CHAPTER 7

IMPACT OF MIXED TRAFFIC ON DELAY AND STOP ESTIMATES AT SIGNALIZED APPROACHES

As discussed in previous chapters, delay incurred by vehicles approaching signalized intersections is an important criterion for the evaluation of traffic performance at these intersections. Reflecting this importance, various models have been developed to estimate the delay caused to traffic by the operation of traffic signals. However, all these models are based on homogeneous traffic conditions, consequently, these models may not estimate the delays satisfactorily under mixed (heterogeneous) traffic conditions. This matter is investigated in this chapter, which conducts an analysis using the INTEGRATION microscopic traffic simulation model to evaluate the impact of mixed traffic conditions on delay estimates.

7.1 INTRODUCTION

Signalized intersections are vital nodal points in a transportation network and their efficiency of operation greatly influences the entire network's performance. Traffic signals are installed at these nodal points in order to allocate the right-of-way to the different competing streams of vehicles passing through the intersection. Pretimed signals, which are the most common type in use, typically rotate through preset signal timing patterns, which are determined in such a way as to maximize the intersection's level of service.

The level of service at a signalized intersection can be assessed based on various criteria. However, delay incurred on vehicles is traditionally the most important criterion because its meaning is generally well understood and by the driving population.

Various models have been developed to estimate the delay incurred by vehicles at traffic signalized intersections. However, most of the previous research efforts have focused on fairly homogeneous traffic arrivals at signalized intersections. Unfortunately, non-homogeneous traffic is a more typical occurrence than homogeneous traffic at urban intersections. At many intersections, vehicles with wide-ranging static and dynamic characteristics can indeed be observed. Moreover, the lateral and longitudinal placements of vehicles on the carriageway are complex, with no discernible lane discipline. To further complicate matters, these non-homogeneous traffics behave differently with some of the traffic stream stopping and bus stops as is the case with buses.

7.2 OBJECTIVES AND LAYOUT OF THE CHAPTER

The objective of this chapter is twofold. First, it demonstrates the unique capabilities of the INTEGRATION software for the evaluation of heterogeneous signalized approaches. Second, it demonstrates the limitations of the current state-of-the-practice analytical models for the evaluation of typical signalized intersections.

In achieving these objectives, four test scenarios are evaluated, as summarized in Table 4.1. The first of these scenarios considers homogeneous vehicle arrivals at a signalized intersection. This scenario serves as a base case for the evaluation of the impacts of mixed traffic flow. The second scenario introduces different levels of transit demand in order to quantify the additional delay associated with mixed flow.

Having established the consistency of the INTEGRATION MOE estimates with the state-of-the-art analytical models in previous chapters, two scenarios are introduced. The first of these scenarios involves the conversion of transit vehicle length differential. The second scenario involves creating vehicle equivalencies based on vehicle ridership. Each of these scenarios is compared to the mixed flow scenario in order to establish the inaccuracies that are associated homogeneous flow approximation.

7.3 TEST SCENARIOS

In order to evaluate the impact of mixed traffic conditions on MOEs at signalized intersections, a four approach signalized intersection was analyzed, as illustrated in Figure 7.1. The four-legged signalized intersection operated at a fixed-time plan of 100 seconds with 50:50 phase split. The figure further indicates that both the eastbound and westbound approaches are two-lane approaches, while both the northbound and southbound are single lane approaches. In addition, a bus stop is located on the eastbound approach 50 meters upstream the intersection. Buses stop at the bus stop load and unload passengers. Bus headways ranging from 1 to 10 minutes were analyzed. The length of bus was assumed to be twice that of passenger car. Bus ridership was assumed to be 15 while passenger car ridership was to be 1.0. Bus dwell times at a bus stop and covariance (COV) are assumed to be 30 seconds and 0.2, respectively. The implications of these parameters are discussed in Scenario 2. It should be note that COV was defined as the variability in bus dwell times at a bus stop at a station. For example, if the dwell time of a bus is 30 seconds and the COV set equal to 0.2, a bus will stay at a station between 24 seconds and 36 seconds. Both the northbound and southbound approaches are 0.5-km long, while both the eastbound approach is 1-km long and westbound approach is 0.5-km long. In addition, the performance of buses is the same as the passenger car units.

Table 7.1: Possible Discrete Values by Scenarios

Homogeneous Traffic Flow (pcu/h)			Mixed Traffic Flow
Basic Volume	**PCE by Vehicle Length**	**PCE by Vehicle Ridership**	**Bus Headway** (minute)
600	120	900	1
800	60	450	2
1000	40	300	3
1200	24	180	5
1400	12	90	10

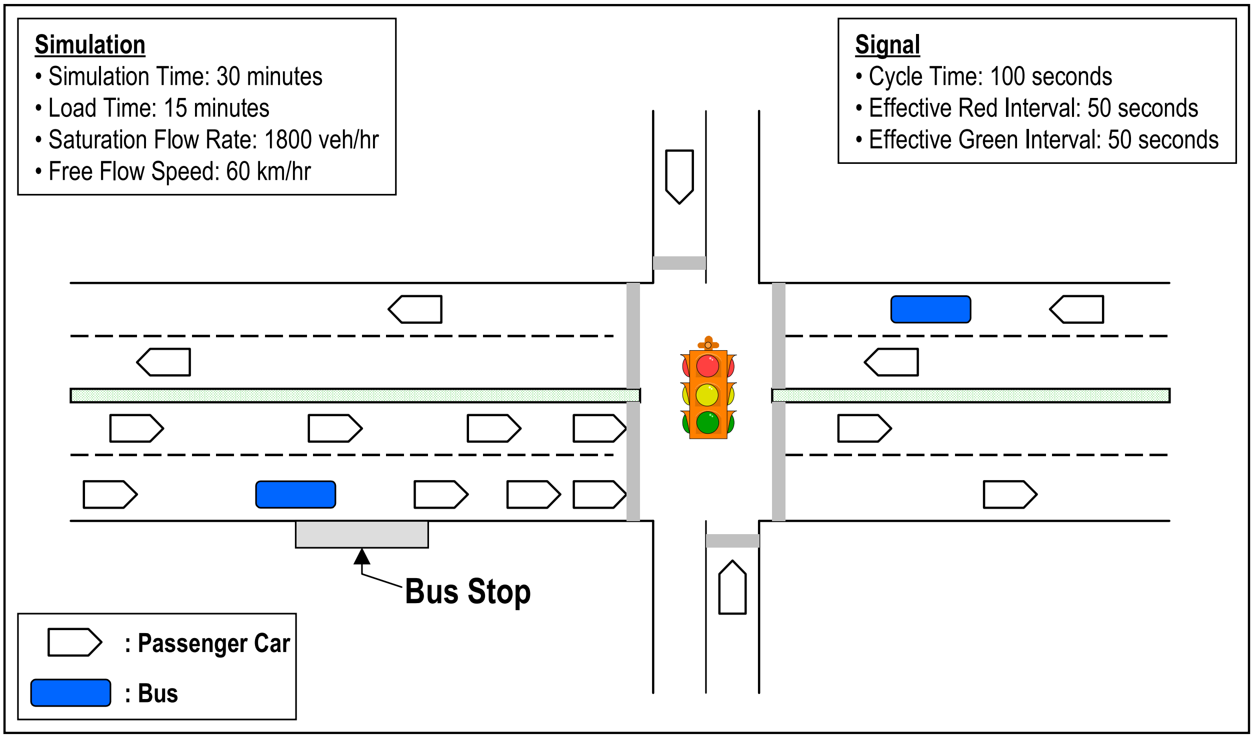

Figure 7.1: Evaluation for Impact of Mixed Traffic Flow Scenario

Using the above setting, four sets of test scenarios were conducted to evaluate the impact of mixed traffic conditions on overall vehicle delay, person delay and number of vehicle stops estimates in a range of traffic conditions. The first set considers homogeneous traffic conditions, while the third and the fourth sets add more vehicles to the volumes of the first set to reflect the passenger car equivalencies associated with buses based on vehicle length and ridership. All these three scenarios are identical, except for the vehicle arrival rate. The second set explicitly models buses as a vehicle class as passenger car equivalencies within the INTEGRATION traffic simulation model instead of considering them. In this scenario, the volumes, number of passengers on the bus and bus headways remain variables, while the bus dwell time at a bus stop, COV and distance of bus station from the signal stop line retain the same values as previously described. The acceleration and deceleration behavior of buses and passenger cars were assumed to be identical for purposes of this analysis. The above four sets of test scenarios were performed forming a total of 80 simulation runs. Table 7.2 shows the summary of the descriptions and number of simulation runs of each scenario.

Table 7.2: Descriptions and Number of Runs in Each Scenario

Scenarios	Descriptions	Simulation Run
1	Basic Homogeneous Flow	5
2	Mixed (Heterogeneous) Flow (PCU and Bus)	25
3	Homogeneous Flow based on Length Equivalency	25
4	Homogeneous Flow based on Ridership Equivalency	25
Total Run		80

7.4 TEST RESULTS

7.4.1 SCENARIO 1: BASIC HOMOGENEOUS FLOW

A simple but fundamental starting point in the evaluation of the impact of mixed traffic flow conditions is to quantify the difference of MOEs in total intersection volume with only passenger car units, i.e., assuming no buses on network. Table 7.3 presents the results of the simulation runs conducted with INTEGRATION for the five volume levels defined in Table 7.1. It should be noted that the table was generated using 15-minute observations for each traffic flow rate. As it can be observed, the average overall delay estimates of 1400 veh/h increases by 15 percent when compared to the average overall delay estimates of 600 veh/h. This increase in delay was expected, as delay is usually a function of traffic demand increases. In addition, it can also be observed that the average number of vehicle stops increases by 3 percents between the 600 and 1400 veh/h scenarios. Figure 7.2 illustrates the average overall delay estimates as a function of the approach volume. It should be noted that the average overall vehicle delays are equivalent to the average person delays for homogeneous traffic flow given that the vehicle occupancy is 1.0.

This scenario is most interesting from a theoretical standpoint since the case of homogeneous traffic is not realistic. However, this scenario does serve as a good starting point to understand the fundamental operation of a signalized intersection on delay estimates. Given this base scenario, the implementation of mixed traffic conditions can now be considered, as is shown in subsequent sections. The v/c ratio in these scenarios varies from a low of 30 percent to a high of 78 percent. The upper limit of 78 percent provides a buffer to add buses to the traffic demand without necessarily resulting in oversaturation.

Table 7.3: Summary of Network Simulation Results for Scenario 1

MOEs	Volume (vehicles/hour)				
	600	800	1000	1200	1400
Avg. Overall Delay (seconds)	32.216	31.939	34.241	36.282	37.806
Avg. Person Delay (seconds)	32.216	31.939	34.241	36.282	37.806
Avg. Number of Stops	0.651	0.657	0.675	0.678	0.675

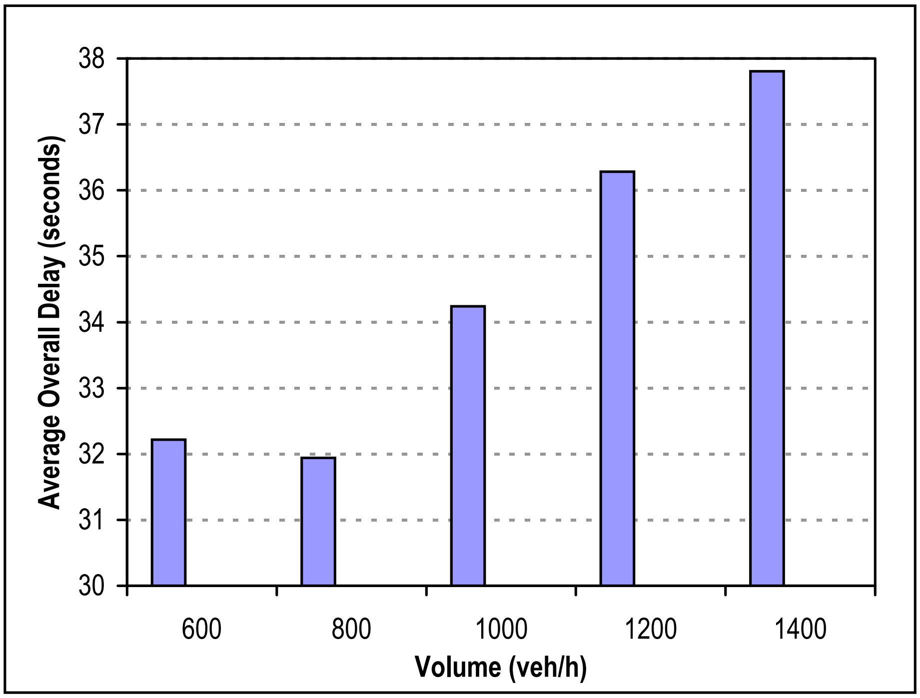

Figure 7.2: Average Overall Delay Estimates for Scenario 1

7.4.2 Scenario 2: Mixed (Heterogeneous) Traffic Flow

In this scenario, an optional input file for bus stop was added in the INTEGRATION model to simulate real mixed traffic, not just increasing volumes based on some bus headway equivalency. The optional input file, as shown in Appendix A, provides the bus dwell time at bus stop, the COV and the distance of the bus stop from the downstream signal stop line. As mentioned before, the distance of the bus stop from the signal stop line was assumed to be 50 meters. The mean dwell time that a bus remains stopped at a bus stop was held constant at 30 seconds, while the COV was set equal to 0.2. To analyze this scenario, simulations were carried out by varying the approach volume, the bus headway, and the number of passengers on the bus. Each of these scenarios included 5 levels, which resulted in a table of 125 simulation runs (5×5×5). However, this scenario was analyzed only for the results of 15 ridership simulation runs since the bus ridership was assumed to be 15.

7.4.2.1 Comparison of Average Overall Vehicle Delay Estimates

Table 7.4 and Figure 7.3 provide the average overall delay estimates that were obtained by varying the volume and bus headway. The results indicate, comparing the scenarios with various headways, that the average overall delay estimates increase by 4 percent when headways are decreased from 10 to 1 minutes within a constant 600 veh/h flow. In case of an arrival rate of 1400 veh/h, there appears to be a more significant increase in the average overall delay between bus headways, i.e., 81 percents between 1 and 10 minutes bus headways. Consequently, the bus headway impact increases as the level of congestion increases.

Table 7.4: Average Overall Delay Estimates for Scenario 2

Bus Headway (minutes)	Volume (vehicles/hour)				
	600	800	1000	1200	1400
1	33.355	33.868	39.660	52.632	72.132
2	32.820	33.347	36.192	39.531	43.391
3	32.277	32.387	34.495	37.717	41.396
5	32.175	31.796	34.238	36.267	37.296
10	32.022	31.685	33.992	36.212	39.752

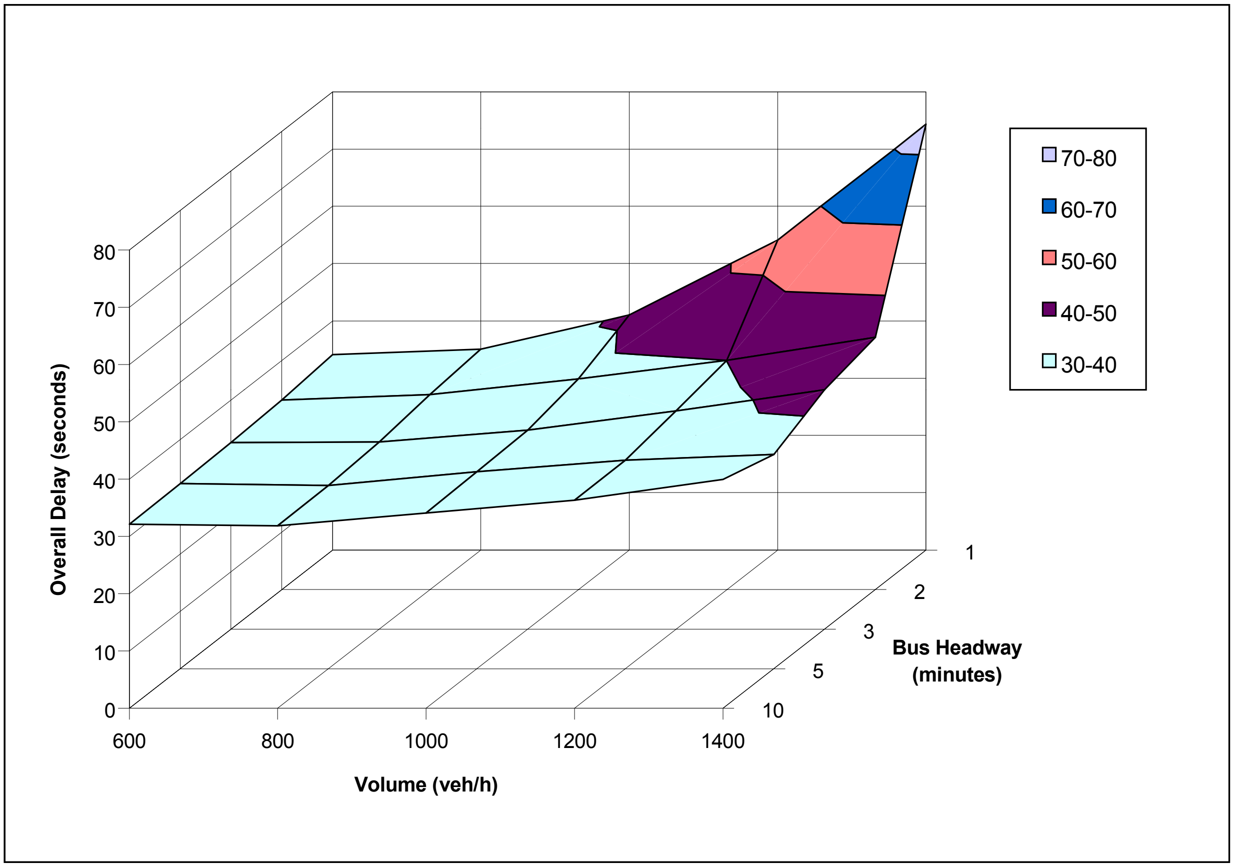

Figure 7.3: Average Overall Delay Estimates for Scenario 2

Table 7.5 reports the results of percentage differences in the average overall vehicle delay estimates between scenarios including buses and scenarios that do not. In this table, it is observed that the average overall delays increases between 0.08 and 95.4 percent depending of the level of congestion and the frequency of buses introduced. Specifically, the buses result in minor disturbance to traffic when the v/c ratio is less than 0.5, however, the impact of buses is significant at a v/c ratio of 0.78 when the frequency of buses exceeds 30 buses/h (headway = 2 minutes). Figure 7.4 illustrates the differences of the average overall delay estimates between scenario 1 and scenario 2. From the results of Figure 7.4, there is a marginal difference between the delays from scenario 1 and the delays predicted by scenario 2, except for bus headways of 1 minute.

Table 7.5: Percent Change in Average Overall Delay Estimates between Scenario 1 and 2

Bus Headway (minutes)	Volume (vehicles/hour)				
	600	800	1000	1200	1400
1	4.24%	7.50%	16.95%	46.70%	95.43%
2	2.57%	5.84%	6.72%	10.19%	17.56%
3	0.87%	2.80%	1.72%	5.13%	12.15%
5	0.56%	0.92%	0.96%	1.09%	1.05%
10	0.08%	0.57%	0.23%	0.93%	7.70%

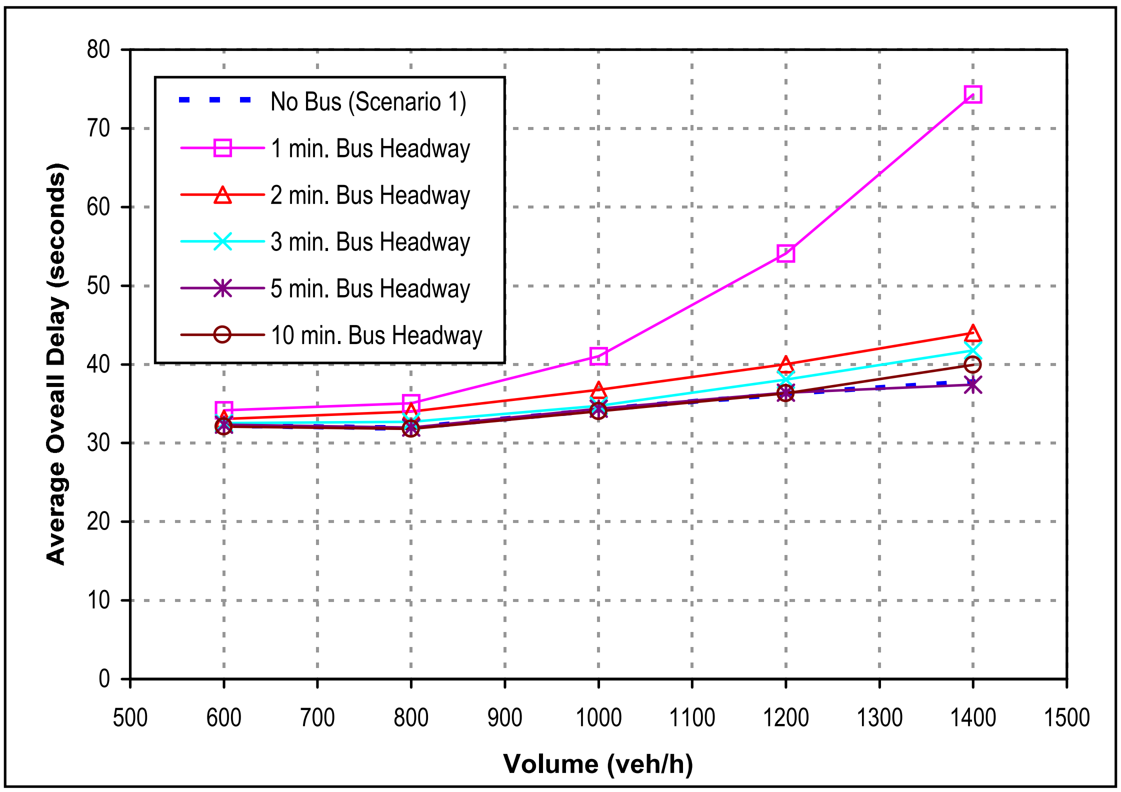

Figure 7.4: Comparison of Average Overall Delay Estimates between Scenario 1 and 2

7.4.2.2 Comparison of Average Person Delay Estimates

So far, this research has dealt with only vehicle delay estimates. In this section, average person delay estimates are introduced as a new MOE. The average person delay estimates produced by the INTEGRATION model can be computed by considering how long an average person takes to reach his/her arrival point from the time they left their departure point within the simulated network. Table 7.6 and Figure 7.5 provide the results of the average person delay estimates. It should be noted that the research assumed an average of 15 passengers on a bus. The results indicate that there is a general agreement with the average person delay estimates in bus headways of 2, 3, 5, 10 minutes, except for person delay estimates of 1-minute bus headway. The average person delay estimates of 1-minute bus headway produced significantly higher person delays than the other delay estimates. This is the fact that the bus headway of 1 minute produced more traffic congestion. In addition, Table 7.6 reports a 46 percent increase in the average person delay estimates between volumes of 600 veh/h and 1400 veh/h compared to a 10 percent decrease for a bus headway of 10 minutes. The reason we observe a reduction in person delay stems from the fact that the increase in vehicle delay (numerator) is less than the increase in the total number of person traveling (denominator). Alternatively, for higher background traffic the introduction of buses results in not only higher travel times for the surrounding traffic but also higher delays for the buses, which increases the total person delay relative to the base case.

Table 7.6: Average Person Delay Estimates for Scenario 2

Bus Headway (minutes)	Volume (vehicles/hour)				
	600	800	1000	1200	1400
1	34.912	39.667	50.503	64.121	92.104
2	27.674	33.312	35.948	38.015	45.347
3	25.818	28.604	30.335	35.963	40.728
5	23.818	24.643	27.593	29.866	31.698
10	22.339	23.668	25.947	29.982	34.144

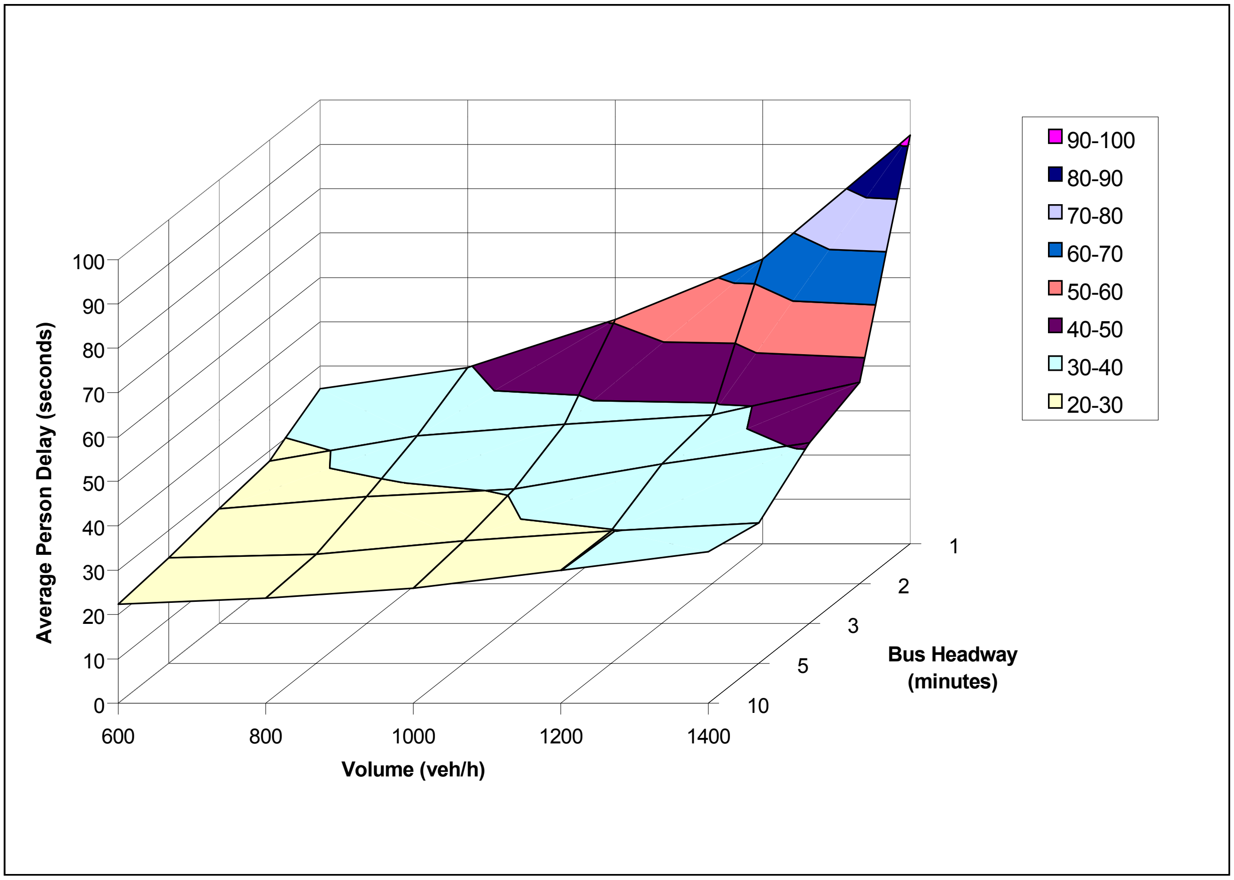

Figure 7.5: Average Person Delay Estimates for Scenario 2

The results of Table 7.7 and Figure 7.6 report that there is a significant difference in the average person delay estimates between scenarios including buses and scenarios that do not for bus headways of 1 minute. In this table, it is observed that the average person delay increased by 143.6 percents for a v/c ratio of 0.78 when the bus headway was assumed to be 1 minute. On the contrary, the average person delays decreased by 9.7 percents when compared to scenario 1 assuming 10 minutes bus headways. The results that presented in Table 7.7 indicate the complexity of the problem.

Table 7.7: Percent Change in Average Person Delay between Scenario 1 and 2

Bus Headway (minutes)	Volume (vehicles/hour)				
	600	800	1000	1200	1400
1	**8.37%**	**24.20%**	**47.49%**	**76.73%**	**143.62%**
2	-14.10%	4.30%	4.99%	4.78%	19.95%
3	-19.86%	-10.44%	-11.41%	-0.88%	7.73%
5	-26.07%	-22.84%	-19.42%	-17.68%	-16.16%
10	-30.66%	-25.90%	-24.22%	-17.36%	-9.69%

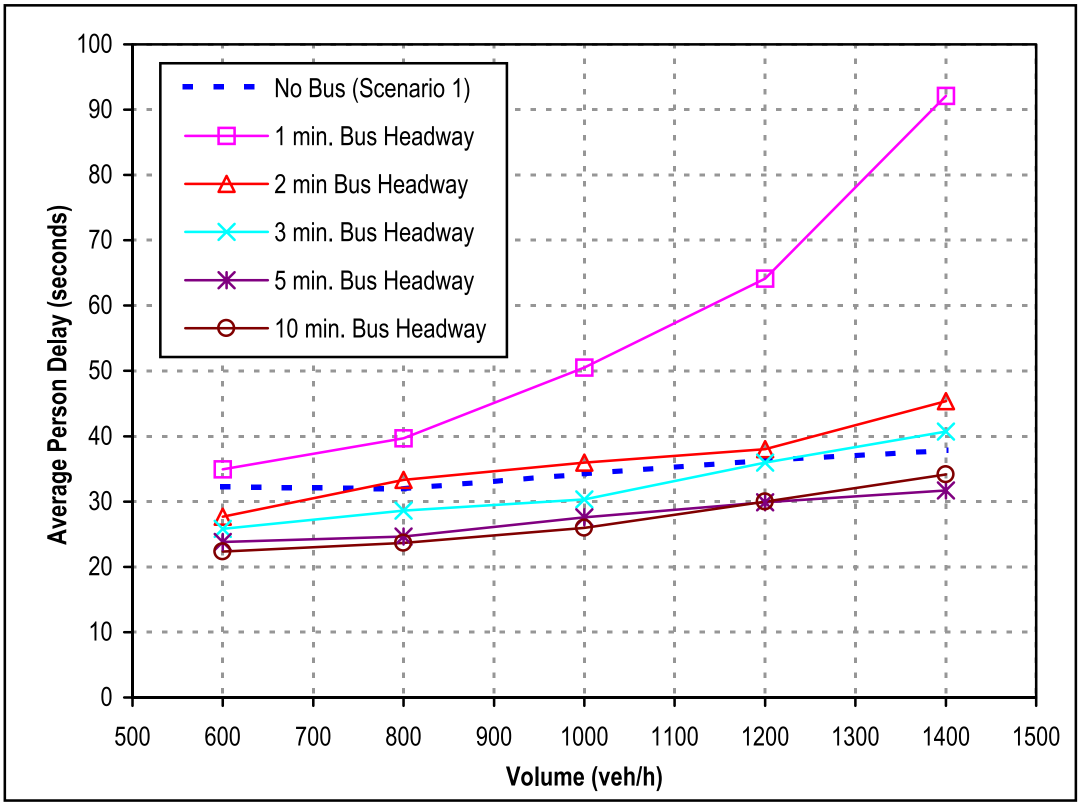

Figure 7.6: Comparison of Average Person Delay Estimates between Scenario 1 and 2

7.4.2.3 Comparison of Average Number of Stops Estimates

As was described in Chapter 6, the number of vehicle stops can be computed as the summation of the partial stops incurred by a vehicle each second as is computed within the INTEGRATION model using Equation 6.1. The results of Table 7.8 and Figure 7.7 report the average number of stops estimated within the model for the various heterogeneous scenarios. As it can be observed, there is a 53 percent increase between volumes of 600 veh/h and 1400 veh/h when the bus headway is 1 minute compared to a 10 percent increase when the bus headway is 10 minutes as shown in Table 7.8. The first observation from the table is that the introduction of buses at a rate of 60 buses/h (headway of 1 minute) to the background arrival rate of 1400 veh/h (v/c ratio of 0.78) results in oversaturation (average number of stops exceed 1.0). This explains the higher delays that were observed for the 1400 veh/h and 1-minute bus headway scenario.

Table 7.8: Average Number of Stops Estimates for Scenario 2

Bus Headway (minutes)	Volume (vehicles/hour)				
	600	800	1000	1200	1400
1	0.716	0.751	0.857	0.979	1.093
2	0.687	0.707	0.745	0.775	0.811
3	0.669	0.688	0.708	0.730	0.761
5	0.667	0.668	0.690	0.689	0.687
10	0.654	0.673	0.682	0.697	0.723

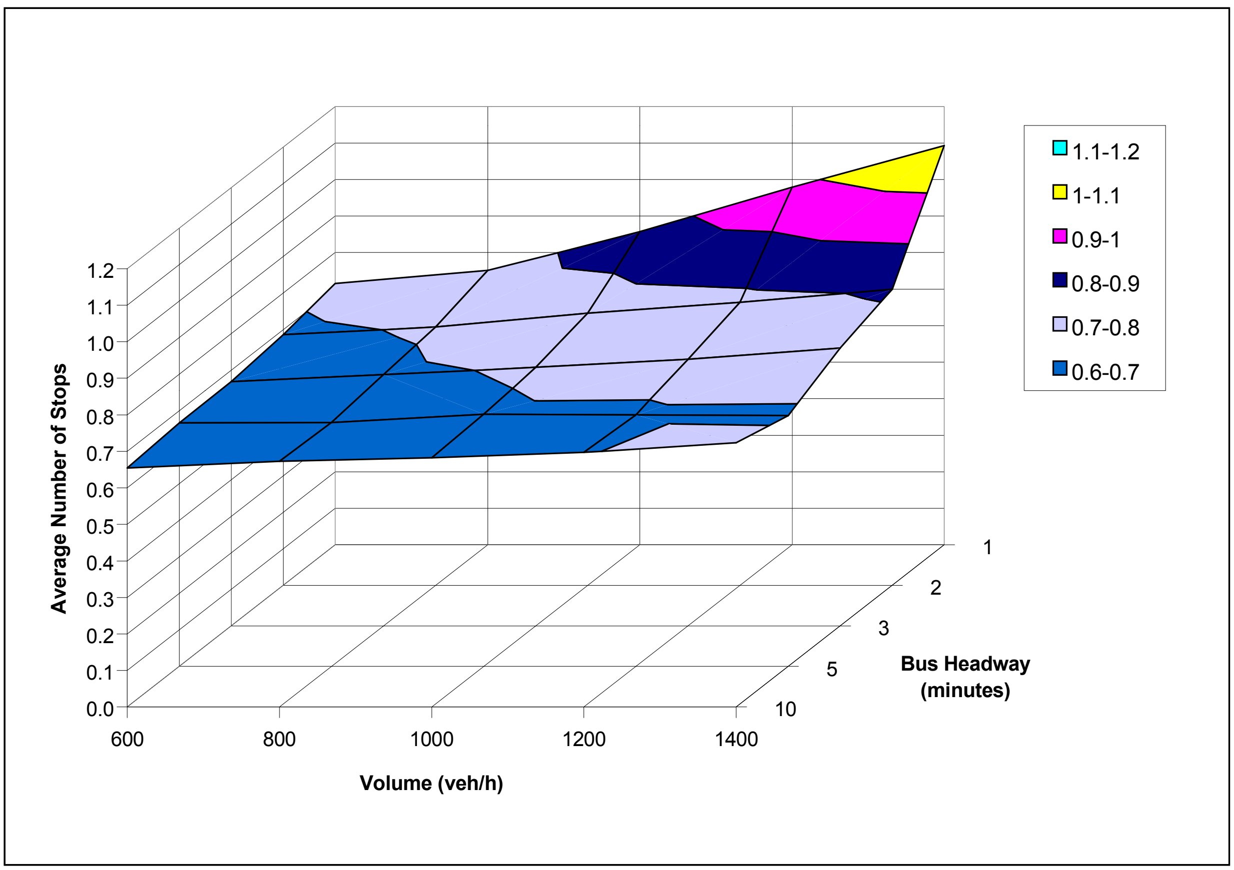

Figure 7.7: Average Number of Stops Estimates for Scenario 2

Table 7.9 reports the percentage differences in the average number of vehicle stops between the heterogeneous flow scenario and scenario 1. These results demonstrate an increase in the average number of vehicle stops as a result of introducing transit vehicles into the network. The increase in vehicle stops ranges from 1.6 to 62 percent. As was the case with delay, the impact of the transit vehicles is more evident as the level of congestion in the network increases. These trends are further demonstrated in Figure 7.8.

Table 7.9: Percent Change in Average Number of Stops between Scenario 1 and 2

Bus Headway (minutes)	Volume (vehicles/hour)				
	600	800	1000	1200	1400
1	9.98%	14.31%	26.96%	44.40%	61.93%
2	5.53%	7.61%	10.37%	14.31%	20.15%
3	2.76%	4.72%	4.89%	7.67%	12.74%
5	2.46%	1.67%	2.22%	1.62%	1.78%
10	0.46%	2.44%	1.04%	2.80%	7.11%

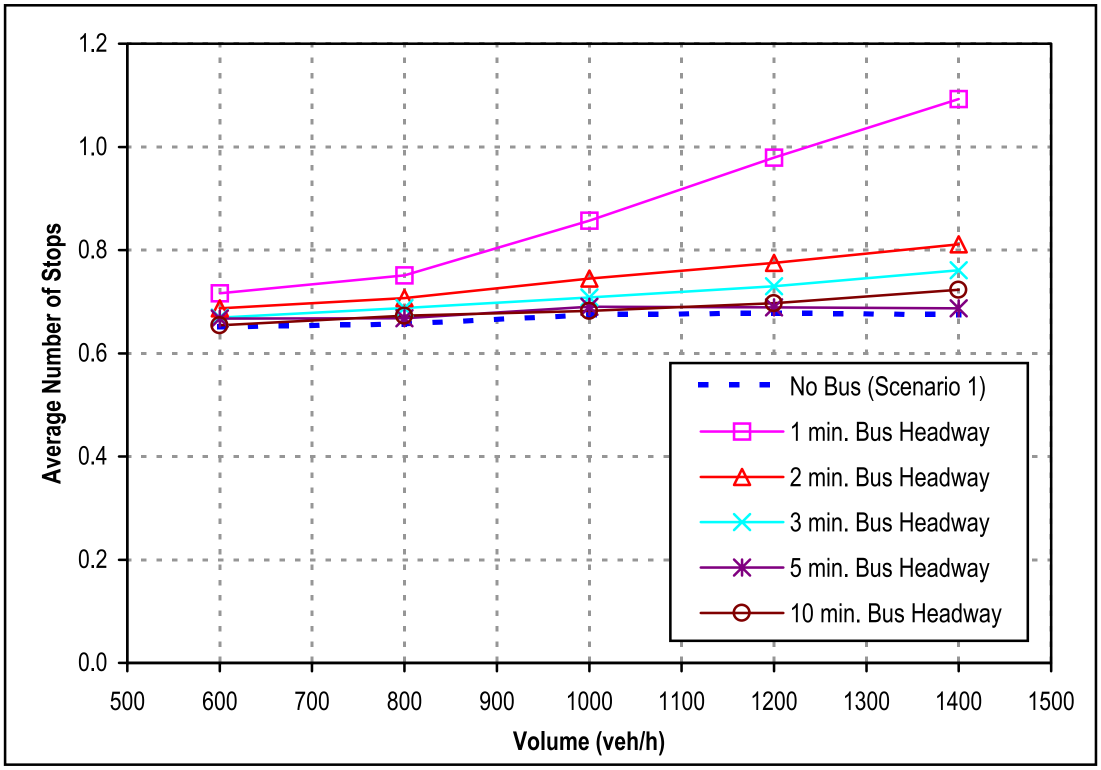

Figure 7.8: Comparison of Average Number of Stops between Scenario 1 and 2

7.4.3 Scenario 3: Homogeneous Flow Based on Length Equivalencies

The next step in the analysis was to evaluate the heterogeneous flow scenario based on equivalent homogeneous flow using Passenger Car Equivalencies (PCE) that are computed using relative vehicle lengths. Using the equivalent homogeneous flow analytical estimates of delay and stops may be computed. Given that the INTEGRATION delay and stop estimates were found to be consistent with analytical solutions for homogeneous flows, this scenario represents the analytical approximation to mixed flow scenario (scenario 2).

The vehicle delay estimates based on the assumption of an equivalent homogeneous flow appears to be consistent with the heterogeneous delay estimates for low levels of congestion (v/c ratio less than 0.8). However, the homogeneous flow approximation significantly underestimates the delay for v/c ratios of 0.8 with high transit vehicle demand, as demonstrated in Table 10 and Figure 7.9.

The underestimation of delay for the homogeneous scenarios results from the fact that the flow normalization ignores the additional delay that is incurred the general traffic when transit vehicles stop at bus stops. Similar findings are observed for the person delay and number of vehicle stops estimates, as illustrated in Figures 7.10 and 7.11, respectively.

Table 7.10: Results of Average Overall Delay for Scenario 3

PCE Equivalency (vehicles)	Volume (vehicles/hour)				
	600	800	1000	1200	1400
120	30.414	31.281	32.937	37.654	41.571
60	29.920	31.302	33.486	35.825	39.234
40	31.163	30.522	32.260	37.334	37.615
24	30.311	31.903	33.531	36.465	39.092
12	29.763	31.715	34.964	36.387	38.437

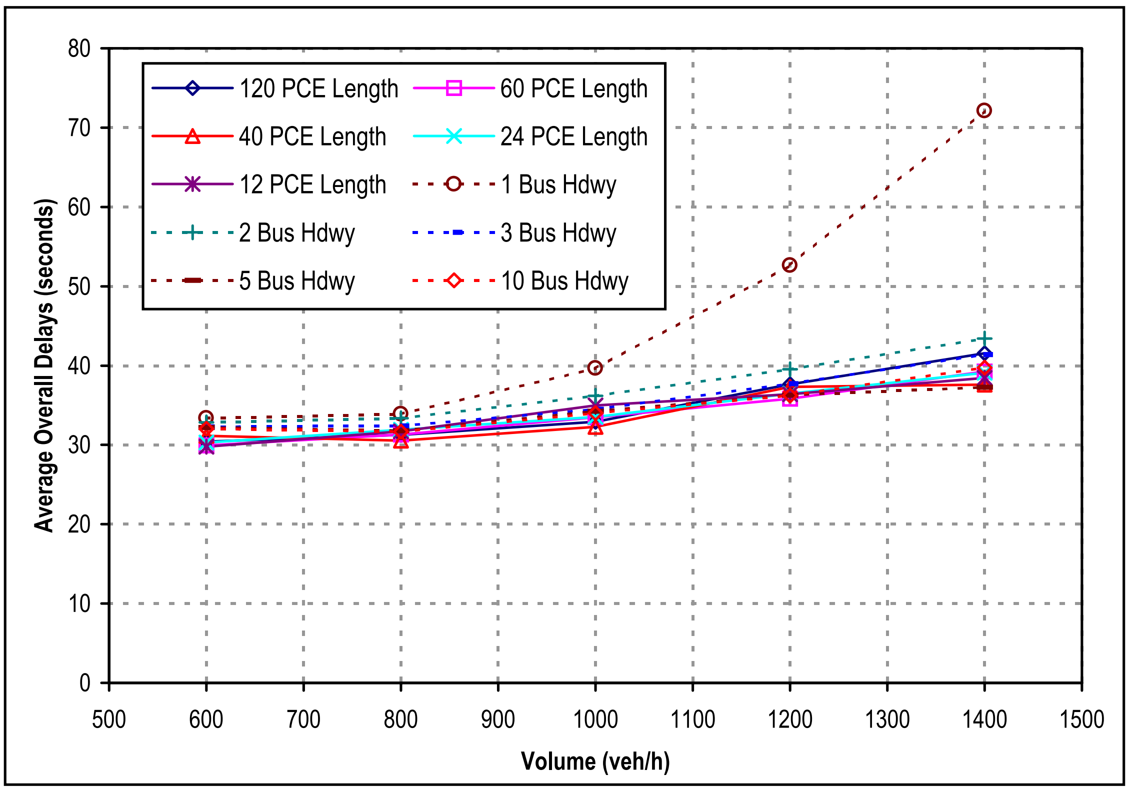

Figure 7.9: Comparison of Average Overall Delay Estimates between Scenario 2 and 3

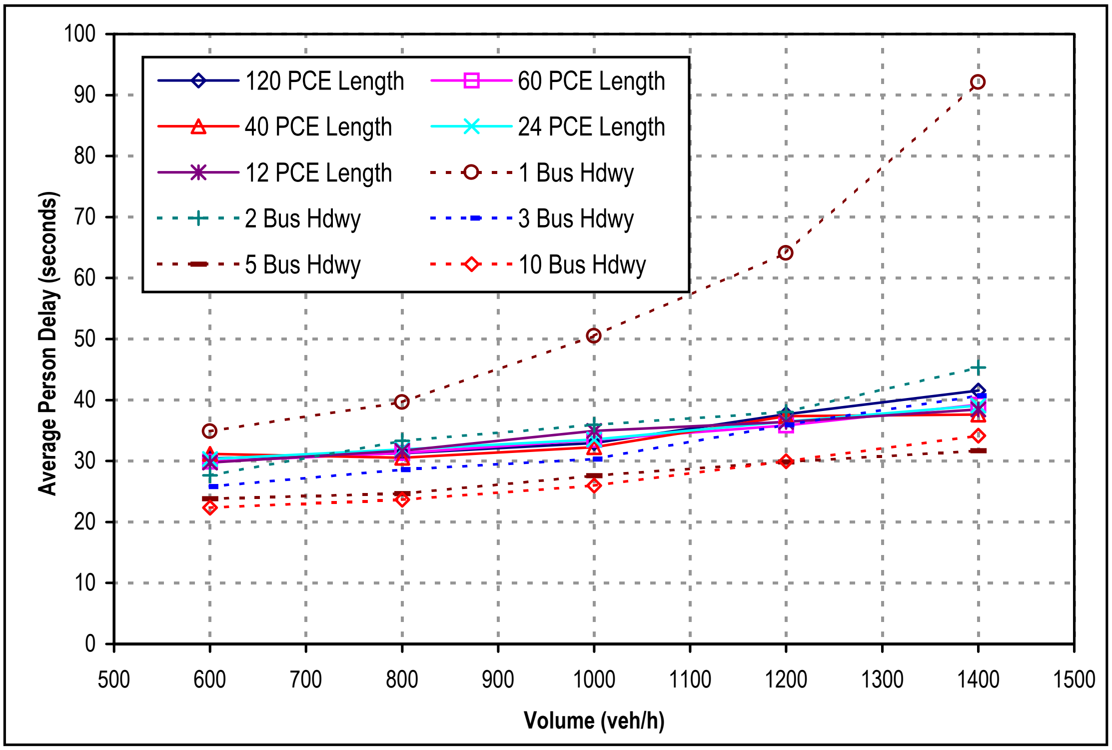

Figure 7.10: Comparison of Average Person Delay Estimates between Scenario 2 and 3

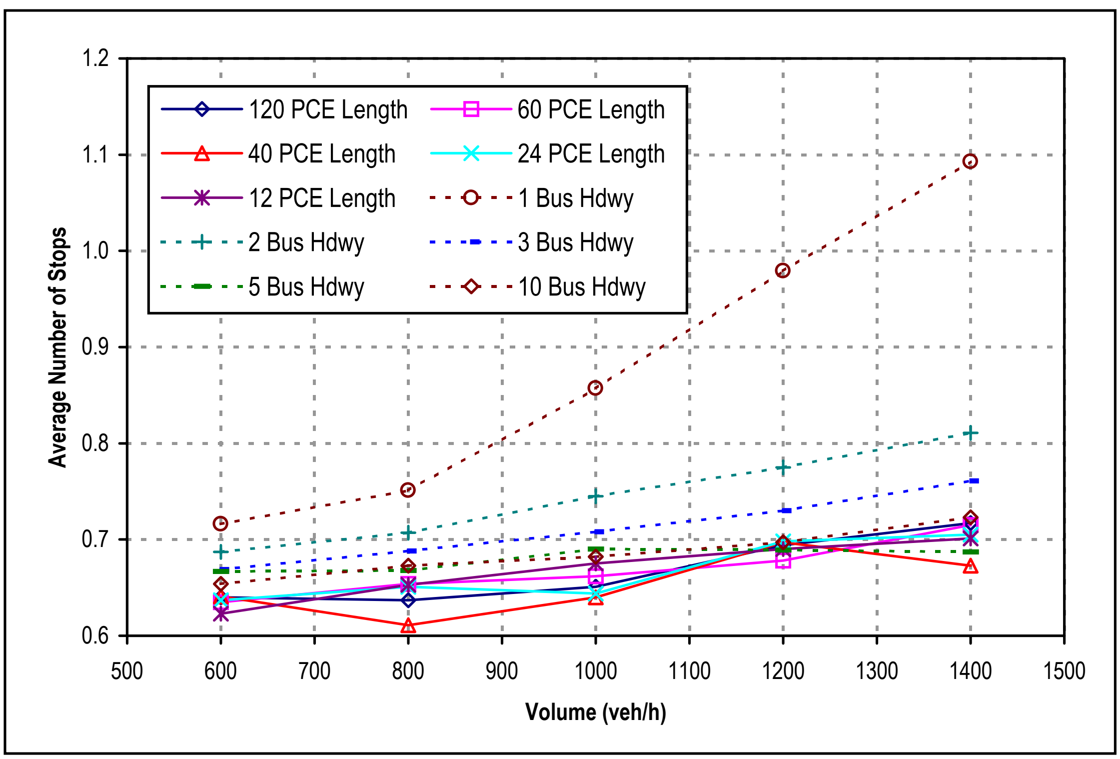

Figure 7.11: Comparison of Average Number of Stops between Scenario 2 and 3

7.4.4 Scenario 4: Homogeneous Flow Based on Ridership Equivalencies

The next scenario involved approximating the heterogeneous demand using PCEs based on vehicle ridership. Specifically, given that a transit vehicle was assumed to carry 15 passengers and a car was assumed to carry a single passenger, a vehicle equivalency of 15 was utilized.

Unlike the finding of scenario 3, the use of a passenger based on PCE results in delay estimates that are significantly higher than those associated with the heterogeneous modeling for high traffic and transit demands, summarized in Table 7.11 and Figure 7.12. The overestimation of delay results from the fact that the use of a PCE of 15 generates demands that exceed the signalized intersection capacity.

Given that a PCE based on vehicle ridership results in a number of person trips that is identical to the mixed-flow scenario, the person delay is more consistent with scenario 2 than the vehicle delay, as illustrated in Figure 7.13. However, as was the case for vehicle delay, the person delay is overestimated when the general and transit demand is high. Alternatively, the number of vehicle stops estimates are consistent with scenario 2, as illustrated in Figure 7.14.

Table 7.11: Results of Average Overall Delay Estimates for Scenario 4

Hdwy Equivalency (vehicles)	Volume (vehicles/hour)				
	600	800	1000	1200	1400
900	40.427	50.931	74.591	109.00	146.34
450	33.320	36.254	38.514	42.671	72.752
300	32.434	34.787	37.887	40.427	50.931
180	31.863	32.683	35.952	37.744	42.064
90	30.104	33.540	33.457	37.119	39.684

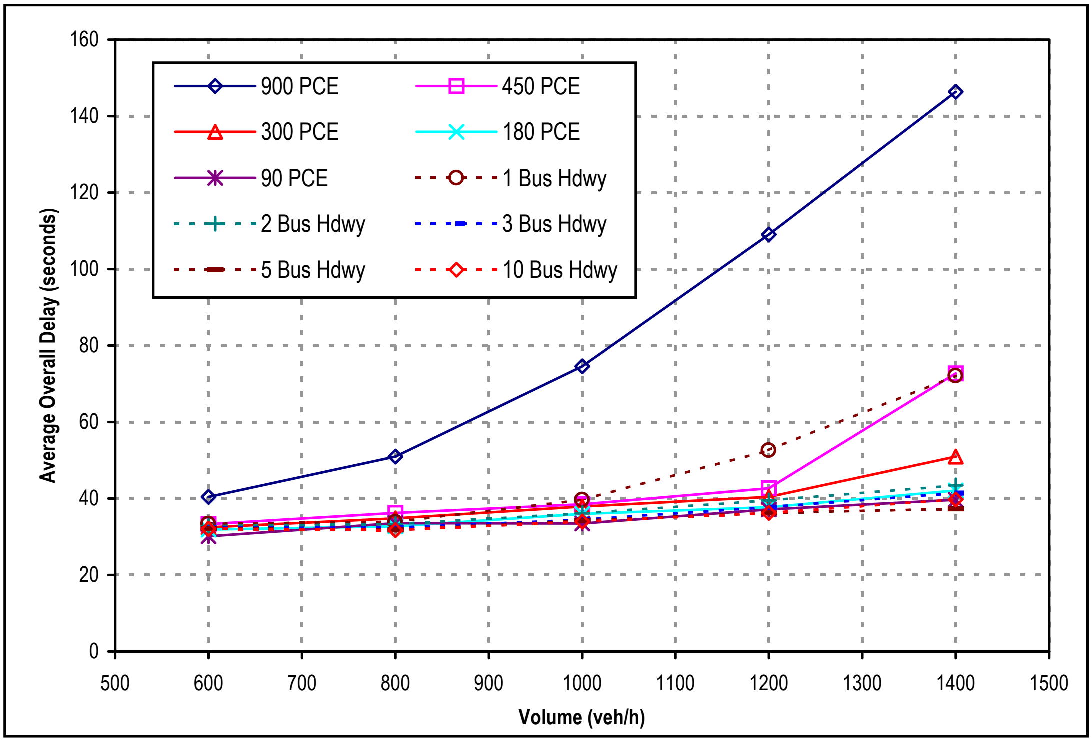

Figure 7.12: Comparison of Average Overall Delay Estimates between Scenario 2 and 4

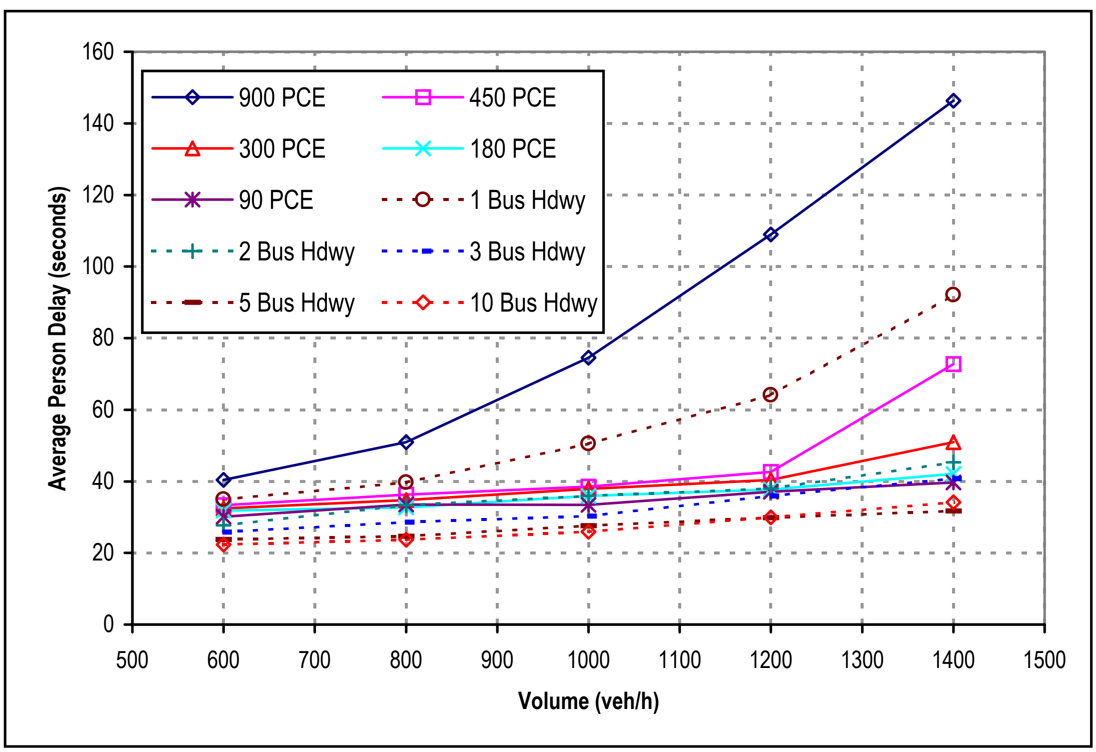

Figure 7.13: Comparison of Average Person Delay Estimates between Scenario 2 and 4

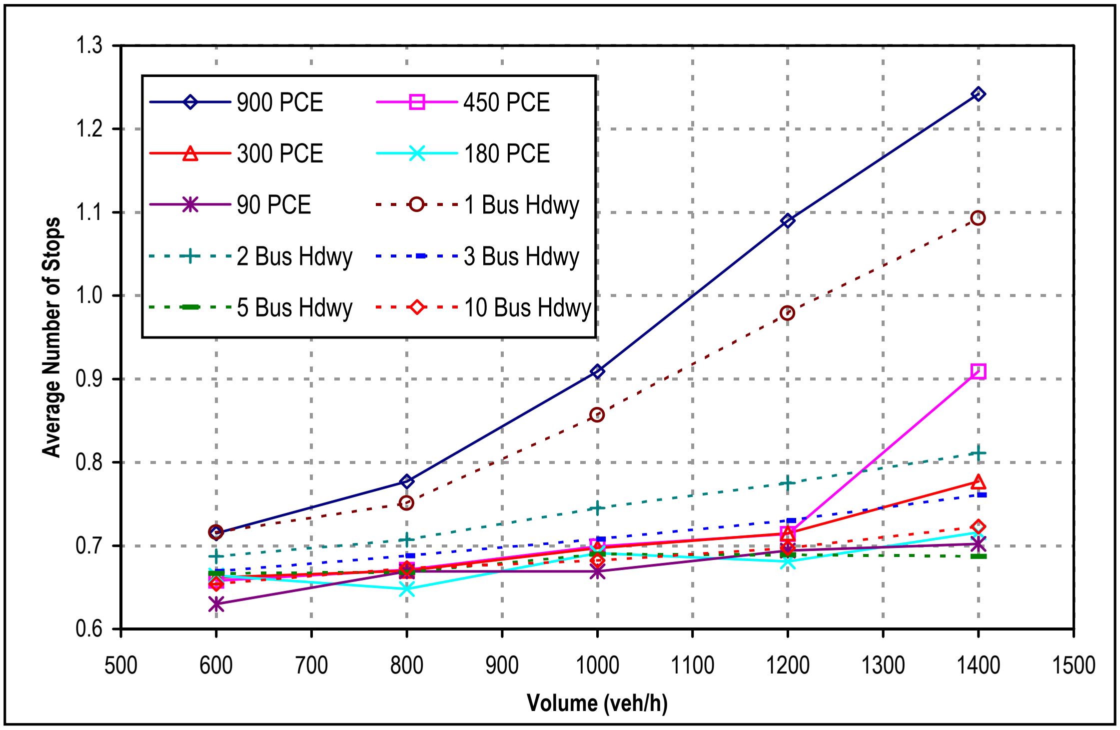

Figure 7.14: Comparison of Average Number of Stops between Scenario 2 and 4

7.5 Summary and Conclusions

This chapter analyzes the impact of mixed traffic condition on the vehicle delay, person delay, and number of vehicle stops at a signalized intersection. The analysis considers approximating the mixed flow for equivalent homogeneous flows using two potential conversion factors. The first of these conversion factors is based on relative vehicle lengths while the second is based on relative vehicle riderships.

The main conclusion of the analysis is that the optimum vehicle equivalency is dependent on the background level of congestion, the transit vehicle demand, and the Measure of Effectiveness (MOE) being considered. Consequently, explicit simulation of mixed flow is required in order to capture the unique vehicle interactions that results from mixed flow. Furthermore, while homogeneous flow approximations might be effective for some demand levels and these approximations are not consistently effective.