Analyzing the Economic Impact of Inefficient Left Turns in Urban Traffic

A Major Qualifying Project

Submitted to the Faculty of

Worcester Polytechnic Institute

In partial fulfillment of the requirements for the

Degree in Bachelor of Science

In

Economic Sciences

By

Stephen Wood

Advised by

Professor Gbetonmasse Somasse

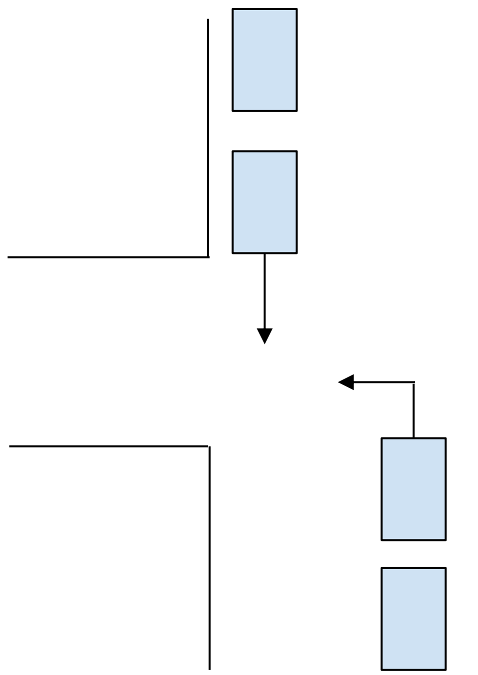
May 17th, 2020

Abstract

I used this project as an opportunity to research the efficiency of left hand turns in urban areas and to try and determine if there were any possible solutions to the inefficiency of left turns. My primary goal when designing this project was to determine if altruistic driving behaviors can reduce traffic in urban environments. To do this, I first conducted a series of observations to determine how inefficient left turns were at various types of intersections (four-way stops, those with a stop-light, and those whose stoplights provide a free left turn). At these intersections, I collected data on how many cars attempted to turn left at the intersection, how long it took those cars to turn left, and how many cars got caught behind those cars trying to turn left. After observing the variations in the different intersections, the study found that normal stop-lights seemed to produce the most efficient left turns while still handling a reasonable amount of traffic. I used the data to estimate the overall impact that inefficient left-turns might have on the US economy. The impact of inefficient left turns on the overall US economy proved to not be negligible, including cars wasting almost 60,000 gallons of gasoline while idling waiting to turn left. This information can give city planners more information on how to reduce congestion when designing city layouts. It also provides further information on the economic benefits that can result from reducing congestion. I then tried to determine if there was a more efficient alternative to the inefficient left turns. The experimental portion of this project wherein altruistic drivers would be “planted” in an observed intersection in order to determine the possible benefits of altruistic drivers had to be cut due to the Covid-19 outbreak. However, the opportunity remains for future researchers to perform this experiment.

Executive Summary

There has been a lot of work done by urban planners to maximize the efficiency of cities. One area of particular importance is road works; trying to organize traffic in the most efficient manner is of the utmost importance to a city. While there is a lot of literature on increasing traffic efficiency, there isn't much literature on left turns specifically. Left turns are particularly inefficient because in order to make a left-hand turn, a driver needs to cut across the opposing lane of traffic. An example of this type of turn can be seen in the figure below:



In order to begin research on the inefficiency of left turns, the project began by running observations to gather some statistical data on left turns. During the observations, I targeted three different types of intersections: those with a four way stop, those with a traffic light, and those with traffic lights that allow for a free left turn. I found six different intersections around Worcester Massachusetts, two of each type I listed above. Those with a four-way stop (Intersection of Institute Road and Dean Street, and the intersection of Lancaster Street and Highland Street), those with normal traffic lights (intersection of West Street and Highland Street, and the intersection of Park Ave. and Institute Road), and those with a left turn light (Intersection of Park Ave. and Highland Street, and the intersection of Park Ave. and Salisbury Street). While observing these intersections, I kept track of three main variables:

1. The number of cars attempting to turn left
2. Time spent trying to turn left (in seconds)

3. The number of cars stuck behind cars turning left

After completing the observations, I came up with three main statistics to try and analyze the data with: Average Time Spent Waiting (which will be an average of all the time waiting statistics), Adjusted Average Time Spent Waiting (which will be an average of all the time waiting statistics excluding those where the wait time equals 0) and Average Cars in Traffic (which will be a statistical average of all the cars left behind cars turning left). These statistics helped me determine which type of intersection was the most efficient at allowing cars to turn left.

Although the project was initially meant to feature an experiment portion, this was not completed due to the Covid-19 outbreak. The original experiment would have featured three drivers driving through a given intersection and instructions to let any two cars attempting to turn left go through. This would allow me to determine how much of the inefficiency could be solved by altruistic behavior from other drivers. However, this portion of the project did have to be cut due to the quarantine imposed in response to Covid-19.

Based on the findings, it appears that stop lights without free left turns are the most efficient type of intersection. Due to this finding, my recommendation for urban areas would be to encourage the use of stop lights instead of stop signs or protected lefts whenever possible. Since I wasn’t able to conduct my experiment, I’m not able to provide backing for my other recommendations. However, I would say that redesigning cities is not feasible in most situations. Because of this, I think that legislative action could be more beneficial. If there were a way to enforce a law, that states that if a car is stopped at an intersection for a given amount of time (around 6 seconds), then the car driving on the opposite side must allow them to turn across. This would provide the same benefit that protected lefts offer, while not bringing the downside of the long amount of time it takes for some cars to turn at those intersections. This would help alleviate traffic congestion without having to redesign the layout of cities. Further research in this area could focus on more densely populated areas such as New York or Boston to see if these findings repeat in these areas.

Table of Contents

Table of Illustrations

1 Introduction

Managing traffic congestion is one of the major concerns when designing a city. Organizing the roads and intersections in such a way that cars aren't spending excessive amounts of time idling while stuck in traffic is a huge economic concern. One of the main causes of idling in traffic is due to left hand turns. In order to make a left-hand turn, it's necessary to cut across the opposing lane of traffic. This not only stops the traffic in the opposing lane, but cars behind the turning car must wait until that car is able to turn across traffic.

The effects of traffic congestion are well known. Particularly in urban areas where the amount of cars is so densely packed in, cars spend a great deal of time and gas waiting in traffic. The average car can waste up to a fourth of a gallon in gas per hour idling. While that may not sound like much, this can really add up when the total number of cars is taken into account.

While the effects of traffic are well known, the causes can be harder to determine. In particular, the effect of left turns on traffic haven't been studied in much depth. The goal of my project was to fill this knowledge gap. In order to determine how much time is spent waiting due to left turns, I observed a series of intersections around Worcester, Massachusetts, keeping track of how many cars turned left and how long it took those cars to turn left. I looked at four different types of intersections in my study: those with four-way stops, those with traffic lights, those with traffic lights that provide a free-left turn, and T-intersections.

Through my studies, I was able to determine that normal traffic lights were the most efficient for allowing cars to turn left through intersections. These types of intersections were able to handle a large volume of traffic while still allowing cars to turn left in a reasonable and fairly consistent amount of time. Due to this, it seems that cities should try and implement these types of intersections whenever possible.

While I wasn't able to conduct the experiment that would have validated this, I still believe that implementing a law wherein people have to allow others to turn left after a certain amount of time would help alleviate a lot of traffic concerns. An interesting future study would be to carry out the experiment that I had planned wherein an experimenter would be in a car, allowing others to turn left to see how that intervention helps alleviate traffic. This would help validate the proposal I made above

2 Background

While the impacts of traffic jams have started to be recorded (Smith, 2019), possible solutions can be hard to come by, and are many times unrealistic or infeasible. In particular the impact of altruistic driving behaviors is not well studied at this point. However, there has been some research done in terms of the causes and effects of traffic. One particular cause of traffic, and all its negative effects, comes from inefficient left turns. When needing to turn left, cars have to cut across the opposite lane of traffic causing that lane of traffic to stop to let that car through. The following sections will discuss the various causes of traffic, the effects of traffic, the possible solutions to traffic, and the studies of altruistic driving behaviors that already exist.

2.1 Causes of Traffic

One area covered in the literature is the study of the root causes of traffic. There are many reasons why traffic jams may occur on highways, city streets, and suburban roads. In particular, accidents are a major source of traffic, especially on highways and busy streets. About half of these accidents are simply due to distracted driving, such as texting or calling on a phone, eating, or looking at maps (Smith, 2019). These accidents can shut down several lanes at a time, causing large delays in traffic flow. Highways can also suffer from “phantom traffic jams”, which aren’t caused by accidents or construction. These are caused by even one car slowing down slightly, causing cars behind them to slow down further. This creates a ripple effect which eventually causes a jam if there are enough automobiles on the highway (Metcalfe, 2018).

Urban traffic patterns can be more difficult to explain. While accidents certainly play a role in creating traffic jams, it is less prevalent than on highways or busier streets. Based on a study in London, less than 15% of traffic is caused by accidents, or other “one-off” events such as strikes, or special events (Chow, 2013). It was found that between 52 and 58 percent of traffic in urban areas was caused by roadwork, bad weather, or other repeated events that can shut down a lane of traffic (Strickland, 2007). Overall, the majority of the traffic was found to be caused simply due to excessive demand for the roads, especially when the roads were compromised for some reason (Chow, 2013).

2.2 Effects of Traffic

The full extent of the effects of traffic are still being researched, but some data has already been compiled. It's estimated that the U.S. economy spends about $121 billion dollars per year dealing with the effects of traffic (Metcalfe, 2018). Through loss of time and fuel, individuals in Germany, Britain, and the United States lose an average of $975 a year waiting in traffic (The Hidden, 2018). In 2010, an estimate was made that traffic caused by accidents cost the United States economy 28 billion dollars and depending on the severity of the accident, each individual crash could cause between 139 and 527 hours of lost time in traffic (across all of the cars affected) (Blincoe, 2015). In terms of measuring the effects of traffic, there are several methods that can be used. Two major methods are congestion intensity, which measures the decline of vehicle speeds during traffic congestion and congestion costs, which takes into account how much people have to drive during peak traffic (Litman, 2019).

While idling, cars can waste between .16 and .25 gallons per hour (Weber 2019). This equates to a car losing between .003 and .004 gallons per minute. In 2009, there were 210 million drivers in the US, who drive an average of 14,000 miles per year (Highway, 2014). This means that in the United States alone, this means that there are 2,940,000,000,000 miles driven in the United States per year.

2.3 Possible Solutions

There have been many options in reducing traffic. One of these methods is expanding roads/highways to have extra lanes. While this idea may seem beneficial, it has been found that once the initial road is laid down, adding extra lanes does very little to increase productivity; although traffic does see a short-term decrease, over time traffic simply expands to once again meet the capacity of the larger road; especially in urban centers (Nadri & Mamuneas, 1996). Public transportation is another mode of transport that does help greatly reduce the effects of traffic. These methods of transport decrease the number of vehicles on the street during peak times among other societal benefits (Nadri & Mamuneas, 1996). Pricing reforms such as increasing toll prices during peak hours or adding a tax to gasoline have also seen success in reducing many of the negative effects of traffic congestion (Nadri & Mamuneas, 1996).

2.4 Studies on Altruistic Driving Habits

While the field hasn’t been extensively covered, there has been some research on the effects of altruistic driving on traffic. One altruistic solution was proposed by Berthold Horn (2018) in response to the “phantom traffic jams” explained above. Horn recommends that highway drivers do their best to keep themselves at halfway between the car in front of them and the car behind them. Making the effort to not tailgate the drivers in front would mitigate the change in speed they’d have to make if said driver slowed down at all (Metcalfe, 2018).

3 Methodology

The goal of this project was to determine if altruistic driving behaviors can reduce traffic in urban environments. Specifically, the study sought to accomplish the following objectives:

- To determine if making it easier for drivers driving in the opposite direction to turn left makes a significant difference in traffic pattern (the situation in question is shown in Figure 1.1).
- To estimate the costs and benefits of promoting easier left turns
- To determine the overall societal effects of promoting these turns

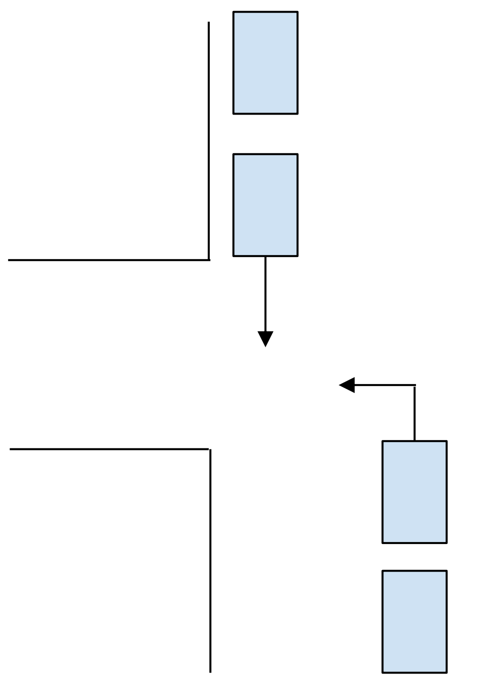


Figure 1.1 Illustration of Left Turn in Traffic

In order to achieve these objectives, the following methodological approach was implemented.

3.1 Observations

In order to determine if allowing opposing drivers the opportunity to turn left affects traffic in any meaningful way, I first collected observational data. For this observation, I stood at various intersections, analyzing the left turns that fit the description of Figure 1.1. The intersections were placed into 3 distinct groups; those with no traffic lights, those with normal traffic lights, and those with traffic lights that allow a "free" left turn for a few seconds before turning fully green (refer to the *Table 1 Intersection Types Studied*). This specific experiment took place in Worcester Massachusetts and analyzed the following intersections: those with no traffic lights (Intersection of Institute Road and Dean Street, and the intersection of Lancaster Street and Highland Street), those with normal traffic lights (intersection of West Street and Highland Street, and the intersection of Park Ave. and Institute Road), and those with a left turn light (Intersection of Park Ave. and Salisbury Street). Refer to Appendix 6.1 for satellite pictures of all these intersections. These types of intersections were chosen as they are some of the most common types of intersections in urban areas, all of which handle left turns in different ways. At a stop sign, turning left is largely irrelevant, since it's a first come first serve system. But on the downside, this means that everyone has to stop, whether it's strictly necessary or not. Traffic lights allow opposing lanes to run against each other, which must be broken if a car wishes to turn left. However, those stop lights with protected left turns give drivers turning left a few seconds to turn left before the opposing lane can go. A T-intersection most closely resembles the intersection depicted in Figure 1.1

Stop Sign	Traffic Lights	Traffic Lights with Protected Left Turn	T-Intersection
- Intersection between Institute Road and Dean Street -Intersection between Lancaster Street and Highland Street	-Intersection between West Street and Highland Street -Intersection between Park Ave. and Institute Road	-Intersection between Park Ave and Salisbury Street	-Intersection between Boynton Street and Salisbury Street

Table 1: Intersection Types Studied

The main variables that were collected were the amount of time it took for the initial driver to turn left. For intersections without stop lights, this began as soon as the car in question started to attempt to turn left. For intersections that did have stoplights, this began as soon as the car was either stopped by the light or attempted to turn left. Data was also gathered on the number of cars that got stuck behind this initial car and couldn't advance. Cars were counted if they were stuck behind the left-turning car once the timer starts based on the criteria given above. To clarify, the three variables that I looked at were

1. Cars attempting to turn left
2. Time spent trying to turn left (in seconds)
3. Cars stuck behind cars turning left (in cars)

3.2 Experiment

The goal of the experiment was to alter the pattern of traffic in order to induce more voluntary stops allowing the opposing drivers to turn left.

The set up of the experiment was similar to that of the observations. The observer (me) sat in a car facing an intersection (in this case the intersection between Salisbury Street and Boynton Street). Another person was in the car in order to help record information. Just like before, anytime that a car tried to turn left at the intersection, we counted how many cars were attempting to turn left, how long it took those cars to successfully turn left (in seconds), and how many cars were stuck waiting behind cars trying to turn left. In this case though, it was noted when a driver in the opposite lane stopped to allow one or more cars to turn left against the flow of traffic (as opposed to cars simply getting through in a break in traffic or traffic being stopped). It was also noted whether or not pedestrians entered the crosswalk (which typically gives an opportunity for cars to turn left as it temporarily halts traffic). In order to ensure that there was a proper number of observations in this experiment, three drivers were continuously driving in circles around the WPI campus, which brought them through the intersection of Salisbury and Boynton. When these cars reach the intersection, if there were any cars trying to turn left, they allowed up to two cars to turn left before continuing in their circle. This ensured that there was a proper number of times that cars willingly allowed other cars to turn left. The data from this experimental portion of the project was then compared to the observational data in order to determine the impact of drivers allowing others to freely turn left.

3.3 Analytical Methods

The end goal of this project was to possibly come up with a recommendation to address inefficient left turns. In order to do this, it was important to first determine if left turns are in fact inefficient, and to what extent they are. We then compared the observations to the experiment to determine if intervention results in more efficient turns than any existing method. After that, I was able to determine what the costs and benefits are of more efficient left turns and what overall impact that those more efficient turns could have on society.

3.3.1 Determining if Making Left Turns Easier Makes a Difference in Traffic Patterns

Once gathered, the data from the different types of intersections were compared. This helped determine if there was a solution to the left turn problem already available (if normal lights or left-turn lights solve the issue, then that may be the large-scale solution). If these were not found to be adequate solutions, then possible solutions would be theorized based on behaviors seen during data collection. Time allowing, these new possible solutions would be tested as well.

In order to compare the data, the different intersections were divided into their various types (intersections with stop signs, those with stoplights, those with protected left turns, and the T-intersection). To have a large enough data set, we will combine all three observations for each intersection (early rush hour, off-hours, late rush hour). This constituted the data set for each interaction. We then came up with three separate statistics for each intersection, Average Time Spent Waiting (which was an average of all the time waiting statistics), Adjusted Average Time Spent Waiting (which was an average of all the time waiting statistics excluding those that equal 0) and Average Cars in Traffic (which was an average of all the cars behind statistics). The reason we were interested in Average Time Spent Waiting was to determine how long the average car waits to turn left at an intersection, important data to understand which intersections work more efficiently. The reason we're interested in Adjusted Average Time Spent Waiting was so that we could have an idea of how bad traffic gets while waiting for cars to turn left. The reason we're interested in the Adjusted Average Time Spent Waiting was slightly more complex. The end goal of this project was to possibly come up with a solution to inefficient left turns. If the turns are already perfectly efficient (take 0 seconds waiting to execute) then there is no room for improvement from an efficiency perspective. So part of what we're looking at for this paper is if the left turn is inefficient, seeing how much room there is for improvement. For instance, if five cars turn left in 0 seconds, but it takes one car thirty seconds to turn, then there is clearly a high chance that this large delay results in a traffic jam and could be improved upon.

One all of this data was compiled, the same was done for the data gathered during the experiment phase. So, the data from the experiment was directly compared to that of the observations. Once those were compared and analyzed, we were able to make a determination on what difference, if any, is made from drivers allowing cars to turn left against traffic.

3.3.2 Costs and Benefits of Promoting Left Turns

Assuming that the data shows that allowing drivers to turn left is more efficient, the extent of that increased efficiency was roughly extrapolated to determine what the impact of that increased efficiency might result in for the entire US economy. Specifically, we looked at the time saved from the more efficient turns, the gas saved from the more efficient left turns (less time spent idling in the road), as well as the money that can be saved due to the increased efficiency.

3.3.3 Overall Societal Benefits

The data was also extrapolated to a larger scale in order to determine the overall economic societal impact of allowing drivers to turn left. This included an estimate on time saved for drivers, as well as the money saved across society. Using basic data that was outlined in the background, we were able to give a rough estimate of how much time, money, and gas can be saved. To perform these calculations, I determined how much time is unnecessarily wasted by cars waiting to turn left. I determined this by finding the difference in *Average Time Spent Waiting* from the most efficient group of observations and the actual experiment. I then multiplied that by the average number of cars that came through the intersections and then converted that figure into hours to determine how many hours an average are wasted per intersection in a 30 minute period. I then roughly extrapolated that to the entirety of the United States to determine how many total hours are wasted. Then, using the figure of how much gas is wasted while idling in a car, we multiplied that times the amount of time spent idling to determine how much gas is wasted. From there, I simply multiplied that number by the average price of gas per gallon to determine the monetary loss (at least from wasted gasoline).

4 Results

After conducting the experiments, I was able to produce several summary statistics to try and make sense of all the data I gathered.

4.1 Summary Statistics

After conducting the observations, I was able to come up with the previously mentioned summary statistics. These statistics can be seen summarized in Table 2. To see the difference between the intersections during peak and off hours, we can look at tables 3, 4, and 5.

	Dean and Institute	Institute and Boynton	Institute and Park	Highland and West	Lancaster and Highland	Salisbury and Boynton
Average Time Spent Waiting (seconds)	.481	4.077	2.690	6.173	5.731	5.318
Adjusted Average Time Spent Waiting (seconds)	5.286	4.479	6.638	6.294	15.302	7.290
Average Cars Behind (cars)	.026	.295	.578	.7556	.463	1.518
Total Observations	77	78	116	90	283	85

Table 2: Summary Statistics for Each Intersection

The first two columns in the table are the intersections that are 4 way stops, the middle two columns are the intersections that have traffic lights, the fifth column has protected left turns, and the final column shows T-intersections. Table 3 shows these statistics broken down by intersection type. In Appendix 7.2 you can find Table A1 Peak Vs Off Hours, which gives more information on which hours and days were used as off-hours and peak hours for every intersection. The number in parenthesis represents the standard deviation for each statistic.

	Dean and Institute			Institute and Boynton		
	Peak Hours	Off Hours	T-test	Peak Hours	Off Hours	T-test Value
Average Time Spent Waiting (seconds)	.447 (1.791)	.533 (2.097)	p=.8743	4.153 (.2964)	3.842 (.2986)	p=.0002 (significant)
Adjusted Average Time Spent Waiting (seconds)	4.2 (4.087)	8 (5.033)	p=.3385	4.455 (2.840)	4.563 (2.683)	p=.8926
Average Cars Behind	.043 (.292)	0 (0)	p=.4236	.322 (.571)	.211 (.535)	p=.5469
Total Observations	47	30		59	19	

Table 3: Summary Statistics for Four Way Stops By Time

Note: Standard deviations in parentheses.

	Institute and Park			Highland and West		
	Peak Hours	Off Hours	T-test	Peak Hours	Off Hours	T-test Value
Average Time Spent Waiting (seconds)	2.380 (4.004)	3 (5.761)	p=.5023	4.197 (4.878)	2.241 (3.592)	p=.0577
Adjusted Average Time Spent Waiting (seconds)	5.308 (4.515)	8.286 (6.972)	p=.0397 (significant)	6.564 (4.650)	5.417 (3.753)	p=.4401
Average Cars Behind	.517 (1.143)	.638 (1.398)	.6108	.984 (1.478)	.276 (.649)	p=.0157 (significant)
Total Observations	58	58		61	29	

Table 4: Summary Statistics for Stoplights By Time

Note: Standard deviations in parentheses.

	Lancaster and Highland			Salisbury and Boynton		
	Peak Hours	Off Hours	T-test Value	Peak Hours	Off Hours	T-test Value
Average Time Spent Waiting (seconds)	5.08 (8.357)	6.788 (12.256)	p=.1648	5.556 (5.701)	4.636 (8.301)	p=.5667
Adjusted Average Time Spent Waiting (seconds)	14.339 (8.018)	16.660 (14.335)	p=.2902	6.863 (5.582)	9.273 (9.870)	p=.2689
Average Cars Behind	.326 (.839)	.685 (1.598)	p=.0140 (significant)	1.165 (2.294)	1.136 (1.833)	p=.9574)
Total Observations	175	108		63	22	

Table 5: Summary Statistics for Protected Left and T-Intersections By Time

Note: Standard deviations in parentheses.

Tables 3, 4, and 5 show the observations broken up by time. These are split into both peak hours and off hours. The conclusions that can be drawn from the analysis of peak vs off-hours are not consistent with what I expected at the beginning. Several of the intersections during their off-hours handled more traffic than during their peak hours. The T-tests suggest differences that are non significant between the average statistics for peak-hours compared to non peak hours. When they are significant, the non-peak hours have relatively higher averages, in contrast with my initial expectations. This unexpected result is probably due to the small sample size, but could also be explained by the variation in the peak/non peak times used for observation at the different intersections. This can also be an issue as different areas would have different actual peak times; the standard accepted hours might not be entirely accurate for Worcester.

	Four-Way Stop	Stoplight	Protected Left	T-Intersection
Average Time Spent Waiting	2.279	4.432	5.731	5.318
Adjusted Average Time Spent Waiting	4.883	6.466	15.302	7.290
Average Cars Behind	.161	.667	.463	1.518
Total Observations	155	206	283	85

Table 6: Summary Statistics by Intersection Type

4.2 Interpretation of Statistics

Looking at the statistics given above, it's important to add some context to the data presented. The four-way intersections have both the lowest Average Time Spent Waiting and Adjusted Average Time Spent Waiting. However, looking at the total observations, these types of intersections tended to have the least amount of cars coming through (although the T-intersection had fewer total observations, only one intersection was observed). So the apparent efficiency of these intersections may be due to the smaller amount of traffic that came through these intersections. It would be interesting and valuable to see how efficient these intersections handled a greater volume of traffic, but unfortunately that exceeds the scope of this project as I didn't have more time to run additional observations. It is interesting to compare the intersections with stop lights and protected left turns however. Based on the observations, while the two had a very similar Average Time Spent Waiting, the protected left turn intersection had a far higher Adjusted Average Time Spent Waiting. This tells me that although every car spends around the same time at these intersections, some cars spend far more time waiting at protected left turns, while others go through without any wait at all.

4.3 Potential Economic Costs

To see the extent of the effect of left turns on the US economy, I chose to extrapolate the data based on the statistics found in the background section. If one averages all of the Average Time Spent Waiting statistics across all of the different types of intersections, you find that the average time spent on turning left based on my data set is 4.078 seconds. There were a total of 709 observations across my entire time observing. This means that a total of 2,891.302 seconds were spent waiting across my observations. Divide that by 60, and that means that 48.188 total minutes were spent waiting by all of the cars I observed. Since cars can waste between .16 and .25 gallons per hour while idling, I cut the difference and assumed that the cars wasted .2 gallons per hour waiting (Weber 2019). This means that .16 gallons were wasted by the 709 cars. There are 210,000,000 drivers in the US (Highway 2014). This means that if every driver in the US drove through intersections at the same rate as in the sample used for this study, those drivers would waste 59,238 gallons waiting while idling. At the time of writing this paper, gas prices are around $2 per gallon. This means that there is $118,476 wasted by inefficient left turns simply from lost gas alone.

5 Conclusion

Based on all of the results above, I would have to make the recommendation that whenever possible, four-way intersections utilize traffic lights without protected lefts in areas with a medium level of density. For areas with higher levels of traffic, the protected left turns may still be necessary to help allow traffic to thin out. These intersections have proven to be the most effective in promoting efficient left turns. I believe that a significant amount of wasted gas and money would be saved by using these intersections.

In addition, I think that legislative action could help to promote greater efficiency with left turns. Although I haven't been able to test this due to the outbreak of the Covid-19 virus, I think that implementing a policy wherein cars have to let cars in the opposing lane turn left after around 6 seconds of waiting. This would give some of the benefits of the protected left turns, without the occasional cars that would have to wait a far longer time than normal to turn.

I think that in the future, it would be beneficial to run the experiment I planned to run before the virus outbreak. This experiment would be similar to how the observations were run. However, several drivers would drive through the observed intersection, allowing any two cars attempting to turn left to turn. This would be almost like a trial of the possible legislative action proposed above. I think that this experiment could go a long way in validating the ideas I have proposed.

6 References

Blincoe, L. J., Miller, T. R., Zaloshnja, E., & Lawrence, B. A. (2015, May). The economic and societal impact of motor vehicle crashes, 2010. (Revised) (Report No. DOT HS 812 013). Washington, DC: National Highway Traffic Safety Administration.

Chow, A. H. W., Santacreu, A., Tsapakis, I., Tanasaranond, G., & Chen, T. (2013). Empirical assessment of urban traffic congestion. Empirical Assessment of Urban Traffic Congestion. Retrieved from https://onlinelibrary.wiley.com/doi/full/10.1002/atr.1241

Litman, T. (2019). Smart Congestion Relief: Comprehensive Evaluation of Traffic Congestion Costs and C

Evaluation of Traffic Congestion Costs and Congestion Reduction Strategies. Victoria Transport Policy Institute. Retrieved from https://www.vtpi.org/cong_relief.pdf

Highway Finance Data Collection. (2014, November 7). Retrieved March 18, 2020, from https://www.fhwa.dot.gov/policyinformation/pubs/hf/pl11028/chapter4.cfm

Metcalfe, T. (2018, February 26). 'Phantom' Traffic Jams Are Real — And Scientists Know How to Stop Them. Retrieved October 7, 2019, from https://www.livescience.com/61862-why-phantom-traffic-jams-happen.html.

M.I. Nadri and T.P. Mamuneas (1996), Contribution of Highway Capital to Industry and National Productivity Growth, FHWA, USDOT; citied in USDOT (1997), Transportation in the United States: A Review, USDOT (http://ntl.bts.gov/data/titustxt.pdf).

Smith, J. (2019, January 10). Causes and Effects of Traffic Accidents. Retrieved October 14, 2019, from https://itstillruns.com/causes-effects-traffic-accidents-7274650.html.

Strickland, J. (2007, September 26). How Traffic Works. Retrieved October 17, 2019, from https://auto.howstuffworks.com/car-driving-safety/accidents-hazardous-conditions/traffic1.htm.

The hidden cost of congestion. (2018, February 28). Retrieved October 13, 2019, from https://www.economist.com/graphic-detail/2018/02/28/the-hidden-cost-of-congestion.

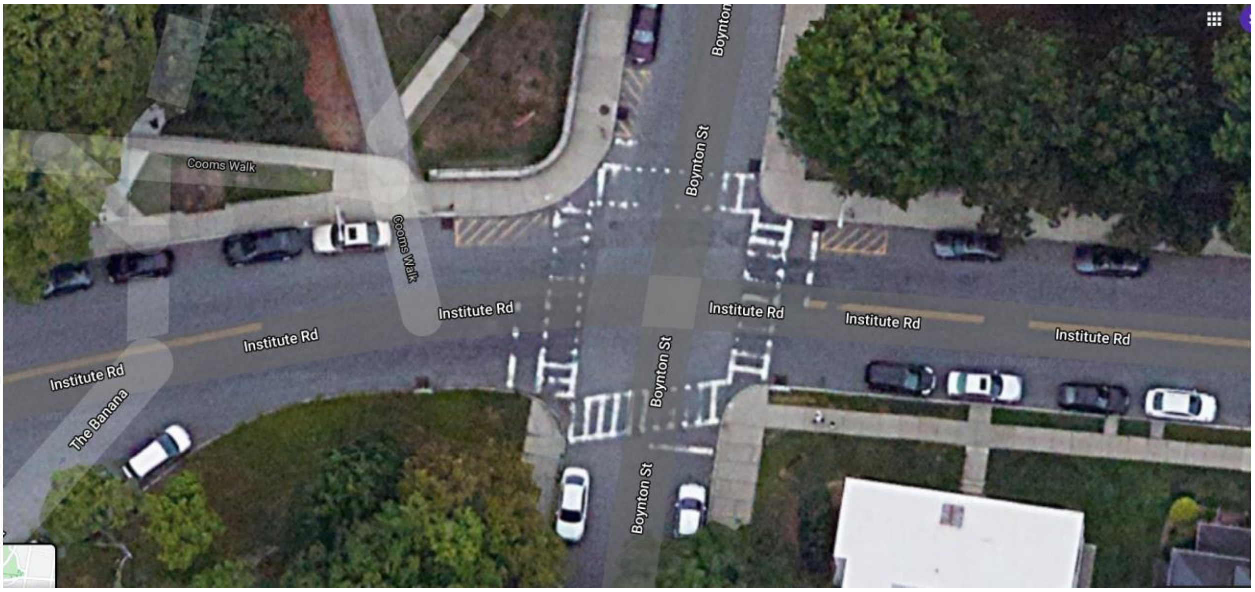
Weber, B. (2019, June 1). How much gas is wasted by idling? Retrieved April 1, 2020, from https://www.chicagotribune.com/autos/sc-auto-motormouth-0308-story.html

7 Appendices

7.1 Pictures of intersections

Intersection of Boynton and Salisbury

Intersection of Lancaster and Highland



Intersection of Institute and Boynton

Institute of Dean and Institute

Intersection of Institute and Park

Intersection of Highland and West

7.2 Peak vs Off Hours Tables

Intersection	Peak Hours Used	Off Hours Used
Salisbury and Boynton	7:50-8:20 AM (Saturday) and 5:15-5:45 PM (Tuesday)	3:30-4:00 PM (Tuesday)
Highland and West	7:30-8:00 AM (Friday) and 5:45-6:15 PM (Thursday)	2:10-2:40 PM (Monday)
Lancaster and Highland	7:10-7:40 AM (Tuesday) and 5:30-6:00 PM (Friday)	2:50-3:20 PM (Monday)
Institute and Park	7:00-7:30 AM (Sunday) and 6:00-6:30 PM (Wednesday)	4:00-4:40 PM (Thursday)
Institute and Boynton	7:00-7:30 AM (Monday) and 4:45-5:15 PM (Wednesday)	2:15-2:45 PM (Monday)
Dean and Institute	8:10-8:40 AM (Friday) 6:15-6:45 PM (Sunday)	2:00-2:30 PM (Tuesday)

Table A1: Peak Vs Off Hours