Simulation of Traffic Flow through the New York City Street Grid

Group Members

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Abstract

Traffic flow at two intersections along Ave J in Midwood, Brooklyn are simulated to better understand how private vehicles, buses, and the traffic signal timing contribute or detract from traffic flow in New York City. Synchronized and phased-delay signal timing were simulated from a traffic engineering perspective. The addition of dedicated bus lanes were simulated from a public-transit perspective. The phased-delay signal timing had no significant net changes to travel times compared to a synchronized signal timing system but it reduces the average queue length and the average maximum queue length in one direction. The addition of bus lanes demonstrated significant improvements to bus travel times while offering modest benefits to all other users of the intersection.

Background

As the effects of the pandemic dissipate, the traffic congestion around the US is picking back up steadily, still remaining below pre-pandemic levels. However, due to a crippling mass transit system and an increased car ownership, New York City faces traffic congestion worse than it had before the pandemic.

Since the pandemic transformed people's shopping habits and work routines, the huge influx of delivery vehicles and new cars has shifted the traffic congestion patterns long affecting Manhattan to the other boroughs of the city. According to the transportation analytics firm INRIX, NYC drivers on average lost 102 hours in traffic last year alone. Which is significantly greater than the overall average in the US of 36 hours/year lost due to congestion.

The hours lost in traffic are not just annoying to the drivers, they also affect productivity levels of businesses whose vehicles/workers spend more time in traffic than doing value-added activities. Apart from encouraging people to carpool and use the public transit system as much as possible, the city's traffic patterns need to be monitored and managed more efficiently.

Application

Due to high transportation demands and rapid increase in the number of vehicles, traffic congestion has become paralyzing to the urban cities' daily business. Traffic signal control is a crucial tool to managing traffic flow and reducing congestion at busy intersections. It is a complex problem which includes vehicular interaction with the network, human behavioral factors, stochastic traffic flow and road safety. Algorithms, theoretical analyses and simulators can be used to model these complexities in order to obtain optimal traffic signal settings at busy intersections. Such analyses can help obtain traffic signal configurations that ensure maximum traffic flow through the network and minimum possible wait times per vehicle.

Traffic modeling and simulation are robust devices used in urban transport network planning. These techniques can be used to identify bottlenecks, network capacity, average wait times per vehicle and achieve optimization goals like exhaust emissions, network configuration, signal cycle duration and network performance indices. Signalized intersection modeling can be used to devise real-time traffic management strategies and avoid out-of-control gridlocks.

Data Collection

A series of two intersections featuring a two-way avenue and two one-way side streets is simulated in this study. Each direction of travel features only one lane and the length between each intersection is on the order of only a few hundred feet. This is a very common street pattern in New York City, being most prominent in the boroughs of Brooklyn, Queens, and The Bronx. Many of the avenues feature one or more bus routes. Since there is only one lane of traffic along an avenue featuring many intersections, buses are regularly late.

The intersection at Ave J and E17th St. in Midwood, Brooklyn was selected for data collection. Ave J is a two-way east-west avenue with one lane of traffic in each direction. E17th St is a one-way north-bound only street. Ave J carries the B6 and B11 bus routes, which both have stops at the Q subway station between E16th and E15th street. Ave J is the last avenue to connect Ocean Parkway and Ocean Avenue, two busy four lane thoroughfares, for over half a mile to the north. Therefore, it features a high volume of traffic compared to similar avenues.

The cycle length of this intersection is 59s. The red phase along Ave J lasts 26s and the combined green and yellow phase lasts 33s. The red phase along E17th St lasts 39s and the combined green and yellow phase lasts 20s.There is a lag of 2s between the light changing to red in one direction and changing to green in the other.

Observations were recorded in three sessions on successive June Monday afternoons between 3pm and 6pm. Traffic traveling along the westbound direction of Ave J was primarily considered but observations from the eastbound direction were recorded to measure the distribution of left turns.

Figure 1. E 17th St and J Avenue (Intersection of Choice)

The following statistics were measured separately for Ave J and E17th St:

- Poisson Arrival Rates of vehicles at the intersection on red and on green and yellow
- Maximum Queue Length
- The probability of a vehicle continuing straight, turning right, or turning left

And the remaining statistics were assumed independent of origin so were measured jointly:

- Process time for the first vehicle in the queue clearing the intersection heading straight, turning right, and turning left
- Process times for all other vehicles clearing the intersection heading straight, turning right, and turning left
- Delay of first vehicle entering the intersection after the light changes from red to green
- Time interval between vehicles entering the intersection when the light is green

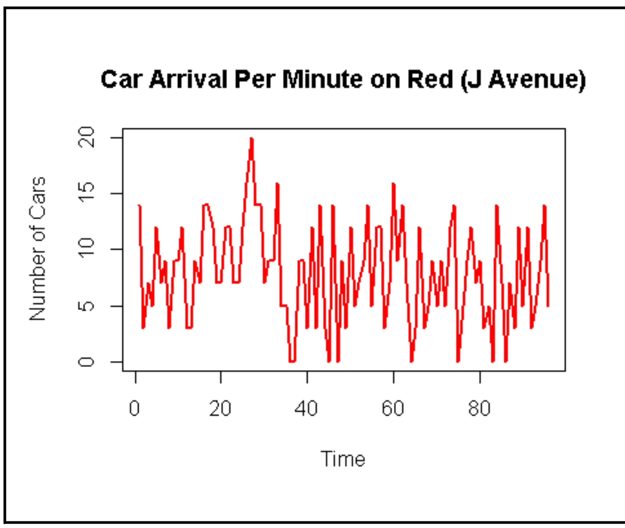
Statistical quantities were measured separately for four vehicle classes: i). Passenger vehicles, ii). Buses, iii). Heavy Trucks, iv). School Buses. All classes of vehicles traverse Ave J but buses do not originate from or turn onto E17th St or any other side street. Due to low counts, mean process times for heavy trucks and school buses turning right or left were not computed.

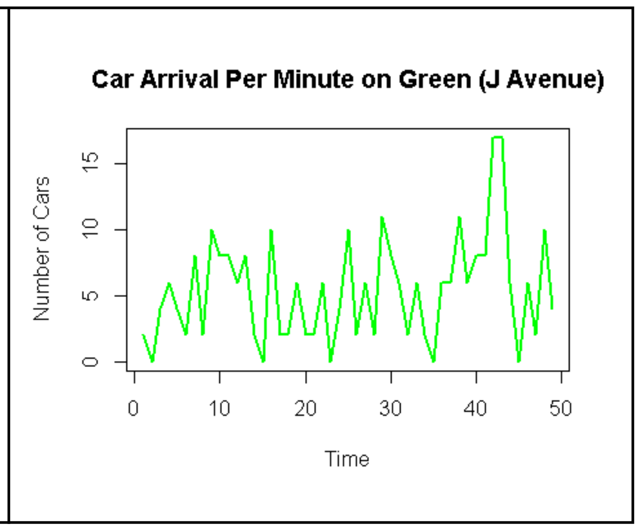
All time measurements were recorded in a journal noting the time elapsed on a stopwatch when a vehicle enters or clears an intersection. The stop watch ran continuously when measuring process times but was reset on green when measuring delay. Measurements were recorded to the nearest half second. Estimates for process time were calculated using sample sizes of 126 and 41 vehicles going straight and turning left, respectively. We assume right turns have a similar distribution as straight process times to simplify the simulation. Estimates of delay were calculated using sample sizes of 97 vehicles first in the queue, and 43 vehicles second or third in the queue. Delay statistics were only computed for cars and buses since the volume of trucks and school buses was too low. We therefore assign them the same values as for buses, which is reasonable given their similar weights and dimensions.

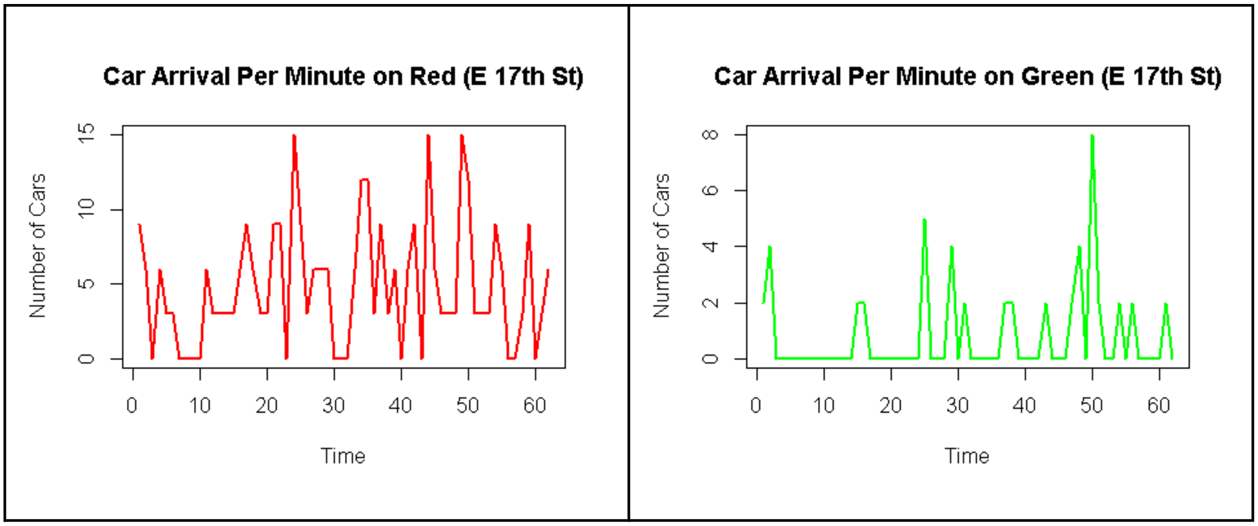
Arrival rates were measured separately from time measurements using sample sizes of 97 traffic cycles for Ave J and 62 cycles for E17th St. Rates of vehicles per minute were estimated by counting the number of arrivals during each phase of the signal cycle and dividing by the fraction of a minute that cycle represents. The arrivals on E17th St were usually low enough to estimate the arrivals on green by subtracting the arrivals on red from the total number of vehicles processed during the green and yellow phase.

Exploratory Data Analysis

As the pandemic restrictions start to ease, New York City's streets see a paralyzing surge in its traffic volume hence we consider arrival rates to be the most important parameters for this simulation. In order to visualize the collected data, we used R to obtain time series plots of car arrivals on red and green lights from both J Avenue and E 17th Street.







While the arrival rates vary according to the signal cycle, there does not appear to be a trend in the rate at which vehicles arrive. We start off with the assumption that vehicle arrivals follow a Poisson distribution and find the arrival rate λ (per minute) for each automobile class on red and green lights respectively.

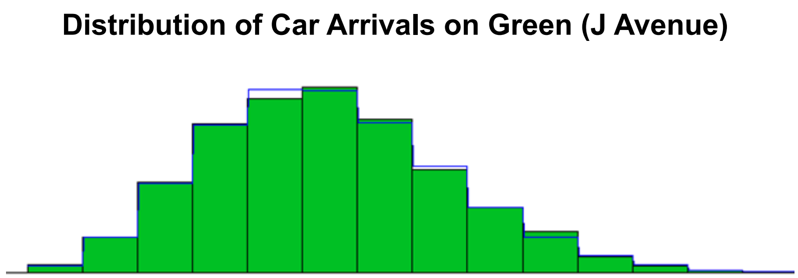
Table 1. Average Arrival Rate (Per Minute) of Vehicles on Red

	λ_{car}	λ_{bus}	λ_{truck}	λ_{school_bus}
J Avenue	7.476852	1.150794	0.231481	0.092593
E 17th St	4.887097	0	0.048387	0.048387

Table 2. Average Arrival Rate (Per Minute) of Vehicles on Green

	λ_{car}	λ_{bus}	λ_{truck}	λ_{school_bus}
J Avenue	5.009276	0.296846	0.074212	0.037106
E 17th St	0.645161	0	0.024814	0.024814

This information allows us to test our hypothesis using Arena's Input Analyzer and fit the most suitable distribution to our dataset. By doing so, we find that our assumption matches well with the underlying distribution of the data. The suggested distribution summaries for cars arriving on J Avenue are given below:

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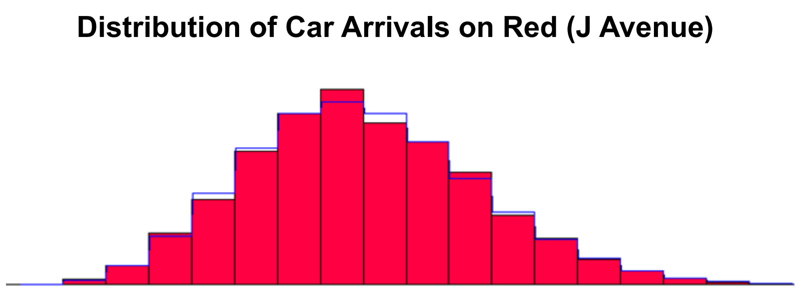
Distribution Summary

Distribution:   Poisson
Expression:     POIS(4.96)
Square Error:   0.000133

Chi Square Test
  Number of intervals   = 13
  Degrees of freedom    = 11
  Test Statistic        = 8.33
  Corresponding p-value = 0.682
```

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Distribution Summary

Distribution:   Poisson
Expression:     POIS(7.49)
Square Error:   0.000219

Chi Square Test
  Number of intervals   = 16
  Degrees of freedom    = 14
  Test Statistic        = 10.7
  Corresponding p-value = 0.708
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This allows us to use exponential interarrival times in our simulation and evaluate if its behavior matches our real-world observations.

Simulation

Baseline Model

We use the arrival rates in Table 1 and 2 to assign interarrival exponential distributions to the vehicles entering Avenue J and E 17th St in the Create modules of our simulation. We then assign entity type and picture depending on the vehicle class using Assign modules.

As the vehicles arrive at the front of the intersection on red light, they wait for their signal to turn green which we modeled using the Hold module. When the light turns green, the vehicle at the front of the queue decides its path based on the probabilities (Table 3) derived from our observations. We achieve this directional movement using the Decide module.

Figure 2. E 17th St and J Avenue Arena Simulation

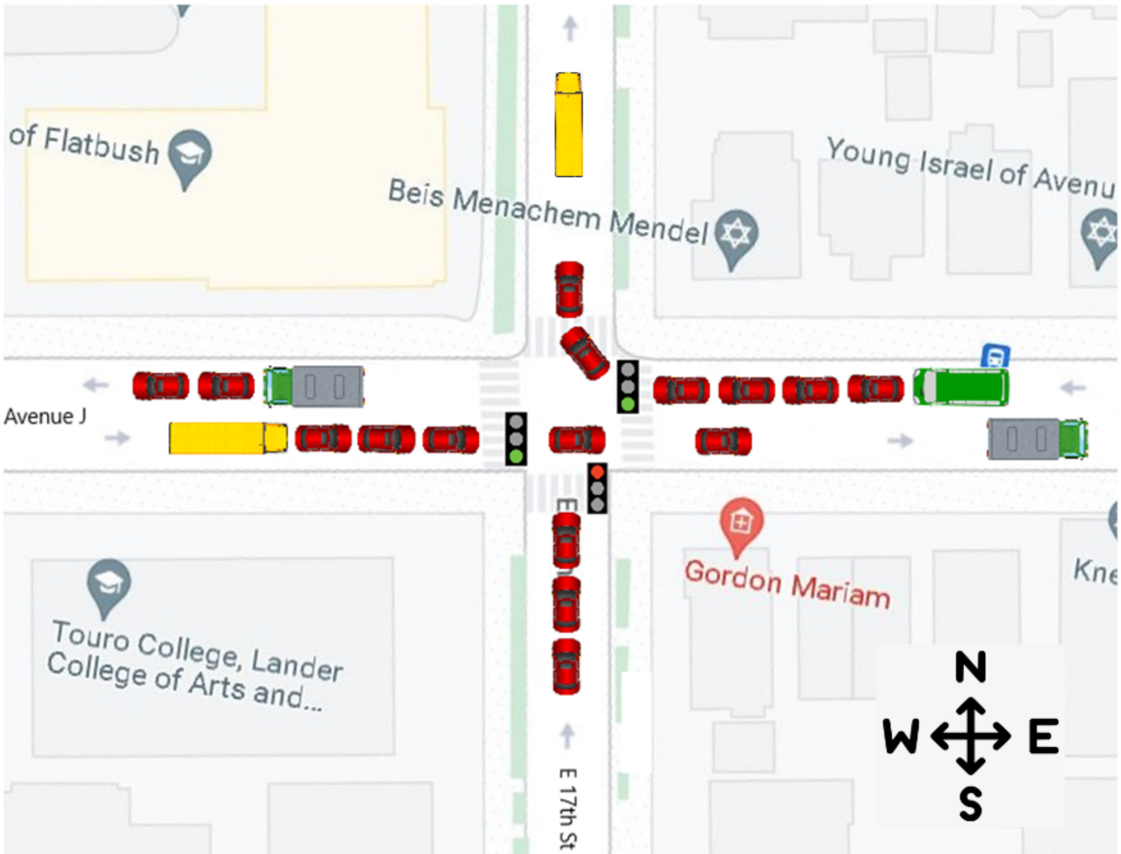

Table 3. Probabilities of Vehicles Choosing a Direction

Probabilities	Avenue J (West Bound)	Avenue J (East Bound)	East 17th St (North Bound)
P(Straight | Car, School Bus, Truck)	0.943182	0.943182	0.169231
P(Right | Car, School Bus, Truck)	0.056818	-	0.661538
P(Left | Car, School Bus, Truck)	-	0.056818	0.169231
P(Straight | Bus)	1	1	-
P(Right | Bus)	0	-	-
P(Left | Bus)	-	0	-

Remark: We assume that East and West bound traffic entering J Avenue follow the same probabilities of choosing a direction.

Scenario Modeling

The signals along Ave J in Midwood use a phased-delay pattern (consecutive lights change green after a small delay) during peak travel times and use a fully synchronized (all lights change green at once) pattern during off peak travel times. We used the synchronized pattern as the “baseline” simulation described above, against which we attempt to verify the use of a phased delay system as was observed during data collection.

Despite having a comprehensive bus network of 336 routes, New York has comparatively little dedicated bus lanes. Bus lanes prevent buses from being stuck in traffic, making buses a more reliable transportation option for the 2 million daily riders who rely on them. And since buses are more fuel efficient than cars, improving bus service can reduce car reliance, which will ultimately reduce air pollution. Our second simulation experiment isolates buses from all other traffic as in an ideal curb-side bus route in an attempt to quantify the improvements a dedicated bus lane offers to city traffic.

Output Analysis

Baseline Model Output

We ran the baseline model for 20 replications for 3 simulation hours each. Using the batch means method, we extracted important system parameters including average queue length for each leg of the intersection, total number of vehicles using the intersection, average wait time for vehicles entering in each direction and total time each vehicle class entering the intersection takes to exit it.

Table 4. Output Statistics Collected from the Baseline Model (1)

Total Throughput	Mean Max Queue Length E 17th St (South Leg)	Mean Max Queue Length Avenue J EB (West Leg)	Mean Max Queue Length Avenue J WB (East Leg)
2969	8	13	13

Table 4 illustrates that the 2969 vehicles including cars, school buses, buses and trucks use the intersection on average. Average max queue lengths the south, west and east legs of the intersection experience are 8,14 and 14 vehicles respectively. Average queue lengths were 0.25, 0.60, and 0.61. Since this is the average throughout the entire traffic length cycle, mean max queue length is taken as a more reasonable statistic.

Table 5. Output Statistics Collected from the Baseline Model (2)

Mean Wait Time E 17th St (South Leg)	Mean Wait Time Avenue J (West Leg)	Mean Wait Time Avenue J (East Leg)
9.72 seconds	7.67 seconds	5.61 seconds

The average waiting time for vehicles entering from the south on E 17th St was found to be 9.24 seconds. While the vehicles entering J Avenue from either direction wait much less on average (about 6-7 seconds).

Table 6. Output Statistics Collected from the Baseline Model (3)

Total Time (Bus)	Total Time (Car)	Total Time (School Bus)	Total Time (Truck)
48.9 seconds	26.45 seconds	32.9 seconds	27.2 seconds

A bus entering the intersection takes about 49.4 seconds on average to leave the system. Other vehicle classes entering the system take less time to exit due to a combination of being allowed to travel on the side streets, where they may only need to encounter one intersection, and because they take less time to clear an intersection compared to a bus.

Phased-Lag Signal Model Output

We set the traffic signal at the intersection of Ave J and E16th St to start 7 seconds later than that of the intersection at E17th St. This is the true phase observed between the true intersections for the 3pm - 6pm window when observations were taken. As before, we ran the simulation for 3 simulation hours each. Using the batch means method, we extracted important system parameters including average queue length for each leg of the intersection, total number of vehicles using the intersection, average wait time for vehicles entering in each direction and total time each vehicle class entering the intersection takes to exit it.

Table 7. Output Statistics Collected from the Desynchronized Intersections Model (1)

Total Throughput	Mean Max Queue Length E 17th St (South Leg)	Mean Max Queue Length Avenue J EB (West Leg)	Mean Max Queue Length Avenue J WB (East Leg)
2906	8	12	15

Table 7 illustrates that 2906 vehicles including cars, school buses, buses and trucks use the intersection on average. Average max queue lengths at the south, west and east legs of the intersection experience are 8,12, and 15 vehicles respectively. Average queue lengths throughout the system were also shorter along Ave J, having values of 0.25, 0.59, and 0.58 vehicles, respectively.

That the throughput is less with phased-delay lights is statistically significant at the 0.05 significance level, with the difference in total throughput compared to the synchronized signal simulation having a value of -63 +/- 53. The reduction in queue length along the westbound section is also statistically significant, with the change in queue length compared to the baseline synchronized signal simulation having a value of -0.029+/-0.027. Confidence intervals were computed assuming the samples come from the same population with common unknown variance.

Table 8. Output Statistics Collected from the Desynchronized Intersections Model (2)

Mean Wait Time E 17th St (South Leg)	Mean Wait Time Avenue J EB (West Leg)	Mean Wait Time Avenue J WB (East Leg)
9.29 seconds	8.1 seconds	5.62 seconds

The average waiting times for vehicles were found to be comparable to the baseline synchronized light system for westbound traffic but it was slightly longer for eastbound traffic. The difference in mean is statistically significant, with a value of

Table 9. Output Statistics Collected from the Desynchronized Intersections Model (3)

Total Time (Bus)	Total Time (Car)	Total Time (School Bus)	Total Time (Truck)
49.60 seconds	26.27 seconds	33.48 seconds	27.18 seconds

The desynchronized traffic signals do not significantly change the average time it takes for vehicles to clear the system. There doesn't seem to be an overall advantage in throughput or time when implementing a phased-lag intersection system. However, given that the queue lengths are statistically shorter in the west-bound direction and the max queue length is shorter in the eastbound direction, this strategy improves throughput in one direction while curtailing it in the other. This may improve throughput away from commercial areas and busy thoroughfares towards residential areas during rush hour without sacrificing overall intersection efficiency. Eastbound traffic for example, would pass through successive green lights more frequently than if the signals were synchronized, since the 7 second lag incorporates the time it takes for the first vehicle to reach the next intersection. westbound traffic would have less time to reach the green light as a result.

Separated Bus Lane Model Output

In an ideal implementation, buses traveling in bus lanes are largely independent of other traffic when driving straight through an intersection. Only vehicles turning right are allowed to enter the bus lane. We attempted to simulate this kind of system by running two simulations independently: one featuring only buses, and another without buses. In the simulation with buses, we changed the "maximum" value in the bus intersection process time's triangle distribution from 20s to 5s, since the 20s value reflects the maximum observed clearing time due to car traffic whereas 5s reflects the maximum observed clearing time of buses without traffic. As before, we ran the simulation for 3 simulation hours each for 20 simulations. The combined results of the two simulations are reported below.

Table 10. Output Statistics Collected from the Separated Bus Lanes Model (1)

Total Throughput	Mean Max Queue Length E 17th St (South Leg)	Mean Max Queue Length Avenue J EB (West Leg)	Mean Max Queue Length Avenue J WB (East Leg)
2906	9	13	13

Table 4 illustrates that the 2964 vehicles including cars, school buses, buses and trucks use the intersection on average. This includes 159 buses which waited 4.02 and 5.04s for eastbound and westbound directions on average, respectively. Average max queue lengths the south, west and east legs of the intersection experience are 9,13 and 13 vehicles respectively, which is about the same as the baseline synchronized intersection. However, on average, queue lengths throughout the system were shorter, having values of 0.24, 0.56, and 0.55 vehicles at E17th St northbound, Ave J eastbound, and Ave J westbound, respectively. The difference in means for the Ave J queue lengths is statistically significant at the 0.05 significance level, having an eastbound value of -0.04 +/- 0.03 and a westbound value of -0.6 +/- 0.03. Confidence intervals were computed assuming the samples come from the same distribution, since the car, truck, and school bus arrival rates don't change. We can therefore say confidently that the queue lengths are shorter when bus lanes are implemented. This translates into fewer instances of the crosswalk being blocked by vehicles waiting in a queue for the next traffic signal at the end of the last traffic signal. In practice, this may alleviate traffic caused by left-turns, since drivers will have to wait for fewer vehicles to pass before it is safe to turn left.

Table 11. Output Statistics Collected from the Separated Bus Lanes Model (2)

Mean Wait Time E 17th St (South Leg)	Mean Wait Time Avenue J EB (West Leg)	Mean Wait Time Avenue J WB (East Leg)
9.47 seconds	10.19 seconds	5.70 seconds

The average waiting times for vehicles entering from the south on E 17th St and from the east on Ave J were found to be comparable to the baseline synchronized light system at 9.86 and 5.62 seconds, respectively. Eastbound travel was delayed compared to the baseline system, with a mean wait time of 10.19s, which is a statistically significant difference from the 7.85s wait time in the baseline model. The reason for this is that since buses don't turn left, there is a greater proportion of vehicles turning left. Left turns have a broader triangular distribution as drivers wait for vehicles in the opposing lane to pass, so they generally take longer to complete than right turns and continuing straight. As described above, these left turns would likely have a different distribution than used in this simulation, being faster to complete on average. But we erred conservative given the lack of data.

Table 12. Output Statistics Collected from the Separated Bus Lanes Model (3)

Total Time (Bus)	Total Time (Car)	Total Time (School Bus)	Total Time (Truck)
37.3 seconds	26.42 seconds	34.2 seconds	28.44 seconds

Buses clear the system 25% faster with a bus lane than when buses share one lane with other vehicles. Other vehicles experience no significant change to their travel times.

Conclusion

New York City's traffic light system is vital to facilitating commerce throughout the city. Millions of private vehicles and public-transit users rely on it to ensure safe and efficient transportation throughout the city. We studied an intersection along Ave J in the Midwood neighborhood of Brooklyn during peak travel times between 3pm and 6pm in order to better understand how the traffic signals affect the flow of traffic.

In an effort to improve the flow of traffic in the direction where most vehicles are heading towards, the signals along Ave J have a phase-delay timing system whereby consecutive traffic lights turn green following a delay of about 7s after the previous signal turns green. Compared to a baseline simulation using instantaneous synchronization, the phased-delay timing system does not offer any significant changes in waiting times, or total travel times. However, it does reduce the average queue lengths and the maximum queue lengths. This makes for safer intersections where vehicles block crosswalks, or even the intersections themselves, less frequently than in a fully synchronized system. In practice though, this system permits more throughput in one direction while reducing it in the opposing direction. Since traffic can be heavy even in the hindered direction, that total throughput is slightly reduced in this simulation is consistent with what is expected in reality.

We also examined the flow of traffic with a dedicated bus lane. This could be implemented along Ave J by removing curb-side parking and replacing it with a dedicated bus lane. Only right turns and local deliveries would be permitted during restricted hours. Therefore, when considering bus lanes, we reduced the “maximum” intersection clearing time for buses from 20s to 5s, since they don’t encounter any traffic in this ideal scenario. This improved travel times for buses by 25% through the two intersections in the simulation while leaving travel times for other vehicles unchanged compared to the baseline scenario. Furthermore, queue lengths at red lights were shorter by about 10%. This reduces the chances of vehicles blocking crosswalks while waiting in the queue for the next signal, improving safety and accessibility for pedestrians. Although we didn’t explicitly account for it, the reduction in queue length also reduces the average time drivers need to wait to turn left, particularly for drivers at the front of the queue, since there are fewer vehicles waiting in the queue on red that immediately pass in the opposing lane on green.

Overall, we demonstrated that the addition of a dedicated bus lane has benefits to all users of the road. However, without data on left turns in bus lanes, we did not make any inferences regarding the left turn completion time distributions. Therefore, wait times at intersections increased on average for the cars, trucks, and school buses, since without buses a greater proportion of vehicles are turning left. Future work could verify the faster left turns by collecting data to adjust the corresponding distribution.

Time constraints limited the thorough experimental output analysis performed in this study. There are a lot of distracted drivers on their phones at red lights. Future simulations should consider the time delay between the signal turning green and the first driver entering the intersection. The short distance between intersections motivates the study of vehicle size on queue length, waiting times, and total travel times. It is suspected that throughput is hindered in this system, and any North American traffic system, since a significant proportion of vehicles classified as “cars” during data collection were really large SUVs. Other scenarios future work should consider include a reduction or uptick in public transit ridership and the implementation of a one-way mode of travel along Ave J.