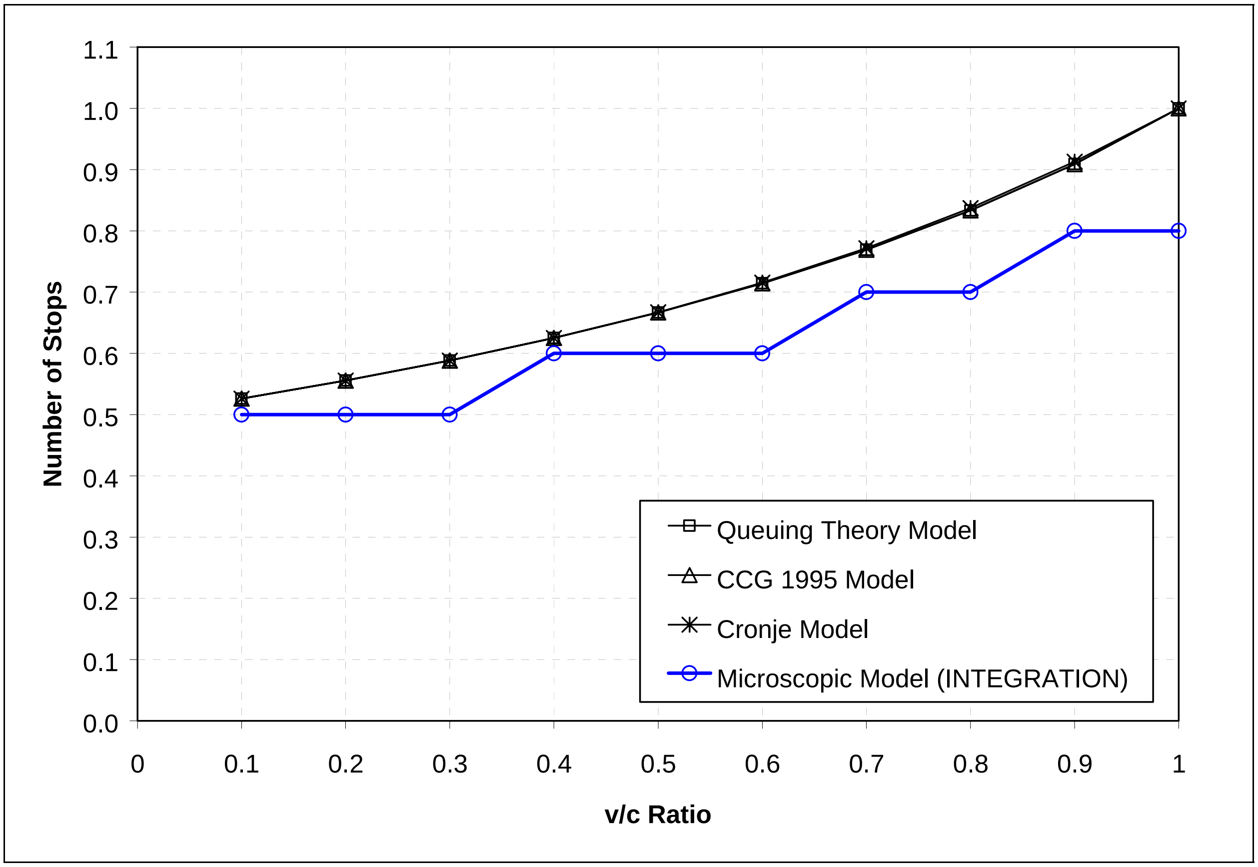


FIGURE 7: Number of Stops Estimates under Uniform Arrivals for Under-saturated Conditions

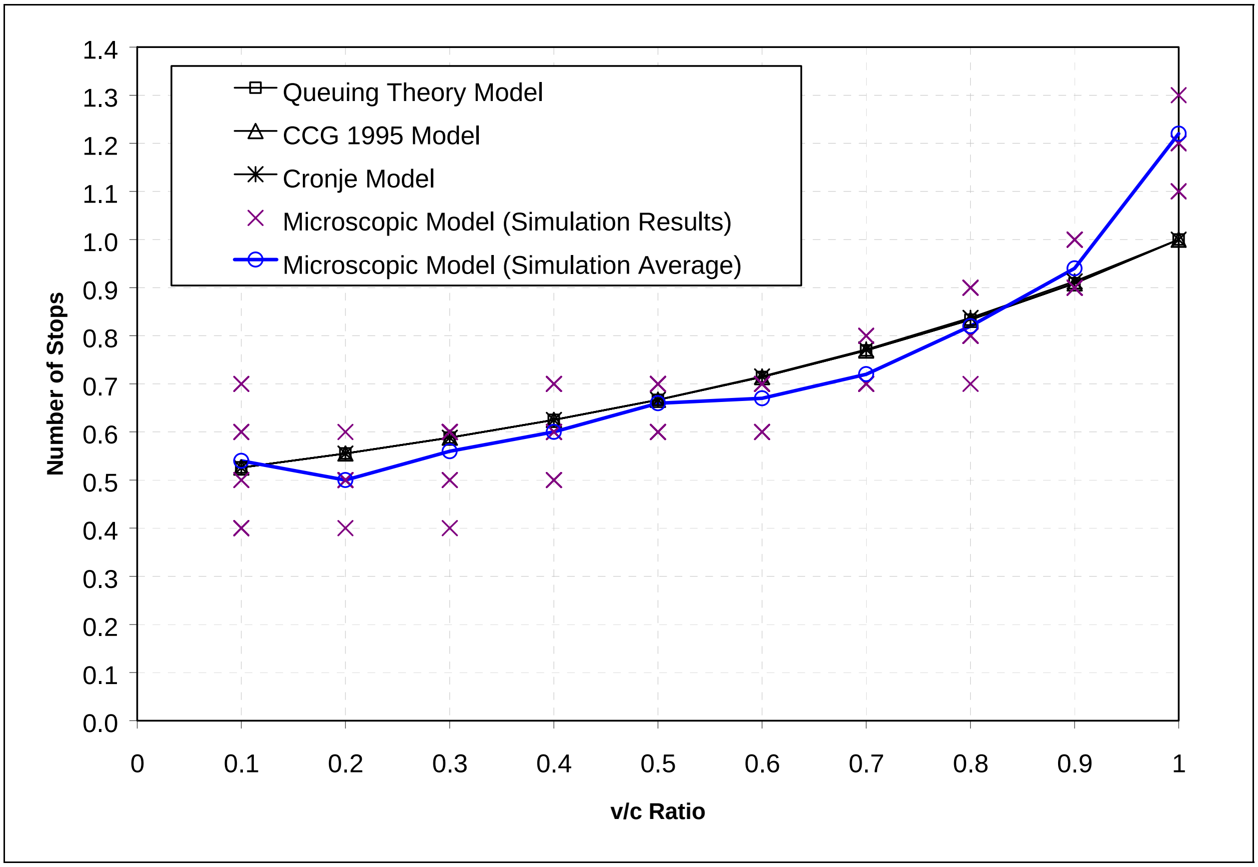


FIGURE 8: Number of Stops Estimates under Stochastic Arrivals for Under-saturated Conditions

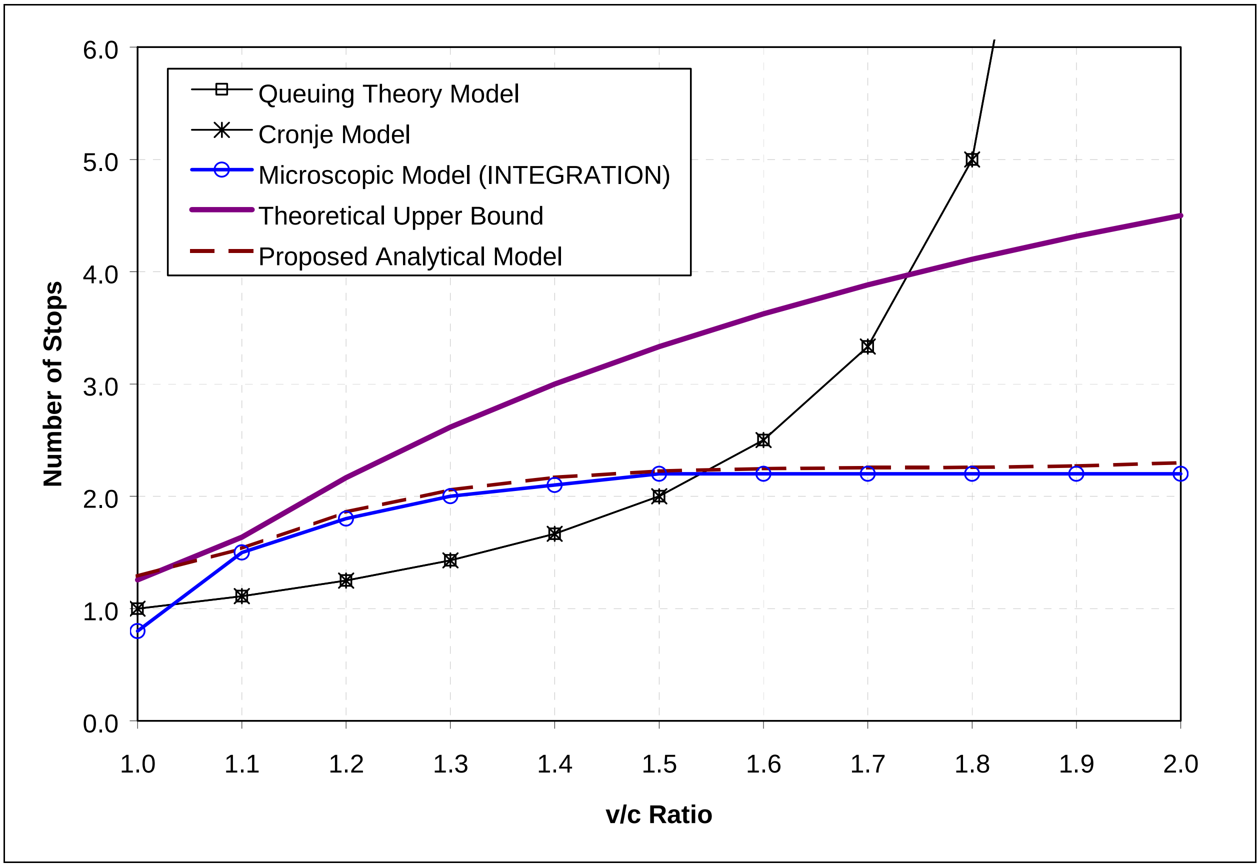


FIGURE 9: Number of Stops Estimates under Uniform Arrivals for Over-saturated Conditions

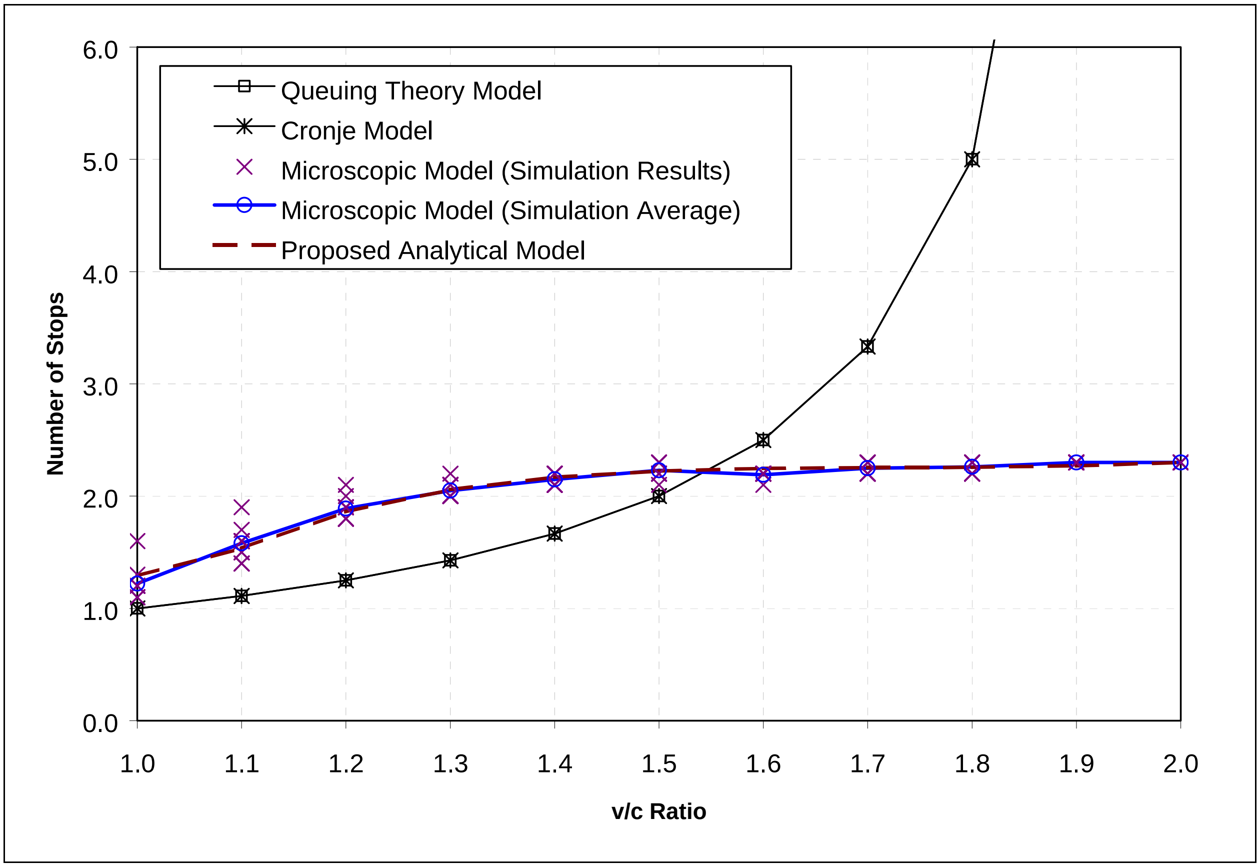


FIGURE 10: Number of Stops Estimates with Random Arrivals for Over-saturated Conditions