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IMPACTS OF LANE BLOCKAGES ON URBAN NETWORKS

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Abstract: Most cities have procedures that allow private construction activities to "rent" public street lanes to facilitate construction activity. Temporary lane blockages due to public or private construction activity can cause a variety of impacts, ranging from increased weaving to path changing that generally cause additional traveler delay. This paper proposes a comprehensive framework to investigate the impact of a lane blockage and compute the user cost resulting from the blockage. In this paper, the impacts of blocking an arterial street lane in an urban network were examined in terms of path choice and traffic delay using a network dynamic traffic assignment (DTA) model called VISTA and a microscopic traffic simulator called CORSIM. The methodology attempts to bracket the impacts by allowing all vehicles to select their best path through DTA (best delay case) and by not allowing any path changing through CORSIM (worst case). The City of Austin downtown network was used as an example in VISTA to demonstrate the impact of blockages on path choice and total system travel time for a range of travel demand scenarios. DTA may underestimate the impact in terms of delay because all travelers can change their routes to reduce travel time. Considering 2005 travel demand, which is low (v/c<0.2), there is hardly any impact in terms of path changing resulting from a blockage. After increasing the demand, VISTA was able to capture some path changing. To obtain detailed impacts, such as additional delay on a blocked link, a CORSIM simulation was performed. The COSRIM analysis demonstrated that delay triggered by a blockage increases with increasing volume to capacity (v/c) ratio and becomes extreme when demand exceeds capacity. The cost summary due to the delay increase and fuel consumption increase resulting from the blockage were calculated. This study also determined threshold values for critical blockage lengths and critical distance from the intersection and models were developed to compute these values. These threshold values should be considered when the cities compute charge rates.

1 Introduction

Temporary lane blockages are routinely applied to urban street networks in most cities. Blockages that occur due to street repairs usually last a very short duration. However, cities typically have procedures that allow private construction activities to "rent" lanes for longer durations including days, weeks or even months. Such activities cause traveler delays that vary with the volume to capacity (v/c) ratios of the affected networks. This effort was designed to assess the potential impacts of lane blockages on the downtown grid network of Austin, Texas in the United States.

In order to quantitatively assess potential impacts, appropriate measures of effectiveness (MOE) were chosen. Travel time and delay are commonly used to describe the excess time consumed in traversing street links or signalized intersections. Delay includes stopped time delay, approach delay, travel time delay, time-in-queue delay, and control delay. The Highway Capacity Manual (HCM) uses control delay as the primary MOE for determination of level of service for a signalized intersection. Webster (Webster 1958) developed models to calculate stopped delay for two cases: 1) where the arrival rate at an intersection is lower (uniform delay model) than road capacity and 2) higher (overflow delay model) than road capacity.

Besides Webster's delay model, there are other commonly used models such as the Akcelik delay model (Akcelik 1988) and the HCM 2000 delay models (Manual 2000).

With respect to traffic flow theory, lane-changing is one of the most important topics. There are several motivations to make a lane change, such as increasing driving speed, avoiding congestion downstream or avoiding a lane drop. The decision to make a lane change is complex because it involves many factors which may conflict with each other at times (Gipps 1986). Lane-changing can have negative impacts on traffic flow, such as causing crashes (Zheng, Ahn, and Monsere 2010) and possibly reducing the discharge rate (Cassidy and Rudjanakanoknad 2005). Although lane-changing is a vital issue in traffic flow theory, it has not drawn much attention until more recent years. A comprehensive review of the developments in modeling lane-changing can be found in Zheng 2014. The modeling efforts can be classified into two themes: the decision-making process and the impact on surrounding vehicles.

This paper presents the impact lane-changing due to a blockage has on traffic delay. It has been proposed that a lane-changing vehicle can be regarded as a moving bottleneck, creating voids in traffic streams and reducing traffic flow in its own lane (Laval and Daganzo 2006). Therefore, lane-changing can increase delay. The impact of lane-changing on delay depends on the nature of the lane-changing maneuvers (discretional or mandatory) (Laval and Daganzo 2006). A lane drop can lead to mandatory lane-changing. Therefore, temporary lane blockage requiring a lane drop on an arterial street will increase delay. This paper presents how a blockage affects the traffic assignment in a network and impacts delay at a signalized intersection in two parts. The first part will address the impact of a blockage on traffic if travelers are allowed to change their paths using a DTA simulator named VISTA. The second part will address how a blockage affects traffic delay when travel paths do not change using a micro-simulation software called CORSIM.

2 Network Impacts with Path Changing Allowed

VISTA (Visual Interactive System for Transport Algorithms) is a transportation modeling framework providing DTA. There are four basic steps to run a VISTA simulation: prepare network, prepare demand, prepare transit, and run DUE (Dynamic User Equilibrium).

The City of Austin downtown network (Figure 1 (a)) was used as an example of grid network. Three demand scenarios were included in the analysis. First, DTA simulations were ran on the original network using the original OD (original-destination) matrix and obtained the v/c ratios for the network links. This first demand scenario included the OD matrix for the City of Austin from 2005. Because the demand in that OD matrix is very low, the v/c ratios obtained were very small. The largest v/c ratios obtained were less than 0.2. As noted earlier, the DTA results likely show a lower impact than what occurs in reality because DTA assumes that all vehicles change paths to minimize travel times.

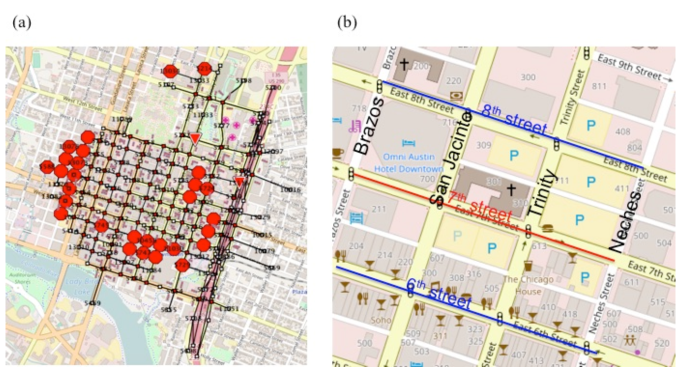

Figure 1: Network used in VISTA. (a): City of Austin downtown network; (b): Blocked street (7th street in red) and two parallel streets (6th and 8th streets in blue).

To assess the effect of a blockage, a lane in this network (shown in red in Figure 1 (b)) was blocked and the v/c ratios on the links parallel to the blocked links were compared as well as the total system travel time before (no blockage) and after (blockage). Because of the low demand, there was hardly any change in the v/c ratios after blocking the lanes.

For the second demand scenario, the demand was proportionally increased to 150 percent of year 2005, resulting in higher pre-blockage v/c ratios on 7th Street. 7th Street is a one-way street with four lanes so for the after cases with this demand scenario, one lane, two lanes, or three lanes were blocked on three to nine consecutive links on 7th Street. Therefore, there were six after scenarios in total. With 3 lanes blocked on 9 links on 7th Street, the largest change in v/c ratio after a blockage was +0.21, no counting the v/c ratio change on 7th street itself. The total system travel times (TSTT) are shown in Table 1 and they clearly indicate that significant network effects were not evident for this demand scenario. This result can be explained by the fact this portion of the Austin network was not congested in 2005 and even in 2017 congestion is rarely seen, and of course that DTA allowed path changing to minimize travel times.

Table 1: Total System Travel Time (Using 150 Percent of 2005 Demand)

	Before Case	1 lane blocked on 3 links	2 lanes blocked on 3 links	3 lanes blocked on 3 links	1 lane blocked on 9 links	2 lanes blocked on 9 links	3 lanes blocked on 9 links
TSTT (h)	10,200	8,780	9,140	9,200	9,780	10,400	10,900

The total system travel time (TSTT) in some of the after cases was a little less than the TSTT in the before case. This was attributed to the randomness present in the simulation. From both the change in v/c ratios on the links near the blockages and total system travel time results, one can see that the impact of the blockage is not significant under this demand scenario.

The third demand scenario was the base case multiplied by two or 200% of the base case. The corresponding v/c ratio change and total system travel times are shown in Tables 2 and 3, respectively. It is worth mentioning that the convergence time of the simulation increased dramatically with this demand scenario. It took about three hours to run a single case while it only took one-half hours to run a case with the original demand.

Table 2: The v/c ratios in the before and after Cases (200 Percent of 2005 Demand)

Road segment, Boundary 1 to Boundary 2 (B1-B2)	4th Street between B1-B2	5th Street between B1-B2	6th Street between B1-B2	7th Street between B1-B2	8th Street between B1-B2	9th Street between B1-B2	10th Street between B1-B2
v/c ratios in the before case							
San Jac-Brazos	0.17	0.22	0.15	0.38	0.17	0.2	0.17
Trinity-San Jac	0.34	0.24	0.19	0.38	0.08	0	0.09

Neches-Trinity	0.21	0.24	0.22	0.32	0.11	0.14	0.08
v/c change after blocking 1 lane on 3 links							
San Jac-Brazos	0	-0.01	-0.02	-0.05	0.02	0	-0.06
Trinity-San Jac	-0.04	0.01	0	-0.05	-0.02	0	-0.07
Neches-Trinity	0.02	0	-0.01	-0.01	-0.02	0.01	-0.06
v/c change after blocking 2 lanes on 3 links							
San Jac-Brazos	-0.01	0.06	-0.05	0.43	0.01	-0.02	-0.01
Trinity-San Jac	0.05	0.08	0	0.43	-0.02	0	0
Neches-Trinity	0.08	0	-0.04	0.63	-0.01	0	0.03
v/c change after blocking 3 lanes on 3 links							
San Jac-Brazos	0.03	0.09	-0.01	0.55	0.01	-0.01	-0.04
Trinity-San Jac	0.03	0.18	-0.01	0.55	-0.02	0	0
Neches-Trinity	0.08	0.15	-0.07	0.65	-0.02	0.03	0.02
v/c change after blocking 1 lane on 9 links							
San Jac-Brazos	0.02	0.01	-0.03	0.2	0	0.02	-0.09
Trinity-San Jac	0.01	0.03	-0.01	0.2	-0.01	0	-0.07
Neches-Trinity	0.04	0.03	-0.03	0.2	0	0.02	-0.06
v/c change after blocking 2 lanes on 9 links							
San Jac-Brazos	-0.01	0.04	-0.04	0.43	0.01	0.03	-0.08
Trinity-San Jac	-0.02	0.12	0.01	0.43	-0.02	0	-0.08
Neches-Trinity	0.09	0.11	-0.02	0.43	-0.02	0.03	-0.06
v/c change after blocking 3 lanes on 9 links							
San Jac-Brazos	0.14	0	-0.02	0.52	-0.02	-0.02	-0.11
Trinity-San Jac	0.04	0.06	-0.06	0.52	-0.01	0	-0.08
Neches-Trinity	0.18	0.03	-0.09	0.64	-0.02	0.09	-0.06

Table 3: Total System Travel Time (200 Percent of 2005 Demand)

	Before Case	1 lane blocked on 3 links	2 lanes blocked on 3 links	3 lanes blocked on 3 links	1 lane blocked on 9 links	2 lanes blocked on 9 links	3 lanes blocked on 9 links
TSTT (h)	39,700	41,600	42,100	45,000	42,200	42,500	58,000

Table 2 shows when 3 lanes were blocked on 9 links, the largest v/c ratio change (except for on 7th Street) in the after case was 0.18. Table 3 shows that the total system travel time increased by 46% when 3 lanes were blocked on 9 links. Therefore, the impact of the blockage depends on the demand level. When the demand is small, the blockage has a negligible impact on the network; when the demand increases to a higher level, the effect of the blockage becomes significant, especially on the delays.

3 User Costs with No Path Changing Allowed

In this section, CORSIM was used to study the effect of blockage on delay when vehicles do not change paths. This case likely represents the worst case for delay since no vehicles are allowed to change paths to minimize travel times. CORSIM is a microscopic traffic simulation model that has a long history of applications. The network used in the simulation, shown in Figure 2(a), included one arterial street (nodes 1, 2, 3, 4) and two cross streets, (nodes 5, 2, 6) and (nodes 7, 3, 8). Two identical pre-timed signal controllers were installed at nodes 2 and 3, and the signal timing is shown in Figure 2(b). Two phases were applied, each of which includes a green time of 35 sec, a yellow time of 3 sec and an all-red time of 2 sec. The free flow speed was 30 mph and the simulation time interval was 1 hour. Results from three replicate simulations were averaged for each case.

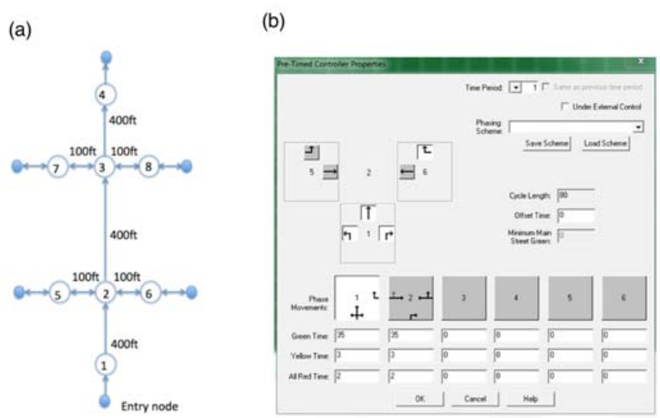

Figure 2: Network and signal design used in the simulation. (a) Network. (b) Signal design.

3.1 Impact of a Fully Blocked Lane

Webster's uniform delay model (Webster 1958) is based on the assumption of uniform arrivals and stable flow with no individual cycle failures. Webster' applies when demand is less than capacity and it can be expressed as,

$$[1]\ UD = \frac{C}{2}\frac{(1-\frac{g}{C})^2}{(1-\frac{g}{C}X)},$$

where UD is the uniform delay per vehicle (seconds/vehicle), C is the cycle length, g is the green time interval, X is the *v/c* ratio, *v* is the demand and *c* is the capacity.

The overflow delay model (Webster 1958) was used to describe the overflow delay in addition to the uniform delay when demand is higher than capacity. This model is time dependent and can be expressed as,

$$[2]\ OD = \frac{T_1+T_2}{2}\left(\frac{v}{c}-1\right)$$

where OD is the overflow delay per vehicle (seconds/vehicle), T_1 and T_2 are the starting time and ending time of the simulation, respectively.

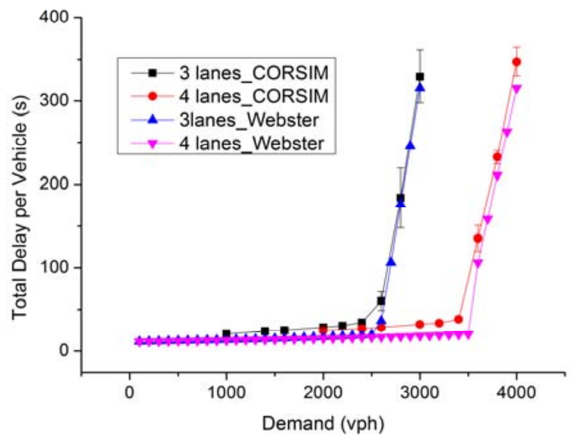

Figure 3: Comparison of the total delay per vehicle (CORSIM vs Webster's).

Figure 3 shows the results from the comparison between CORSIM and Webster's model for an arterial street with 3 lanes and 4 lanes. Figure 3 shows that reaching capacity is the critical point in terms of total delay per vehicle. When demand is lower than capacity, total delay per vehicle increases linearly with a small slope. The slope becomes large when demand exceeds capacity. The slope is proportional to the simulation time, which means that the average delay suffered by each driver is proportional to the congestion time. The average delay is proportional to the congestion time because a queue extends over time when the demand is higher than the capacity. In order to account for the queue, the street was set to be long enough (longer than 400 feet shown in Figure 1 (a)) to accommodate the entire queue for the simulation in which demand exceeds capacity.

Figure 3 also shows that blocking one lane from a 4-lane street increases delay when travelers cannot change their paths by using another street, especially when the demand is higher than the capacity. To quantify the impact of the blockage, we assumed that the impact of the blockage is significant only during peak hours and that there are five hours of peak conditions. Fuel consumption was also taken into account with respect to user costs. A person's time value was estimated at $16/hour and the fuel price at $2/gallon. Table 4 shows the cost summary resulting from blocking one lane on a 4-lane street.

Table 4: Cost Summary Resulting from Blockage

Demand (vehicles/hour)	**1000**	**1500**	**2000**	**2500**	**2600**	**2700**	**2800**	**2900**
v/c (after blocking one lane out of	0.38	0.58	0.78	0.97	1.01	1.05	1.09	1.12

4)								
Delay increase (hours/day)	0.93	2.50	5.44	10.67	70.18	333.28	615.60	917.16
Fuel consumption increase (gallons/day)	4.13	11.90	17.09	34.57	68.91	220.18	395.04	537.14
User cost due to blockage ($/day)	25	61	126	241	1,260	5,774	10,614	15,748

The capacity of a 3-lane street under the signal design shown in Figure 2 (b) is approximately 2580 vehicles per hour. The cells left of the double vertical line in Table 4 represent demand < capacity while the cells to the right of the double line represent demand exceeding capacity. The impact of a blockage on a street with heavy traffic demand (v/c>1.0) is significant, whereas the effect on a street with light traffic demand (v/c<0.5) is negligible. Note that the cost jumps up rapidly when demand exceeds capacity.

3.2 Impact of a Partial Lane Blockage

In reality, there may be times when a lane is blocked for only part of the length of a link (block). This section reviews the effect of a partial blockage on delay in terms of size and location. A 4-lane arterial street was used as the base case. The partial blockage measuring 400 feet in length was moved to five locations varying in distance from the intersection (Figure 4). The vertical axis, total delay, represents the total delay experienced by all of the vehicles passing through the link. The black line and red line indicate 3-lane and 4-lane arterial cases, respectively. The blue line represents a blockage located from 0 to 400 feet away from the intersection. All others can be understood in an analogous way.

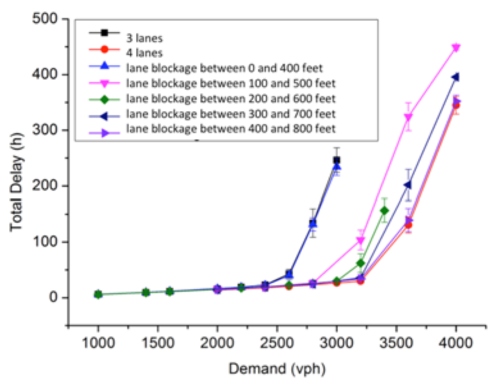

Figure 4: Total delays resulting from different partial blockage positions.

Figure 4 shows that the case with 3 lanes and the case with a blockage at the intersection have the same total delay. When the blockage is 400 feet away from the intersection, the total delay is the same as the case with 4 lanes. Moreover, the further the blockage is away from the intersection, the less delay there is. Obviously, a blockage at any location would increase the total delay compared to the case without a blockage.

Any partial blockage of the length of a link will cause two lane changes. The first lane change is mandatory, which occurs when a vehicle traveling on the blocked lane approaches the blockage, while the second one is discretionary, which might happen if a vehicle wants to go back to the blocked lane after the blockage ends. These lane-changes create voids in the traffic stream and reduce the discharge rate, which increases the total delay.

Figure 5 shows the total delays from partial blockages with two different lengths: 60 feet and 400 feet. It was found that when the blockage is further away from intersection (100 feet and 200 feet away shown in Figure 5), the total delay decreases with increasing blockage length.

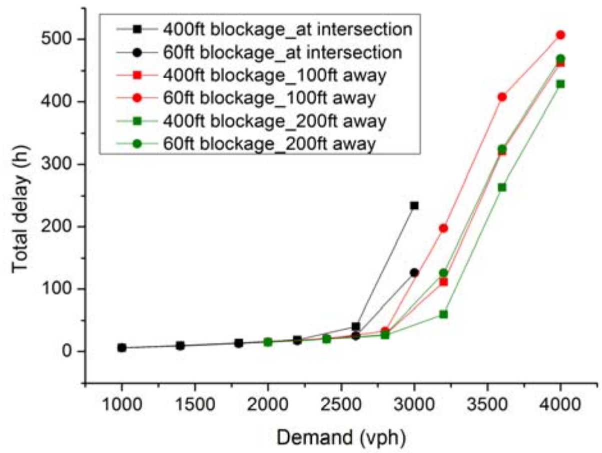

Figure 5: Total delay resulting from different blockage lengths.

Although this conclusion is counterintuitive, it is reasonable. The blocked street can be divided into three parts shown in Figure 6 (a): the green part with four lanes in front of the blocked lane, the blue part with 3 lanes parallel to the blocked (red) lane and the orange part with 4 lanes behind the blocked lane. The length of the green segment is *d,* and the length of the blue segment is *l.* Figure 6 (b) shows the schematic diagram to calculate the total delay.

The area between the arrival curve and departure curve is equal to the total delay for the corresponding simulation time. Assuming the arrival rate during the simulation is constant, the cumulative number of arrival vehicles is linear with respect to time. The departure curve can be divided into four parts. The red segment indicates that there are no vehicles departing during the red signal. Assuming that the length of queue at the end of red phase is longer than *d+l,* then the slopes of the green, blue, and orange segments (v_1, v_2, and v_3) on the departure curve represent the departure rate of vehicles stuck in the green, blue, and orange segments during the red signal, respectively. In Figure 6 (b), v_1 is equal to the capacity of a 4-lane street, v_2 is approximately equal to the capacity of a 3-lane street. If the time cost of the second lane change is neglected, and v_3 is lower than the capacity of a 3-lane street because of the first mandatory lane change, then the relationship between these three slopes is $v_1 > v_2 > v_3$. With a fixed blockage location, i.e. fixed green segment length, then the shortening of the blue segment leads to the extension of the orange segment, as shown with the dashed line in Figure 6 (b). Because $v_2 > v_3$, this increases the area between two curves indicating the total delay. Above all, a shorter blockage will cause longer delays when the blockage is away from the intersection. When the blockage is long enough shown as the longer blockage case in Figure 6 (b), the departure curve may only include the green and blue segments, meaning that vehicles behind the blockage cannot pass the intersection during the green phase. If the vehicles cannot pass the intersection during the green phase, then the area between two curves, which is the total delay, decreases. The shortest length of the blockage that satisfies this condition is the threshold of the length of the blockage. When the blockage is longer than the threshold length, the total delay reaches its minimum. This length can be expressed as,

$$[3]\ l_t = \frac{\frac{\min(c,D)}{3600}C - n*\frac{d}{s}}{n-n_b} * s,$$

where l_t is the threshold value of the blockage length, c is the capacity, D is the demand, C is the signal cycle length, n is the number of lanes before blocking lanes, n_b is the number of blocked lanes, d is the distance between the intersection and the blockage, and s is the space headway.

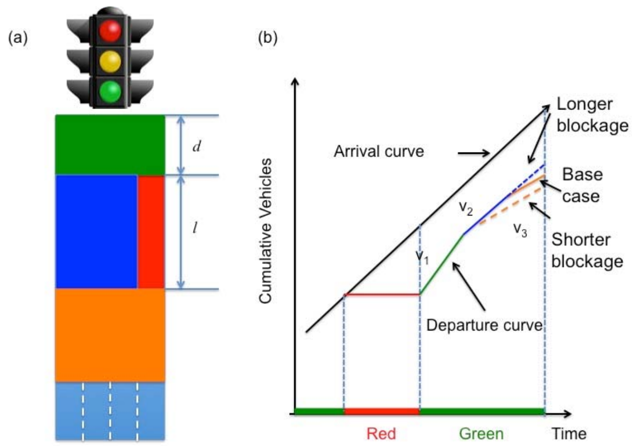

Figure 6: Schematic explaining the relationship between delay and blockage length.

Figure 7 shows the total delay comparison between a partial blockage length equal to the threshold value and a partial blockage length longer than the threshold value. For each of two cases with different distances from the intersection, the total delay from the threshold value agrees well with that from 400 feet.

Figure 4 indicates that the impact of the blockage can be ignored if it is far away from the intersection. In addition, Equation (3) shows that the threshold value of the blockage length is dependent on the distance d. Therefore, there is also a threshold value for the distance. Let l_t equal zero, meaning there are no impacts from the blockage, the expression for the threshold value of the distance is,

$$[4]\ d_t = \frac{\min(c,D)}{3600} * \frac{C}{n} * s,$$

where d_t is the threshold value for the distance. d_t is linear with respect to demand when demand is lower than capacity, and it becomes a constant when the demand is higher than the capacity. This means the heavier the traffic is, the further away the blockage should be from the intersection to reduce the negative impact.

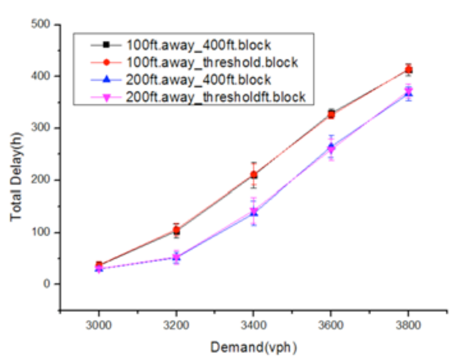

Figure 7: Comparison of total delay between threshold value and 400 feet.

4 Conclusion

In this paper, the impact of a temporary lane blockage on an arterial street in a grid network was examined. The method examined the best and worst-case scenarios using DTA and CORISM. The DTA scenario probably underestimates the impact since all travelers change their paths to minimize travel times while the fixed demand scenario probably overestimates the impact since no travelers can change paths to minimize their travel times. It was shown that the cost due to blockage increased rapidly when demand was higher than capacity. Moreover, the effect of a blockage on only part of the length of a link or block demonstrated that the impact of a blockage declines with increasing distance away from the intersection. Last but not least, two models were developed to compute the threshold values for blockage length and distance from intersection to blockage, respectively. In the future, we hope to extend the analysis to include effects on pedestrians and cyclists. Another promising extension of this work would be to utilize the proposed model to optimize roadway project locations

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