A Solution to the Houston Traffic Crisis

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Abstract

Morning rush hour traffic in Houston often results in a large amount of congestion and increased travel time. Because the amount of vehicles on the road exceeds the number of vehicles the road can accommodate, many traffic jams form as shown through our model of maximum vehicular flux. Considering the suburban sprawl of the city as well as cost and cultural values, there are many methods of reducing traffic that would not be appropriate in this situation. However, implementation of a carpooling app to decrease the number of individual vehicles as well as the addition of ramp metering are both viable options for reducing traffic congestion in Houston. Using a traffic model, the proposed carpooling app would decrease the number of traffic jams by 63 percent. Ramp metering would have the potential to decrease commuter travel time by over 22 percent. By employing these methods, worker productivity would be increased as commuters would not be stuck in traffic for long periods of time.

Introduction

Houston, Texas, is a densely populated city that covers an area of 669 square miles. Due to this large area, many residents must commute from the suburbs to the inner city for work every morning. However, traffic flow is often congested due to the limited capacity of the existing highways. Large amounts of traffic increase the risk of automobile accidents and prolong travel times, causing decreases in economic productivity as workers do not get to work on time. Therefore, Houston is in need of solutions to alleviate the amount of congestion that occurs during rush hour every morning.

Phase 1

Model Description

In order to observe whether or not a traffic jam is occurring at a given location, the collected data must be leveraged in a way that allows one to quantitatively describe the state of the system. Each instance in the dataset provided contains an attribute describing the real vehicular flux at a given crossroad which is assumed to be constant over the one-hour interval of time we are studying. If the real vehicular flux is greater than the maximal flux of vehicles (MFV), which is the maximum number of vehicles per hour that a point in the highway system can accommodate, then it must be that a traffic jam has occurred. Thus, comparing the MFV to the real flux at each point in the highway system can be used to determine where the jams are occurring. Using the data provided in the spreadsheet, we propose the following formulation for MFV in a single lane:

$$MFV = \frac{1000 \cdot v}{1 + FD} \cdot \frac{1}{5 \cdot p_{car} + 15 \cdot p_{truck} + 10 \cdot p_{bus}} \qquad \text{(Single Lane MFV Formula)}$$

Where v is the expected average speed of the drivers in km/hr, FD is the average following distance between the cars, and p_x represents the proportion of vehicle x on the highway. To calculate the MFV for a highway, the flux of the right lane was calculated based off of the speed limit given. Since cars often drive faster in the leftmost lanes, these individual MFVs were calculated at 5 mph (8.04 kmph) over the given speed limit. The following distance (FD) depends on the speed limit, which is provided in the spreadsheet and is assumed to be the same for all types of vehicles. Based off of DMV regulations, the proper following distance is 1 car length for every 10 mph. Thus the formula for following distance would be speed in miles per hour divided by 10, which would generate a unitless number representing the following distance in car lengths. However, this assumption is much too generous and is therefore not realistic, especially since Texas is the state with the fourth worst tailgating (Safelite). Other rules of thumb dictating following distance were even more unrealistic. Since data detailing the actual following distance used by drivers was not available, various formulas substituting 20, 30, or even 40 into the denominator of the formula for following distance were used to compute where traffic jams would have occured. Once the resulting traffic jam locations were identified, they were compared to a map containing real traffic jam data to determine the most accurate formula for following distance. It was found that the following following distance (FD) formula produced the most accurate data: $FD = \frac{0.621371 \cdot v}{20}$. In the information given, we were told the lengths of cars, buses, and trucks are 5, 10, and 15 meters respectively. Using the proportions of each type of vehicle, we were able to determine the average amount of space taken up on the road by vehicles at one time. To determine how much distance a single vehicle would take up, the length of that vehicle was multiplied by one plus the following distance, which was in units of car lengths. Multiplying this effective car length by the proportion of each type of vehicle and adding the products resulted in the average length of road taken up by each car in meters per car. To calculate MFV in cars per hour, dimensional analysis yielded the above formula in which the speed in kilometers per hour must be multiplied by 1,000 to obtain the speed in meters per hour. Dividing this value by the average car length in meters per car resulted in units of cars per hour, which describes the maximum vehicular flux (MFV). The total MFV for the highway was found by adding the flux of each lane using the following formulation for MFV:

$$MFV = \frac{1000 \cdot s}{5 \cdot p_{car} + 15 \cdot p_{truck} + 10 \cdot p_{bus}} \cdot \left[\frac{(s+8.04)(n-1)}{1+\frac{0.6213\cdot(s+8.04)}{20}} + \frac{s}{1+\frac{.6213\cdot s}{20}} \right] \tag{Total MFV Formula}$$

where s is the speed limit of the crossroad and n is the number of lanes. An intersection was determined to have a traffic jam if the real flux was greater than the maximum flux. Once each point in the system was classified as either having a jam or not having a jam, GPS coordinates were geocoded from the provided crossroad names and a map was created to provide a visual representation of where the jams were occurring.

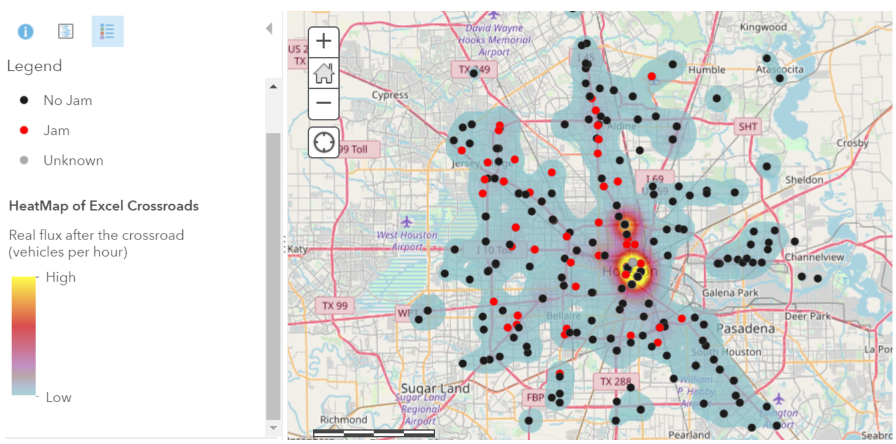

Figure 1: Heatmap of the Traffic System According to our Model

The red dots indicate a traffic jam at the intersection based on our MFV-calculated values while the black dots indicate no jam. In total, there were 186 jams and 460 no jams according to this method. Figure 2 below shows the percentages between these jammed intersections and no jammed intersections.

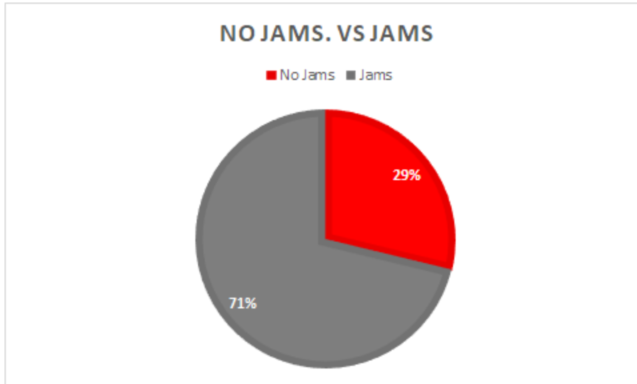

Figure 2: Jams vs No Jams

In comparison with publically available heatmaps of the highway system in Houston from the day we are studying, our model appears to be a sufficient representation of the actual system. The referenced map is from the Houston TranStar archives [1] and shows the average speeds at 8:30 AM on Monday, January 29, 2018.

The heat map comes from another formula which calculates travel time shown below based on the fundamental equations for transportation [2]. This formula works by dividing the section length by the velocity of the cars to obtain time. The velocity is calculated by multiplying the real flux veh/hr by spacing km/veh where spacing is the following distance between cars and car length to get speed km/hr. Because speeds at congested areas are of interest, the spacing is assumed to be 6 meters as a car is typically 5 meters, allowing for 1 meter of following distance in bumper-to-bumper traffic. The section length km is divided by speed to obtain travel time in hours and multiplied by 60 to obtain time in minutes. The travel time was calculated at each intersection. The heat map displays these real travel time values with yellow being the highest amount of travel time and blue being the lowest.

$$\text{TravelTime} = \frac{\text{section length}}{\text{real flux} \cdot FD \cdot 60} \qquad \text{(Real Travel Time in Minutes)}$$

The MFV-created map is not a perfect model but both graphs have their similarities. Both maps indicate traffic jams to the north and northwest. External sources report these regions as particularly infamous for their lack of traffic improvement [3]. However, it should be noted that there are some differences such as the indication of traffic on the east and southeast side of Houston. The MFV-created map is in much better agreement with another heatmap from Google Maps shown below.

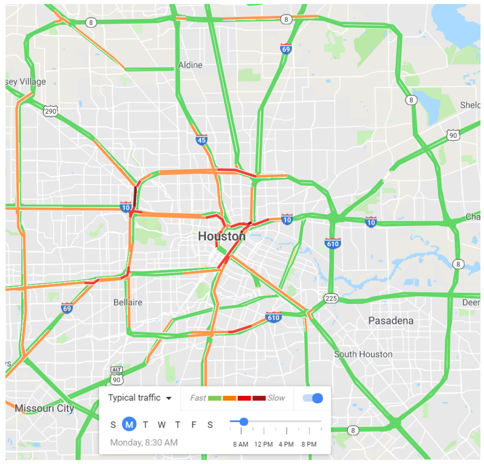

Figure 3: Heatmap of the Traffic System According to Google Maps

This heat map shows the "typical" traffic of Houston at 8:30 AM on a Monday. Like the MFV-created map, this map shows traffic occurs in focused points in Houston away from the east side. Perhaps this is because Google Maps has a much more narrow definition of slow compared to the TranStar map or TranStar's "$<$ 20 MPH" speed is too high.

Phase 2

Impractical Solutions

Many methods for reducing traffic were considered, but few met satisfactory levels of impact and cost. For example, increasing public transportation was not considered a practical solution since Houston covers such a widespread area. It would be difficult to design and implement an efficient transportation to serve those who live in suburban areas. Other methods that were rejected included adding new highways and congestion pricing.

Increasing Speed Limits

One method one might consider to mitigate traffic jams is to increase the speed limits along the highway - intuitively, if cars are driving faster, then they should leave the highway system faster, increasing the MVF that a given intersection can support. However, according to our model, the effects of increasing speed limits is simply not impactful enough considering the various risks that come with higher speed limits. A barplot comparing MVF versus various speed limit increases is shown below.

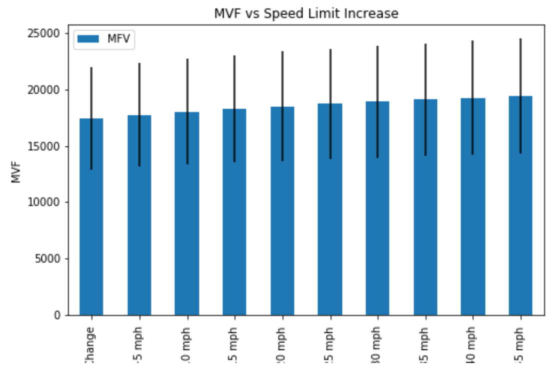

Figure 4: MVF versus Various Speed Limit Increases

Clearly, the benefits of increased speed limits are marginal when safety isn't a consideration, so increasing speed limits in order to increase MVF isn't a good solution. We suspect that speed limit increases have a small impact on MVF because increasing the speed limit also increases the following distances of vehicles.

Adding More Exits

The benefits of adding more exits to the Houston traffic system are hard to measure. On one hand, busy exits can result in queues that extend back into the travel lanes, which increases congestion. On the other hand, most highway sections in Houston already have multiple exits every mile, so adding more exits between them could potentially cause more congestion, as there would be less space for cars to form a queue for any given exit, resulting in more congestion for popular exits. Assuming that adding more exits would be beneficial, there is still a cost consideration to be made. Recently in Boston, a proposal to build a new exit between two existing exits is under debate, as it is estimated to cost around \$37.8 million USD [4]. Additionally, transportation officials say that the creation of interstate exits can take decades to complete, so one would assume that the creation of a highway exit would also take a considerable amount of time [5]. Thus, considering the amount of resources and time required to add exits with no concrete evidence of mitigating traffic congestion, we don't consider adding more exits to be a viable solution.

Increasing the Number of Lanes

After analyzing the various benefits and consequences of adding more lanes on highways, it was concluded that the addition of lanes is an ineffective way to reduce traffic. Civil engineers have compared traffic to gas: "it expands to fill the space provided" [6]. Adding lanes will most likely improve traffic at first. However, as soon as commuters hear of the improved traffic conditions, more individuals will populate the new lanes and congestion will occur once again. This idea is called the Fundamental Law of Road Congestion [7]. In addition to this phenomenon, building new lanes is expensive and time consuming. Besides the construction costs, there are many expenses involved in the process such as engineering costs and right of way acquisition costs. The cost of road maintenance would also continue to cost the city money. In Texas, it would cost roughly $30,000 per mile to build a one lane road, and the process would take years to complete [8]. Furthermore, Houston highways are already 5 and 6 lanes wides in some areas. It would be impractical to widen these highways even more. Therefore, it was determined that adding lanes would not be a beneficial solution to improving traffic in Houston.

Congestion Pricing

While congestion pricing is a trendy topic with New York City announcing a congestion pricing plan, this is not the best option to reduce traffic in the Houston, Texas area. The premise behind congestion pricing is that as demand exceeds supply, prices will rise and some consumers will choose not to buy. While the goal of congestion pricing is sound, Houston is not the best city to implement this idea, due to the high cost associated with the infrastructure and the its function as a regressive tax. The implementation cost of congestion pricing is could be high compared to the carpooling app or ramp metering, depending on the method used to track vehicles in the network, and where congestion pricing would be charged. Some places currently using congestion pricing, and plans for New York, are charging fees through an electronic tolling system, building upon already existing EZ Pass technology. If Houston were to implement congestion pricing with the use of current EZ Pass technology, additional funding would be required to install the necessary toll booths at every entrance. Another alternative for charging drivers would be a GPS-based system to track the movement of vehicles through a network, similar to what countries in Europe currently use for roadways that are not all highways and interstates. Notably, the cost of such a system is high, at up to $500/vehicle in Germany[9]. Thus, the monetary cost for congestion pricing could be prohibitively large, coming from the need to purchase and install an electronic tolling system and GPS-based system, as well as cameras to monitor for potential violators not paying a fee or without the necessary tag [10].

Congestion pricing can be viewed as a potentially regressive tax, putting an unfair burden on working class drivers who can't afford to pay the tax. Congestion pricing works well in cities such as London, where more higher income people drive and more poor people take the bus [11]. However, Houston is a large city, and public transportation is not a realistically feasible option for most people commuting into the city at peak rush hour. The high cost of congestion pricing, in addition to the need to get into the city to work, could create an impossible situation for many drivers who could not afford to get into work, and not afford to not be at work. Houston does not currently have a good system for people to use as an alternative to get to their desired destination. Current public transportation in Houston includes MetroRAIL, offering a way to travel within the heart of the city, and a Park & Ride bus service available for long distance commuting. The commuter bus ridership is not heavily utilized, seeing a 17% drop in ridership from October 2015 to 2016 [12]. Additionally, the feasibility of congestion pricing and its reliance on accessibility to public transportation is dependent on the size of the city. Following the implementation of congestion pricing, with a charging zone covering an area of 8 square miles, London's transit agency put hundreds of extra buses on the street [13]. Thus, it can be assumed starting congestion pricing in Houston would also require additional funding for public transportation. The size differential of London and Houston has to be taken into account while making comparisons. London is the most populous city in the UK, with a population density around 7,200 inhabitants within the city limits [14]. According to the 2010 Census, Houston was home to 2.1 million people within 599 square miles, putting the population density around 3,662 people per square mile [15]. It would be more difficult to make public transportation available to people in Houston, with both the decreased population density and wider area that would be impacted by congestion pricing. Seeing as there are no viable options that are easily accessible to Houston commuters who can't afford the congestion pricing, this added cost for driving was not a recommended option to mitigate Houston traffic.

Viable Solutions

Two solutions were considered appropriate for implementation to reduce traffic congestion in Houston. One method aims to increase carpooling through an app while other option, ramp metering, would decrease the amount of traffic allowed on the highway at one time. If executed together, these options could have a significant impact of the traffic flow in Houston.

Carpooling Application

Increasing carpooling is an inexpensive and relatively foolproof method of reducing vehicular flux on the highways. Unlike the addition of lanes and roads, carpooling is less likely to cause unintuitive increases in traffic. However, carpooling is not a popular option for many reasons. Work schedules have become increasingly irregular, making it hard for neighbors to coordinate rides. This issue includes emergencies that require sudden trips home and pre planned events that interfere with one's normal work schedule. Other commuters rely on running errands on their way to and from work, which prevents them from committing to a carpool. Carpools can be especially hard to organize if a worker is new to the area and does not know many people that live or work nearby. To solve this problem, an app may serve as a convenient platform for coordinating carpools. By considering the user's home and work locations as well as their day to day work schedule, an app would be able to put potential carpoolers in contact. Not only does this overcome unfamiliarity, but it can also help form carpools for those who might have a different schedule every day since an app could easily match riders up on a day to day basis. The app could be used to either plan carpools in advance or sign up for a last minute ride. The user would specify whether they would like to drive or ride that day, and a list of potential matches would be generated. Based on a short biography and anonymous rating system, the user would be able to choose which other users they would like to ride with. Additional information that could be provided includes the user's preferences with regard to music and talking in the car. Only when both users in the interaction have expressed interest in riding together would they be able to correspond or see each other's addresses for safety purposes. Workers would not be likely to use the app unless there were incentives for doing so. These incentives must be attractive enough to overcome the commuter's desire for privacy and independence, which is another value that causes workers to choose individual commutes over carpooling. In many cases, the ability to use the HOV lane is not enough of a benefit. To add to the incentives for carpooling, the app could have a rewards program for dedicated users including perks like reduced parking and toll fees. The app could also partner with sponsors such as restaurants, gas stations, and other stores to award discounts after a certain amount of use. The user would receive rewards points for every time they participated in a carpool, eventually building up enough points for a coupon or discount. Businesses such as restaurants and stores could be convinced to offer discounts and rewards in return for increased business at no cost to the city. Rewards would cost about $2,000 per company per month. We estimate that about 15 local companies will participate in this program, coming out to a cost of $30,000 per month [16]. In order to attract commuters to sign up quickly upon introducing the app, the city could directly pay the first 1,000 users a small sum of money, perhaps around $20. We would expect the initial cost of app incentives to be about $100 per user per year in order to build up a user base; however, this figure would decrease drastically as the cultural shift to carpooling would eliminate the need for such high incentives. Other than the cost of incentives such as donations from partnering businesses and decreased revenue from toll roads and parking services, the only cost of the app would be in its development. Although the cost of building a free, high quality app that connects to websites and social media is about $81,600, this cost is much less than that of building new roads, which is about $11 million per mile. The app would also take less time to produce than a new road. We predict that it would take approximately 4-6 months to create with another 6 months to generate a user base large enough for the application to be useful. In order for the app to be successful, enough commuters would need to use it to form carpools in each area of residency. Therefore, awareness about the app would have to be raised through local advertising. This can be done through local radio stations, billboards, and even online through social media platforms. These advertisements would also notify local residents of the potential benefits of using such an app, such as reduction of traffic, environmental impact, and travel costs. Radio advertisements range from $200 to $5,000 per week, depending on the station [17]. In a Nielsen study, 40% of people sought more information about a product after hearing 3+ radio advertisements [18]. In Houston, a billboard costs $3,395/month and is expected to generate 3,938,743 weekly views [19]. Advertising on Facebook would also cost between $0.20 and $0.80 per click [20]. Using the averages of these price ranges and assuming 20,000 clicks per month, the total cost of advertising is about $15,995/month. Overall, these advertisements would greatly increase local residents' awareness of alternative transportation solutions. Although the city must invest money to market this mobile application, the price is still significantly lower than the cost of creating new roads or making dramatic infrastructure changes.

Table 1: Carpooling Cost Summary

Expense	**Cost**
App Production	$81,600
Initial Incentives	$20,000
Rewards Program	$30,000/month
Advertising	$15,995/month

Marketing campaigns to increase awareness of the carpooling app would be advantageous in recognizing why the app is something they would benefit from utilizing. Through informing the citizens of the costs of driving, including pollution and congestion, and offering them a solution to reduce the negative consequences, this can help with the cultural shift that would be required to allow people to share their time in the car with others. According to analysis by the US Census Bureau (2004), the share of people carpooling was 12.2% in 2000. A study by Fielding and Klein found that 43% of current carpoolers are members of the same household as the other carpooler [21]. Thus, the cost of changing the stigma and attitude towards carpooling as a mode of everyday transportation is necessary.

Recent research suggests that carpooling or ride-sharing apps can effectively reduce traffic in urban areas. A study by Li, Hong, and Zhang about the popular ride-sharing app Uber has shown that the service reduced many traffic measures such as travel time index (the ratio of travel time in the peak period to travel time in free-flow conditions), delay time, delay cost, etc. Their analysis of traffic conditions in several cities found that the introduction of Uber led to a 0.24% decrease in travel time index, 1.2% decrease in delay time, and a 1.2% decrease in delay costs. Since this app would be comparable to Uber, we can expect similar results to this study.

Table 2: Impact of Uber on Traffic Measures

	Travel Time Index	**Delay Times**	**Delay Costs**
% Decrease	0.24	1.2	1.2

In order for this method to effectively reduce traffic in Houston, many residents would need to use the app. A study by Alexander and Gonzalez found that adoption of ride-sharing would lead to significantly reduced traffic congestion. Based on our model, if 10% of automobile drivers used the ride-sharing app, then the number of traffic jams across all intersections would be go down from 197 to 151. This results in a 23% decrease in the number of jams. The data shows that carpooling apps encourage users to increase the average number of riders per vehicle. If effectively implemented in Houston, a carpool app would reduce the number of cars on the road and decrease the real flux at intersections on the highway. Since traffic jams are caused by the real flux exceeding the maximum flux, this would help alleviate many of the traffic problems that the city faces.

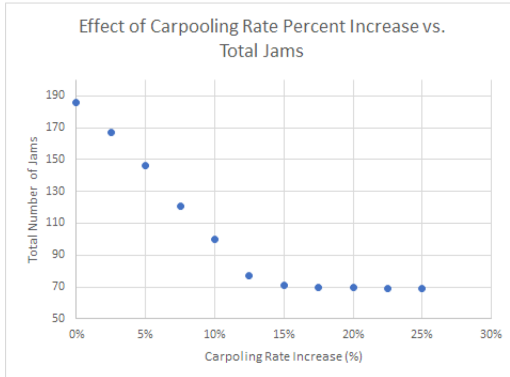

Figure 5: Effect of Carpooling Rate Increase vs Number of Jams

Furthermore, this application is unlikely to disrupt Houston residents' day-to-day lives. Construction or expansion of roads would likely require residents take alternative routes on their daily commute, causing even more traffic or increasing their travel time for a period of time. Also, charging drivers to use the roads (e.g. congestion pricing, tolls) would put unfair financial strain on low-income residents, since many would not be able to afford the commute to work if these systems were put into place. With the carpool app, residents have the freedom to choose whether or not to use it. Thus, the app is unlikely to disrupt their day-to-day lives. Given the possible benefits a carpool app and the relatively low cost, this method provides the most cost-effective solution to Houston's traffic problem.

In order to evaluate the impact of carpooling on the MFV formula, the flux in the Excel data was reduced by carpooling rates. These reduced flux rates were plugged into the MFV formula and intersections that had a jam were summed up to get total jams. It appears that after an increase by 12.5%, the total jams plateau. An increase by 12.5% yields 77 jams, more than half the reduction of number of jams, and an increase by 15% yields 71 jams. However, for context, about 11.1% of Houston commuters already carpool based on 2010-2012 data [22]. A 12.5% increase would be a carpooling rate of 23.6%, hypothetically putting Houston as # 4 on the national carpooling rates of cities. So aiming for a 12.5% increase may be a optimistic but it could be a valid, long-term goal.

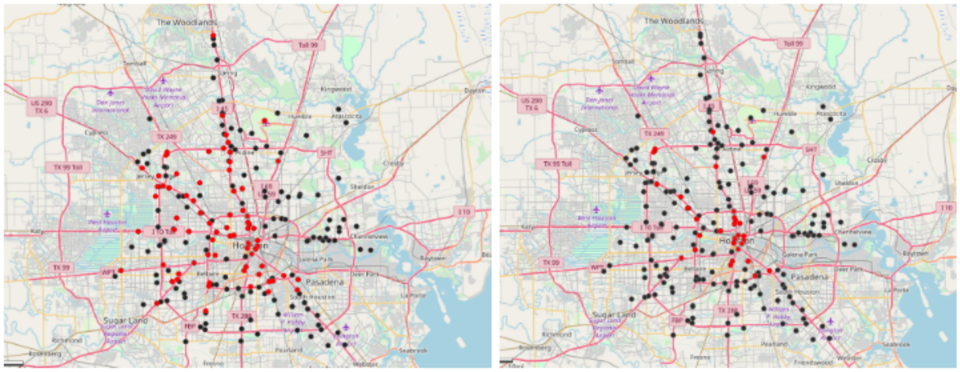

Figure 6: Location of traffic jams before and after carpooling

The map was updated to display the locations of the jams after increasing the carpooling rate by 12.5% which can be seen on the right map above. The image on the left is the original map with no adjustment to carpooling. It appears carpooling reduces the jams outside of downtown Houston but for intersections in Houston that have already have a small amount of outgoing flux, such as exits 41-46 on 45 Northbound, it is clear reducing the total number of cars on the road will not fix that. In order to make these intersections more efficient, we propose the implementation of ramp metering to increase the outflow of the system.

Ramp Metering

Because ramp metering is on a much smaller scale than reducing the total number of cars, calculating its effect on traffic is difficult. One way to calculate the effect of ramp metering is to increase outflow for the intersections of the map with jams. Because ramp metering increases outflow by 0-5%, the outgoing flux at jammed intersections can be multiplied by 1-1.05, consequently changing the real flux for the MFV formula. However, this method, assuming an outflow increase of 2.5%, was tried on exits 41-46 on 45 Northbound data but it still returned jams as the real flux changed very little. Another method is to increase the speed in the merging lane for the MFV formula. This method was also tried on the Excel data. It was optimistically assumed that the merging lane increased in speed by about 16 km/hr. However, these intersections still returned traffic jam values. The travel time was then calculated for each intersection, allowing us to compare the travel times per jammed intersection rather than the MFV. However, this would also mean comparing carpooling and ramp metering is less reliable because it would be across two parameters.

Ramp metering is another method of decreasing traffic congestion that uses a basic traffic light with a signal controller to regulate the flow of traffic entering freeways based off the current traffic conditions. While freeways were originally conceived to provide unlimited mobility to users, recurring congestion is common. Congestion occurs from too many vehicles trying to use limited road space in an uncontrolled manner. To fully utilize the current infrastructure, a more orderly, controllable operation is necessary. Instead of "spontaneous" use of the freeway and other roads, suitable control actions to benefit all users would provide a more efficient method of transportation [23]. Ramp metering controls the demand at a level near the capacity of the highway, which can be determined using the max flux model [24].

One of the most common reasons for traffic delays is inefficient merging. Many vehicles often enter freeways at the same time in tightly pack groups, causing vehicles already on the highway to have to slow down or come to a stop to allow for them to merge. Ramp metering helps to improve this phenomena by controlling the rate at which vehicles enter highways to allow for a smoother transition into the mainline, reducing the need for other vehicles to slow down. Ramp metering has also been proven to be beneficial when there is a breakdown in traffic on the highway by further slowing down the rate of vehicles entering the highway. This allows for the traffic to be cleared up instead of causing bottlenecking.

A study by Cambridge Systematics found that the benefits of ramp metering went beyond reducing travel time [25] (table below). In addition to the decrease in travel time, several field evaluation results demonstrate that ramp metering improves the overall merging behavior of drivers, having a positive impact on the number of lane changes and overall driver stress.

Table 7.3 Annual Ramp Metering Benefits

Performance Measure	Change	Value
Travel time	25,121 hours saved	$247,443
Travel time reliability	2,583,694 hours saved	$25,449,390
Fatality accidents	5.6 accidents avoided	$6,628,063
Injury accidents		
Severe	29.9 accidents avoided	$1,711,617
Moderate	120.7 accidents avoided	$2,621,074
Minor	183.3 accidents avoided	$2,469,895
Property damage only accidents	702 accidents avoided	$4,766,992
Hydrocarbons	104 tons saved	$186,247
Carbon monoxide	1,213 tons saved	$4,527,229
Nitrous oxide	157 tons added	($612,442)
Fuel use	5,494,829 gallons depleted	($7,967,502)
Total annual benefit		**$40,028,008**

Figure 7: Annual Ramp Metering Benefits

There are three different ways to implement ramp metering: fixed time, local control, and systemwide control. Fixed time is the easiest method to implement but the most in effective. Therefore, it is proposed that Houston uses a combination of local control and systemwide control. Local control chooses the metering rates based off traffic conditions on the ramp and adjacent mainline while systemwide control also monitors corridor wide traffic conditions. Systemwide control should be the main method of ramp metering used as it is the most effective method to reduce traffic. However, local control is a good backup for situations where the systemwide control method fails. Ramp metering requires a signal head which are lights that signal to the driver when they can merge, detectors that monitor conditions on the road, and proper signage at the entrance of ramps, so drivers know that ramp metering is being employed. It has been determined that this system should be used wherever there is consistent congestion and where ramps have enough room to hold the incoming traffic [26].

Notably, with ramp metering in use, delays and traffic build up on the ramps leading onto the freeway may occur. However, when keeping the entire system in mind it is clear that short delays on the ramp are better than congestion that continues to build while on the freeway. The total time spent of all drivers in a traffic network is longer when the exit flows are lower from vehicles delayed within the network. Thus, control measures such as ramp metering are effective in decreasing the total travel time of drivers. An added cost of infrastructure to increase the lanes or lengths of merging ramps may be necessary, but this analysis of ramp metering is focused solely on the cost of construction and maintenance of the lights as the infrastructure currently present in Houston may be suitable for these additions. The costs determined are based off the assumption that no queue will be spilling back onto adjacent surface streets.

Simulations by Cambridge Systematics Inc have shown that ramp metering can result in a 0-5% increase in the flow and 0-10% increase in the speed [27]. Studies have found that an increase of outflow of 5% can result in a decrease of the total time spent in the network of 20%. This can be explained as when the outflow is higher, there is less congestion so the queue does not grow and continue to build. Even a small increase in the outflux of vehicles can have a large impact on the total travel time of drivers in Houston, making ramp metering a viable and effective option in decreasing congestion and travel time.

It was determined that ramp metering should be used in the regions that had the most congestion as shown in the maximum flux model. Through selecting the areas with recurring congestion, the goal is to prevent backup on the freeway, benefiting everyone going to all exits. The table below lists the range of exits that have been determined to need ramp metering the most. It was found that a total of 198 crossroads should employ ramp metering.

Freeway Name	Crossroad Numbers	Total Number of Crossroads
10 Eastbound	751–768B	15
45 Northbound	38–47D	21
69 Eastbound	114–129A	28
610 Clockwise Southwest	2–8D	13
610 Clockwise Northwest	15–17	5
610 Clockwise Southeast	32–38A	9
8 Clockwise Northwest	42–44	3
290 Eastbound	1–7	9
288 Northbound	5–9,13–15	8
8 Counter–Clockwise Northwest	41–36	7
610 Counter–Clockwise Northeast	20–10	18
69 Westbound	132C–129C	9
45 Southbound	61–46B	29
10 Westbound	775C–756C	24

Figure 8: Crossroads that should employ ramp metering

Costs for ramp metering include metered ramp construction to improve current on-ramps to support ramp metering, the detection and control elements necessary, operation, and maintenance [28]. Ramp metering can vary by location and required function, so the cost estimates are based off published literature (table below). Notably, the annual maintenance is usually around 10% of the construction cost, with an expected lifetime of 10 years for the signaling equipment.

Table 13 Unit Cost of Ramp Metering ($1000)

	Case 1 1)	Case 2 2)	Case 3 3)
Construction Cost	750	300	113
Annual Maintenance Cost	75	30	2.2

Source: 1) Conversation with traffic engineers at Caltrans District 4
2) Banks and Kelly, 1997
3) JHK, 1992

Figure 9: Unit Cost of Ramp Metering

Based off the cost analysis in Twin Cities, Minnesota, where ramp metering was upgraded in 2000, it was found that the total annual cost for ramp metering is approximately $2.6 million [29].(table below) This cost is for 433 ramp meters along 210 miles, some only operating during morning peak hours, others during afternoon peak hours, and others during both.

Table ES.2 Annual Congestion Management and Ramp Metering System Costs (Year 2000 Dollars)

Cost Item	All Congestion Management Capabilities	Amount Related to Ramp Metering
Annual capital costs		
Congestion management/ramp metering	$5,035,950	$745,667
HOV ramp bypass	$730,000	$730,000
Subtotal	*$5,765,950*	*$1,475,677*
Annual operating and maintenance costs		
Operations costs	$893,836	$431,879
Maintenance costs	$967,489	$464,395
Research costs	$250,000[a]	$250,000
Subtotal	*$2,111,325*	*$1,146,274*
Total annual cost	**$7,877,275**	**$2,621,950**

[a]Represents only those research activities related to ramp metering.

Figure 10: Annual congestion Management and Ramp Metering System Costs (Year 2000 Dollars)

Thus, it can be expected that the total cost of ramp metering for Houston would be around $1 million for a system of 198 meters in Houston.

To analyze the effects of ramp metering, the total travel time, whose formula can be found in part 1, was reduced by 22% for all points and remapped on the heat map. However, because these meters would only be in severely congested areas, the spacing was assumed to be a constant 6 meters to simulate a bumper to bumper traffic scenario. This is because cars are typically 5 meters in length and it will be assumed there is a 1 meter following distance in bumper-to-bumper traffic. The 22% was chosen because an original ramp metering experiment yielded a 22% reduction with about 50 ramp meters. Considering it is assumed there is almost 4 times the amount of ramp meters, this 22% is a rather feasible goal and consistent with the 20% reduction in total time spent in traffic. As shown by the following graphs, there is a dramatic visual difference in reduction of travel time using both ramp metering and carpooling.

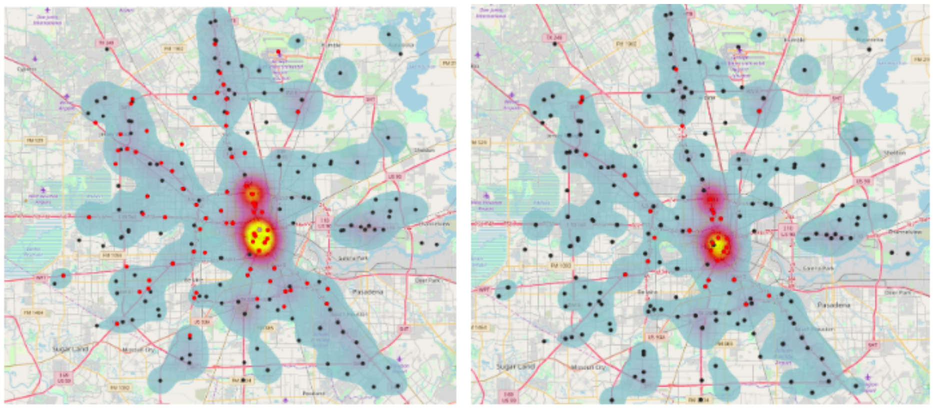

Figure 11: Travel Time Before Ramp Metering vs After Ramp Metering

Conclusion

In order to mitigate the traffic jams present in Houston morning traffic, multiple modifications to the current system were considered. It was determined that a carpooling app would work as a viable option to decrease the number of traffic jams by 63 percent. Additionally, ramp metering would work to decrease commuter travel time by over 22 percent. Through decreasing the number of traffic jams, the overall efficiency of commuters will increase as they will be spending less time stuck on the road.

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