Operational Effects of the Consolidated Intersection Design on Urban and Suburban Arterials

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ABSTRACT
Along urban and suburban arterials, closely-spaced signalized intersections are commonly used to provide access to adjacent commercial developments. Often, these signalized intersections are designed to provide full access to developments on both sides of the arterial and permit through, left-turn, and right-turn movements from every intersection approach. Traffic signal timing is optimized to reduce vehicle delay at the intersections and/or provide progression to vehicles on the arterial. However, meeting both of these criteria (low delay and progression) can be cumbersome, if not impossible, under high-demand situations. This research proposes a new design that consolidates common movements at three consecutive signalized intersections into strategic fixed locations along the arterial. The consolidation of common movements allows the intersections to cycle between only two phase pairs, which, in turn, promotes shorter cycle lengths, lower delay, and better progression. This concept is designed to be applied at areas where three consecutive intersections provide access to one or more commercial developments that are (or can become) interconnected, allowing a driver to access any location inside the development from any other location inside the development on a given side of the arterial without using the arterial. This research tested the consolidated intersection concept by modeling a real-world site in a microsimulation software and obtaining values for delay and travel time for multiple vehicle paths along the corridor and adjacent commercial developments in both existing and proposed conditions. Because some turning movements were eliminated at each of the three intersections, some vehicle routes were displaced; that is, the driver had to use an alternate path to access the desired destination. With the exception of unsignalized right turns at the periphery of the study area, all non-displaced routes showed a reduction in travel time and delay. Travel time and delay changes are reported for displaced routes, but these measures only take into account the portion of the trips that occur along the arterial or within 200 ft of the intersections. Additional research is needed to understand how additional travel through the commercial developments adjacent to the arterial may effect travel time and delay. Trips that originate in one commercial development and end in the commercial development on the opposite side of the arterial appear to be the most negatively affected by the proposed design. Other expected benefits of the proposed design include a major reduction in conflict points, shorter pedestrian crossings and wait time, and the opportunity to provide pedestrian refuge areas in the median.

INTRODUCTION
Urban and suburban arterials serve dual purposes: offering mobility for traffic traveling on the arterial, and providing access to adjacent properties and other streets. Large commercial centers tend to impose stress on the operation of the arterials that serve them, because the intersections that provide access to the property must maintain a level of service for through traffic on the arterial while also providing drivers (and pedestrians and cyclists) with access to desired destinations. When these commercial centers flank both sides of the arterial and multiple (sometimes closely-spaced) signalized intersections are used to provide access to these developments, it becomes very difficult to provide adequate levels of service to the side street movements while at the same time providing bi-directional progression for the through traffic on the arterial. As these competing demands increase, cycle lengths and green splits are increased, often resulting in increased signal delay and longer queues.

Equation 19-16 of the Highway Capacity Manual (*1*) defines capacity of a lane group for which there are no permitted left-turn movements as the product of the number of lanes in the lane group, the saturation flow rate of the lane group per lane, and the green split. This equation is shown below.

$$c = Ns\frac{g}{C}$$

Where:
c = capacity (veh/h)
N = number of lanes in lane group
S = saturation flow rate (veh/ln/h)
g = effective green time (s)
C = cycle length (s)

According to this equation, increasing the number of lanes in the lane group (N) increases capacity. However, adding lanes can be a very expensive solution for increasing capacity at signalized intersections along an arterial with commercial developments on both sides. Increasing the green split (g/C) can also increase capacity. This can be accomplished by reducing the number of conflicting phases at an intersection, because the green time in the cycle is divided into fewer parts.

There are several examples of alternative intersection designs that reduce the number of conflicting phases, accomplishing the goal of increasing capacity at the intersection without the need for additional through lanes (although additional auxiliary lanes are sometimes needed for channelization). These intersection types include:

- Restricted crossing U-turn
- Median U-turn
- Displaced left-turn (also called continuous flow)

These intersection types have been heavily documented in the *Highway Capacity Manual* (*1*) and other research papers (*2, 3, 4*). Another example intersection that is currently being deployed and studied is the diverging diamond interchange. The diverging diamond interchange displaces left-turn movements, and arterial through movements, such that the signalized ramp terminals operate two-phased.

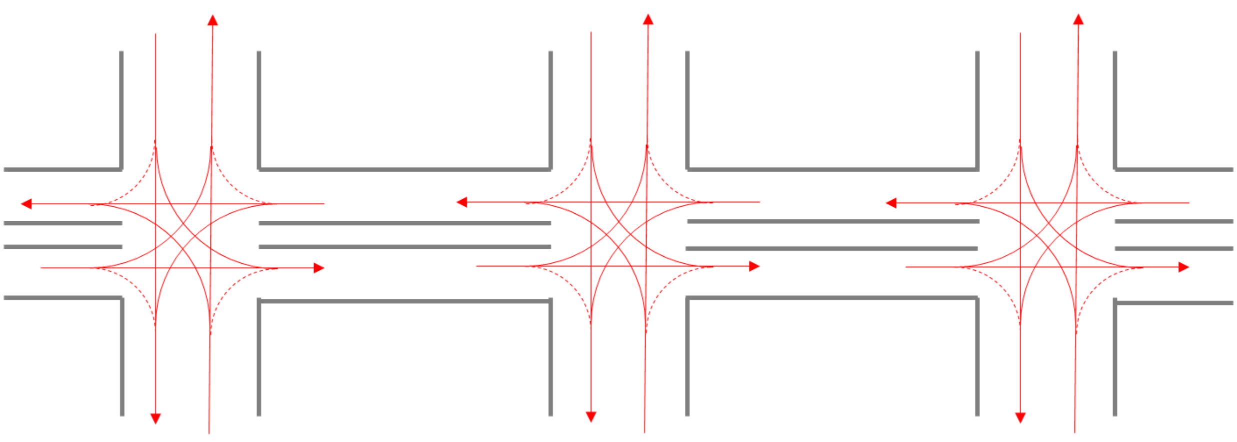
The *Highway Capacity Manual* states that alternative intersection designs have significantly reduced travel times and delay, reduced the number of conflict points between vehicles, and can often be implemented with minimal disruptions to existing right-of-way.

The *Highway Capacity Manual* also defines “distributed intersections” as a group of two or more intersections that operate interdependently by virtue of close spacing and displaced or distributed traffic movements. Analyzing distributed intersections as a single unit is best given their interdependent operation. The level of service for a route in a distributed intersection is based on the travel time experienced by the driver, which the *HCM* refers to as experienced travel time (*ETT*). *ETT* is the sum of all control delay experienced by the driver traversing the distributed intersection and all the travel time due to extra distance required to be traveled in the distributed intersection.

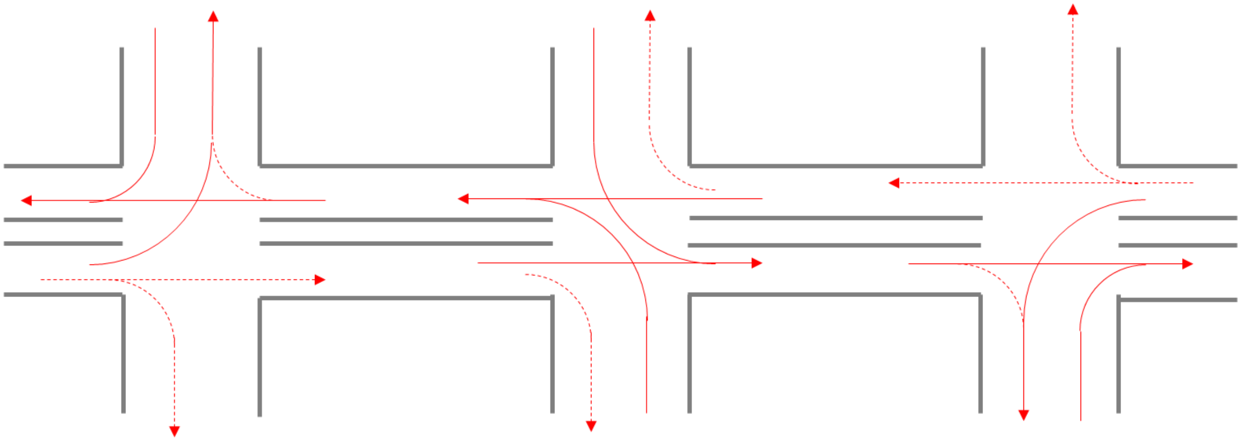
Adjacent intersections that serve the same commercial developments along an arterial have redundant movements. For example, a driver traveling westbound on the arterial who wants to turn left into the commercial development on the south side of the arterial can use any of the intersections along the arterial that provide access to this development. Similarly, a driver wanting to cross from the development on the north side of the arterial to the development on the south side has several route choices. This study proposes a new distributed intersection design for the arterial that consolidates redundant vehicle paths at three adjacent intersections by limiting turning and through movements at each intersection. Access to or from the commercial developments is provided, generally, by a single route to or from the arterial or between developments.

The goal of this study was to create a new arterial design that improved traffic operations for all movements on an arterial that is adjacent to commercial development on both sides of the roadway. The base condition is a segment of urban or suburban arterial with three consecutive fully accessible intersections, where there is commercial development (mall, big box stores, strip mall, etc.) on both sides of the arterial. The three intersections serve as access to these commercial developments, and not as streets that access other developments or neighborhoods. Figure 1 (a) shows a basic plan view of the base condition with all permissible movements shown in red.

The proposed design, shown in Figure 1 (b), consolidates common movements together to eliminate many of the redundant turning movements. This design requires that all traffic within the commercial development can access each of the three intersections via roadways internal to the commercial development, such as a frontage road or a ring road around a large mall. Without proper internal circulation in the commercial development, the proposed design will not function properly because displaced routes will not be able to access the proper intersection to make their turn onto the arterial.



(a)



(b)

Figure 1. Base condition and proposed design permissible movements

This study uses the term “consolidated intersection design” to refer to the proposed solution shown in Figure 1 (b). The singular form of intersection is used in this phrase because all three individual intersections from the base condition now function together as a distributed intersection. Throughout this report, the term “consolidated intersection” refers to the entire arterial and its three access points to adjacent commercial developments.

The consolidated intersection is designed to utilize existing right-of-way. Each of the traffic signals within the consolidated intersection operates in a two-phased operation. All arterial traffic turning left must use the first access point they approach. All traffic originating from the commercial development must use the last access point available to make a right turn onto the arterial, and the center access point to make a left turn onto the arterial. To move from the development on one side of the arterial to the development on the other side, drivers must use the center access point followed by an immediate right turn to go across the arterial to the other commercial development.

The dashed lines shown in Figure 1 (b) represent movements that could potentially bypass traffic control, such as signal control, because they have no conflicting crossing movements. Assuming all three intersections in the base condition are signalized, through traffic on the arterial only traverses two signals while traveling through the consolidated intersection, because the through movement does not have to be signalized at the first intersection encountered.

All intersections in the consolidated intersection design can be operated with just two-phase signal operation. This fact lends itself to lower optimal cycle lengths than the cycle lengths that would be required to operate the intersections in the base condition. Lower cycle lengths have a high potential for lower delay. Lower delay means faster travel times throughout the consolidated intersection. The two-phased signal operation also allows for more flexibility in optimizing bidirectional progression on the arterial.

METHODOLOGY

Microsimulation was used to test the hypothesized operational improvements of the consolidated intersection design. Vissim 8 was used as the microsimulation platform. A real-world site was selected to represent a baseline condition against which to test the proposed consolidated intersection. A calibrated microsimulation model was built for the base condition, and then a microsimulation model of the proposed design was built. The operational characteristics of each condition were gathered from the microsimulation and compared with a statistical analysis.

As discussed previously, the consolidated intersection is intended to improve operations along urban and suburban arterials in which there are three closely-spaced intersections, commercial development on both sides, and internal circulation within the developments on each side of the arterial. A baseline location was sought with these parameters in mind. Also, a site in the Kansas City metropolitan area was desired to allow the research team access for site visits.

39th Street in Independence, Missouri, was selected as the arterial to serve as the base condition in the study. There are three intersections along 39th Street included in the analysis area. For simplicity, these intersections will be referred to as Western, Center, and Eastern intersections throughout the rest of the paper, correlating with the intersections' relative geographical position along 39th Street. Figure 2 shows an aerial view of the study area from Google Earth.

Figure 2. Google Earth aerial view of study area.

The Eastern intersection is an unsignalized intersection with stop control on the side streets. While it would have been desirable to have all three intersections signalized, the unsignalized intersection was included in the model to remain as true as possible to existing conditions. A large enclosed mall with several big-box retail stores are located on the south side of the arterial.

This mall is served by a ring road that distributes mall traffic to the three arterial access points. A strip mall and several restaurants and retail stores are located on the north side of the arterial.

Turning movement counts, origin-destination data, mainline travel time and other observations were collected for the study area. The purpose of this research was to test a new intersection concept using realistic data that represents real-world conditions, rather than to design a solution for a specific location. The data collection performed in this study was used to provide a realistic baseline condition rather than to calibrate the model to exactly match existing conditions. Therefore, the data collection performed for this study was not as detailed as would be needed to design a solution for this specific location.

Turning movement counts were collected on a weekday afternoon during the week before Christmas, when shopping traffic was high, but regular weekday traffic was still present as well. This combination of turning traffic and through traffic presented the optimum conflicting volumes to present a good test for the consolidated intersection design. Heavy vehicles were classified separately during the data collection, however very few trucks were present. For the sake of the simulation analysis, 1 percent of the vehicle fleet was assumed to be heavy vehicles.

There are 8 points in which a vehicle can enter the study area and 8 points where a vehicle can exit the study area. Figure 2 shows how these access points are labeled in this report. For example, an eastbound vehicle on 39th Street enters the study area at point 1. If that vehicle turns left at the Center intersection, the origin-destination (O-D) route for this vehicle is 1-7. Initial observations of the study area showed that no traffic entered the arterial to later turn back into the same commercial development downstream. O-D route 8-7 is an example of this route type. This assumption is based on the fact that vehicles can always access other locations within the commercial development on the same side of the arterial without needing to use the arterial.

To collect O-D data, video cameras were used to record vehicles traveling within and through the study area. The video was later reduced to produce O-D percentages for each approach. These O-D percentages were multiplied by the origin demand volume to determine the volume for each route. These volumes are imprecise, but sufficient to create a realistic baseline for microsimulation model. Figure 3 shows the O-D routes' volumes in the study area.

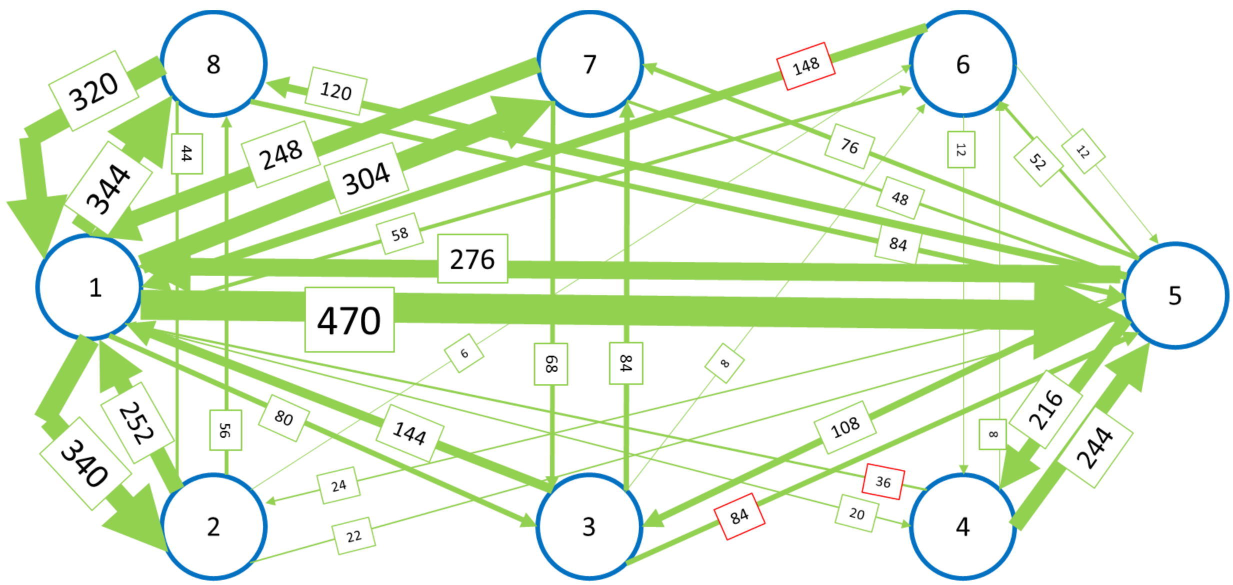


Figure 3. O-D route design hour volumes

Vissim 8 was used to build a microsimulation model of the existing baseline condition and a model of the consolidated intersection design. The base condition model approximates field conditions, using turning movement counts and O-D data collected in the field. The three intersections modeled in the base simulation model are shown in Figure 4 (a), (b) and (c). It is important to note that nonmotorists were not modeled in the simulation even though pedestrians were observed sparingly on the corridor. The scope of this study focused on the operational effects of the proposed intersection design on motor vehicles. See the Discussion section for more discussion on nonmotorists.

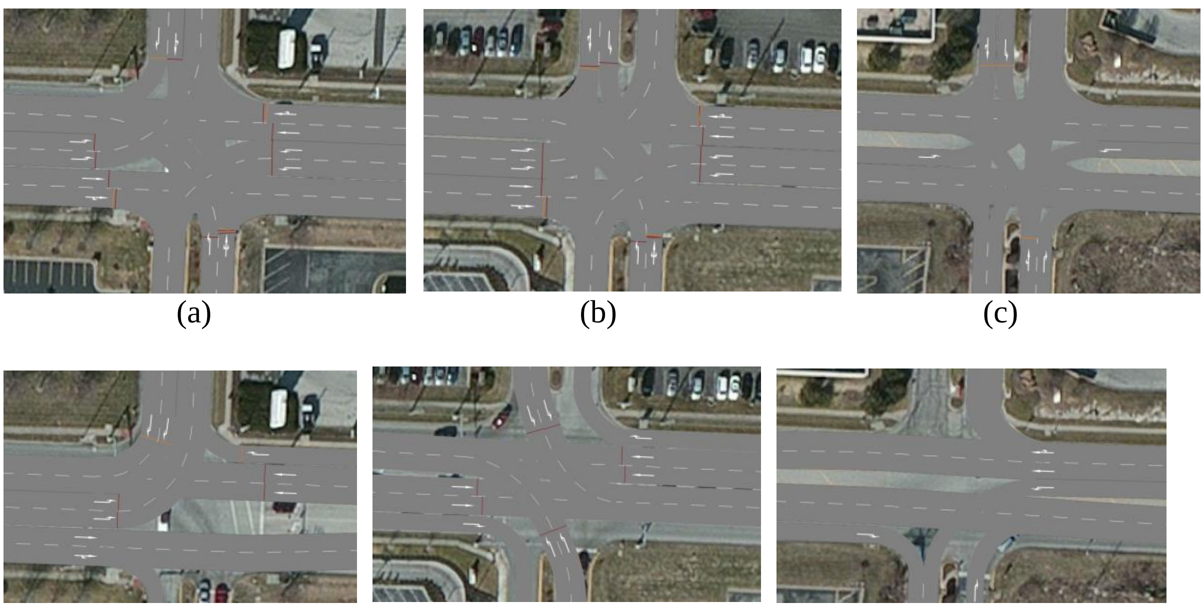
Field timing plans were not used in the simulation model. The signals at the Western and Center intersections were optimized with in-house software using the collected turning movement counts in order to provide optimum progression for both east- and westbound directions as well as to optimize level of service for side-street approaches. The resulting phasing diagrams are shown in Figure 5 (a) and (b).

The main goal of the proposed design was to utilize existing right-of-way without the need for additional space. This goal is quite achievable given the fact that several intersection turn lanes in the study are removed, freeing space within the right-of-way to be used for other purposes.

The outer intersections of the consolidated intersection design only allow left turns from the mainline direction entering the study area. That is, eastbound traffic can turn left from the arterial into the development on the north side of the arterial only at the western intersection (and vice versa). The left-turn movement’s complementary right turn is the only movement permitted from the side street. The eastbound through and right-turn movements of vehicles entering the study area on the arterial are essentially unimpeded, except when pedestrians are present (nonmotorists are discussed later in the report). Figure 4 (d) shows the Western intersection configuration in detail.

Left-turn movements are the only permissible movements on the side streets at the Center intersection. Left turns from the arterial are prohibited, and right turns from the arterial are free-flow. All traffic from the side street traveling to the commercial development on the other side of the arterial must turn left at the Center intersection, then make an immediate right turn at the downstream intersection. Figure 4 (e) shows a detailed layout of the Center intersection. Note that because left turns are no longer permitted from the arterial at this intersection, the opposing through lanes can be moved closer together to allow for the accommodation of right turn lanes on the arterial. In the existing condition, there are no right turn lanes.

The access permitted at the Eastern intersection is identical to that of the Western intersection. However, the operation is quite different. In the base condition, there was only stop control on the minor approaches. There was concern about whether the westbound left turn could handle the increased volume due to the consolidation of all westbound left turns in the study area. However, since the only conflicting movements are the opposing through movements, it was deemed unnecessary to either provide signal control or provide an extra left-turn lane to accommodate the additional volume. Figure 4 (f) shows a detailed layout of the Eastern intersection.



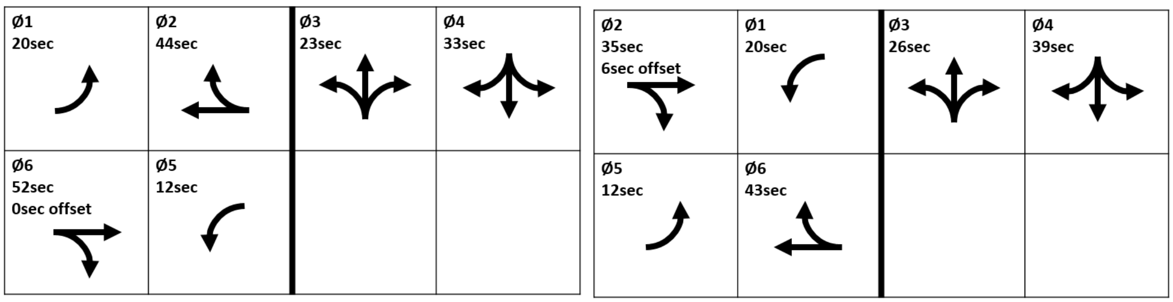
(a) (b) (c)

(d) (e) (f)

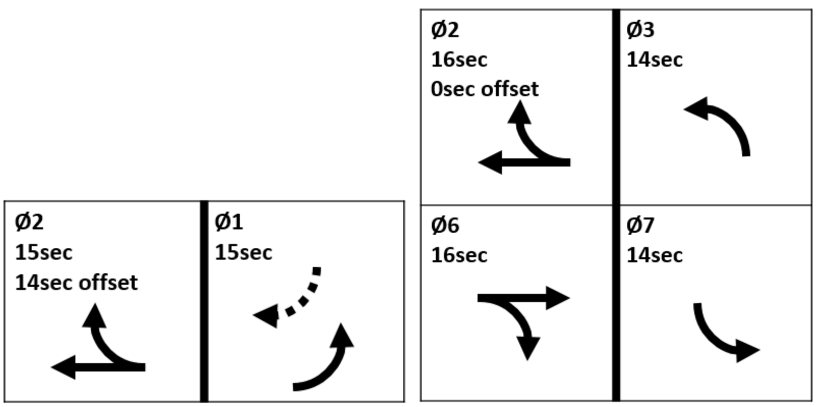
Figure 4. Intersection configurations in simulation models

Whether one, two, or three intersections in the consolidated intersection are signal-controlled, optimizing the signal timings to provide bi-directional progression and minimal delays is quite simple. The core philosophy of the consolidated intersection is to only have two-phase signal operation at each signalized intersection. This allows for lower cycle lengths, thus lower delays and queue lengths (in most situations). Also, the arterial through movements only proceed through two signals. As discussed previously, the through movement at the first intersection entering the study area is unimpeded. Since the through movements in both directions of the arterial receive green at the same time at the Center intersection, providing downstream greens for the platoon in each direction is simple.

The signal timings were optimized with in-house software using the updated turning movement counts in order to provide optimum progression for the Westbound direction (Eastbound traffic only uses one signal) as well as to optimize level of service for side-street approaches. The resulting phasing diagrams are shown in Figure 5 (c) and (d). The resulting cycle length is very short relative to the base condition's cycle length.



(a – Western Intersection) (b – Center Intersection)



(c – Western Intersection) (d – Center Intersection)

Figure 5. Optimized signal timing plans used in the simulation models

Guidance on calibration and validation was obtained through two sources: *Microscopic Simulation Model Calibration and Validation Handbook* (*5*), and *Protocol for Vissim Simulation* (*6*).

The base design simulation model was run four times with different random seeds to collect a baseline to compare travel time data on the mainline to travel time data collected from 39th Street. The travel time was collected from the beginning of the first intersection traversed to the beginning of the last intersection traversed. The averages of the simulation and real-world dataset were compared to see if there was any statistical difference. The eastbound average travel time from the simulation was 41.3 s and 42.0 from the field data. A t-test showed no statistical difference between the two mean travel times. The westbound average travel time from the simulation was 66.0 s and 43.3 s from the field data. A t-test showed these averages to be significantly different. Westbound vehicles in the field arrive in a platoon formed by upstream signalized intersections while in the simulation westbound vehicles arrive randomly. This fact explains the differences in the average westbound travel times between the simulation and field data. Since this study is analyzing the operational effectiveness of the consolidated intersection using real-world data, and not a design solution for a particular location, it was deemed unnecessary to calibrate the base simulation model any further for arterial traffic.

While collecting data, it was observed that vehicles turning right at the Eastern intersection minor approaches did not come to a complete stop if no conflicting vehicles were present. However, all vehicles in the model turning right at the stop signs came to a complete stop every time. To adjust for this, the stop control was removed for right-turning vehicles in the simulation, and replaced with yield control. A reduced speed zone was placed on the right turn to force vehicles to slow to a speed no higher than 5 mi/h to replicate a vehicle rolling through a stop sign. If there were oncoming conflicting vehicles in the simulation, the right-turning vehicle would indeed stop before proceeding; otherwise, the vehicle would slowly roll through the stop sign.

DATA ANALYSIS

Each simulation model was run 100 times with different random seeds. Each model ran for 4,500 seconds, but data was collected only for the time period 900 to 4,500 seconds (1 hour). Travel time and delay data were collected for each vehicle and grouped by each route. Travel time for each vehicle started at a point 240 ft upstream of the first intersection traversed on the route, and the travel time ended for each vehicle at a point 120 ft downstream of the last intersection traversed.

There were 35 unique O-D routes in the base model for which there was traffic volume. Several of these 35 O-D routes were consolidated into common O-D routes in the proposed design, which produces 16 unique O-D routes in the Consolidated Intersection model. When comparing travel time and delay between the two models, it is important to compare the routes that a driver would have to drive in each of the two models if the origin and destination of the driver are the same. The O-D routes were derived using the same labels as shown in Figure 2.

A statistical analysis was performed separately for travel time and delay to test for levels of significant change.

A two-way ANOVA was fit to the data where condition (existing or proposed) and route were factors. Two-sided pairwise comparisons (using Bonferroni's adjustment for multiple comparisons) were made to compare base design routes to related proposed design routes. Pairwise comparisons between common O-D routes follow in Table 1 for travel time and Table 2 for delay. The results shown in these tables are discussed in the Results section.

Table 1. Change in travel time for common routes.

Base O-D Route	CID O-D Route	Travel Time Change (s/veh)	Percent Change	P-value
4 to 6	3 to 8	22.504	70.8%	<.01
6 to 4	7 to 4	19.036	69.8%	<.01
4 to 1	3 to 1	-37.0216	-40.0%	<.01
4 to 5	4 to 5	-4.9674	-20.5%	<.01
6 to 5	7 to 5	14.348	53.9%	<.01
6 to 1	8 to 1	-68.9153	-77.7%	<.01
3 to 5	4 to 5	-52.377	-73.2%	<.01
3 to 6	4 to 5	-23.3242	-30.0%	<.01
3 to 7	3 to 8	-22.006	-28.8%	<.01
3 to 1	3 to 1	-74.3411	-57.2%	<.01
7 to 5	7 to 5	-35.2556	-46.3%	<.01
7 to 4	7 to 4	-33.5287	-42.0%	<.01
7 to 3	7 to 4	-19.8448	-30.0%	<.01
7 to 1	8 to 1	-59.6483	-75.1%	<.01
2 to 5	4 to 5	-107.582	-84.8%	<.01
2 to 6	3 to 8	-73.139	-57.4%	<.01
2 to 8	3 to 8	-23.88	-30.5%	<.01
2 to 1	3 to 1	-18.2379	-24.7%	<.01
8 to 5	7 to 5	-74.7225	-64.6%	<.01
8 to 2	7 to 4	-18.6585	-28.7%	<.01
8 to 1	8 to 1	-5.5745	-22.0%	<.01
5 to 4	5 to 4	1.7571	8.4%	<.01
5 to 6	5 to 6	0.059	0.3%	1
5 to 3	5 to 4	-69.174	-75.3%	<.01
5 to 7	5 to 7	-23.1558	-40.7%	<.01
5 to 2	5 to 4	-89.5736	-79.8%	<.01
5 to 8	5 to 8	-28.1174	-33.4%	<.01
5 to 1	5 to 1	-27.4598	-33.6%	<.01
1 to 2	1 to 2	-14.3138	-42.0%	<.01
1 to 8	1 to 8	-44.6779	-64.1%	<.01
1 to 3	1 to 3	-23.3194	-41.0%	<.01
1 to 7	1 to 8	-58.8182	-70.2%	<.01
1 to 4	1 to 4	-22.4626	-29.4%	<.01
1 to 6	1 to 8	-54.2284	-68.5%	<.01
1 to 5	1 to 5	-22.8728	-31.5%	<.01

Table 2. Change in delay for common routes.

Base O-D Route	CID O-D Route	Delay Change (s/veh)	Percent Change	P-value
4 to 6	3 to 8	4.1393	26.7%	<.01
6 to 4	7 to 4	-0.0943	-0.8%	1
4 to 1	3 to 1	-25.9047	-53.9%	<.01
4 to 5	4 to 5	-2.9997	-48.2%	<.01
6 to 5	7 to 5	-1.2765	-11.3%	0.51
6 to 1	8 to 1	-38.7196	-83.6%	<.01
3 to 5	4 to 5	-36.4756	-91.9%	<.01
3 to 6	4 to 5	-23.5676	-54.6%	<.01
3 to 7	3 to 8	-35.946	-64.7%	<.01
3 to 1	3 to 1	-73.9769	-77.0%	<.01
7 to 5	7 to 5	-35.5504	-78.1%	<.01
7 to 4	7 to 4	-34.4766	-74.7%	<.01
7 to 3	7 to 4	-37.5546	-76.3%	<.01
7 to 1	8 to 1	-43.9213	-85.3%	<.01
2 to 5	4 to 5	-77.2858	-96.0%	<.01
2 to 6	3 to 8	-59.2583	-75.1%	<.01
2 to 8	3 to 8	-38.3086	-66.1%	<.01
2 to 1	3 to 1	-31.2778	-58.6%	<.01
8 to 5	7 to 5	-63.8494	-86.5%	<.01
8 to 2	7 to 4	-41.575	-78.1%	<.01
8 to 1	8 to 1	-5.5461	-42.2%	<.01
5 to 4	5 to 4	0.9722	20.0%	<.01
5 to 6	5 to 6	-0.015	-2.3%	1
5 to 3	5 to 4	-52.5833	-90.0%	<.01
5 to 7	5 to 7	-23.1995	-96.0%	<.01
5 to 2	5 to 4	-59.7987	-91.1%	<.01
5 to 8	5 to 8	-27.8717	-71.6%	<.01
5 to 1	5 to 1	-27.412	-72.3%	<.01
1 to 2	1 to 2	-14.3009	-88.4%	<.01
1 to 8	1 to 8	-44.8443	-82.8%	<.01
1 to 3	1 to 3	-23.8064	-90.6%	<.01
1 to 7	1 to 8	-43.9325	-82.5%	<.01
1 to 4	1 to 4	-23.0978	-74.1%	<.01
1 to 6	1 to 8	-25.1498	-73.0%	<.01
1 to 5	1 to 5	-22.8481	-75.3%	<.01

RESULTS

Some routes in the consolidated intersection are not displaced due to the proposed design, but some are. It is important to differentiate the two while evaluating the results. Twenty-four of the

44 O-D routes that contain traffic remain unchanged due to the geometric changes of the Consolidated Intersection design. Because these routes were not displaced, the change in travel time and delay can be evaluated directly from Tables 1 and 2 without needing to consider the effect of increased or decreased trip length.

With the exception of unsignalized right turns at the periphery of the study area, all non-displaced routes showed a statistically significant reduction in travel time and delay. Travel time and delay changes are reported for displaced routes, but these measures only take into account the “in-network” portion of the trips. The in-network reduction of travel time was 31.9 s/veh (-48.5%), and the in-network reduction of delay was 29.1 s/veh (-76.4%).

Displaced routes must travel within the commercial development, but the simulation did not model this. The travel time and delay of vehicles within commercial developments is highly variable, but some common ground must be established in order to compare the before condition to the proposed design. An average speed of 15 mi/h within the commercial development was used to adjust the travel time of displaced routes. Figure 6 shows the percent change in travel time for each O-D route in the study area, taking into account the 15 mi/h average speed within commercial developments. The thickness of the lines and the size of the label correlate with the volume of the O-D routes.

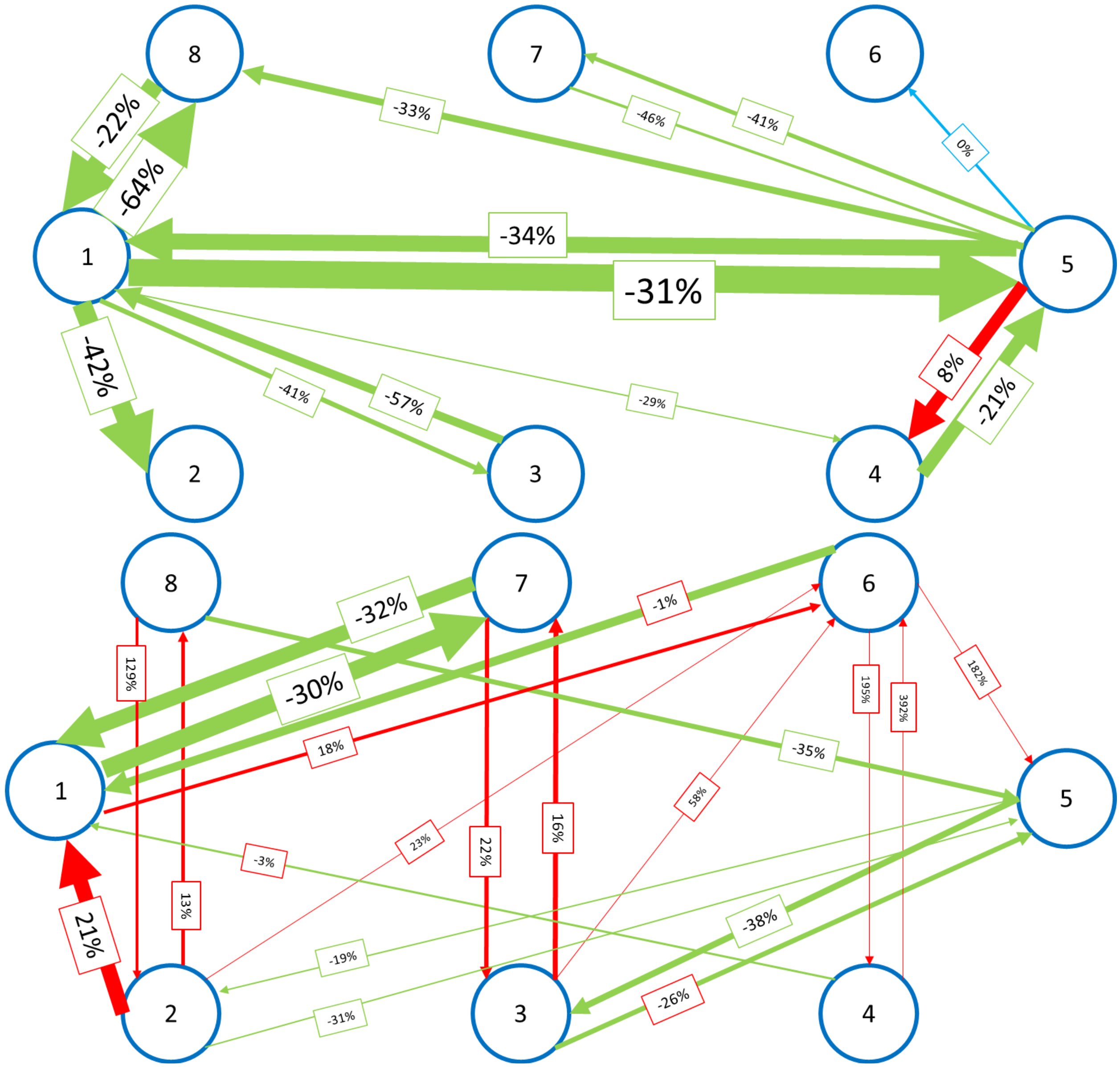


Figure 6. Percent change in travel time with consolidated intersection design

Assuming a 10 mi/h average speed within the commercial development is a more conservative assumption. Table 3 shows the overall changes in travel time and delay in the network, and also assuming average speeds within commercial developments of 10 and 15 mi/h.

Table 3. Overall Effectiveness of Consolidated Intersection Design

Overall Effectiveness based on Travel Time Reduction		**Commercial Development Speed**	
	In-network	Assume 15 mi/h	Assume 10 mi/h
Weighted Average Change in Travel Time	-31.9 s/veh	-16.2 s/veh	-8.3 s/veh
Percent Change	-48.5%	-24.6%	-12.6%
Weighted Average Change in Delay	-29.1 s/veh	--	--
Percent Change	-76.4%	--	--

Table 3 shows that even a conservative assumption of 10 mi/h results in an overall reduction in travel time of 8.3 s/veh (-12.6%).

DISCUSSION

The scope of this research was on operational performance, so safety can only be discussed here in qualitative terms. The consolidated intersection design reduced conflict points from 96 in total amongst the three intersections in the base condition to only 18 in the proposed design. If a conflict point represents a point were conflicting vehicles could potentially collide, then it can be inferred that there is much less potential for collisions with the consolidated intersection design. Of course, many factors play into the occurrence of crashes beyond just the number of conflict points, but the 81 percent decrease in conflict points shows promise that the proposed design is not less safe than the conventional base design.

Bike lanes, sidewalks, crosswalks, and median refuge areas are facilities that may be considered with the consolidated intersection design. Bike lanes can be added parallel to the travel lanes. Sidewalks may be installed parallel to the roadways as well. There are two primary options when providing adequate crossings for pedestrians. Figure 7 (a) shows a plan view of the Western intersection if pedestrian crossings were provided. Note that this same concept can be applied to the Eastern intersection, except the image would be rotated 180 degrees.

Signal control must be installed to stop eastbound through vehicles to allow pedestrian phase P4a to operate. Otherwise, all other signal operations are the same as outlined previously in the report. P4a can run concurrently with the eastbound left/southbound right phase pair. P4b can also run concurrently with the same phase pair as P4a, but the eastbound through phase may remain green. A pedestrian refuge area between these two crosswalks should be built in the median to accommodate pedestrian storage. P6 can run concurrently with the eastbound through/westbound through phase pair. Also, an additional crosswalk may be added parallel to the eastbound lanes, crossing the south leg of the intersection.

Figure 7 (b) presents a pedestrian crossing option for the Center intersection. This crosswalk traverses the entire arterial in one stage. The side-street approaches must be offset a little to provide enough space for the crosswalk to slip in between the opposing side-street left-turn movements. This option only works if sufficient right-of-way is available to offset the side street approaches. Pedestrian phase P4 could only operate concurrently with the side-street left-turn phase pair. Signalized crosswalks may be added parallel to the arterial.

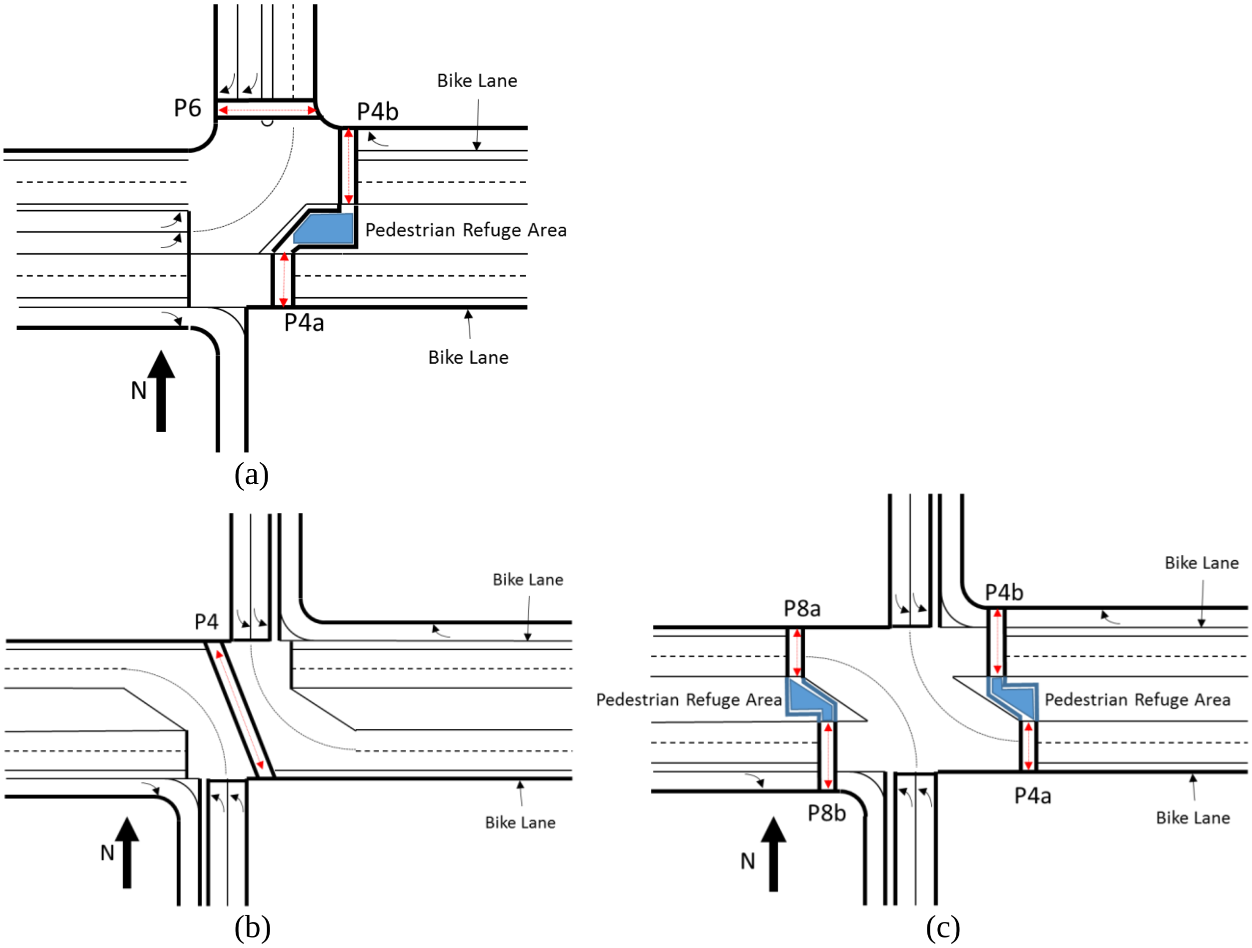


Figure 7. Center intersection pedestrian and bicyclist accommodations, option 1 (not to scale).

Figure 7 (c) displays a second option for providing a signalized pedestrian crossing across the arterial. This option allows for two separate two-stage pedestrian crossings, each having a pedestrian refuge area in the median. Pedestrian phases P4b and P8b would operate concurrently with the side-street left-turn phase pair. The challenge with operating P4a and P8a is that these pedestrian phases conflict with every vehicular phase pair. These two pedestrian phases could operate only as an exclusive pedestrian phase at the intersection. If this were to occur, then P4b and P8b could operate during this exclusive pedestrian phase as well. Signalized crosswalks may be added parallel to the arterial.

Each commercial development is unique, and the required emergency access points must be determined prior to designing a consolidated intersection for a particular location. If emergency access is required at all three intersections in all directions (as provided in the base condition), then the design of the consolidated intersection must strategically use pavement markings and other delineators to channelize traffic flow, but still allow emergency vehicles to use pavement that was retained from the base design.

CONCLUSIONS

Two microsimulation models were compared to determine the operational effectiveness of the consolidated intersection design at a real-world site. The first model simulated base conditions of the study site, with traffic data collected during peak shopping demand. The second model simulated the consolidated intersection design for the same location. Travel time and delay were measured with the simulations, and a comparison test was conducted for each unique O-D route in the study area.

The overall reduction of in-network travel time is 31.9 s/veh (48.5%), and 29.1 s/veh (76.4%) for in-network delay. The consolidated intersection design heavily benefited travel for vehicles using the arterial as a through route. The arterial eastbound through route saw a travel-time reduction of 23 seconds, which was a decrease of 32%. The delay per vehicle in this direction fell by 23 seconds, which was a 75% reduction. The westbound through route had a travel-time reduction of 27 seconds, resulting in a decrease of 34%. The delay per vehicle in this direction dropped by 27 seconds, amounting to a 72% reduction.

All non-displaced routes, not including uncontrolled right-turn movements at the periphery of the study area, saw statistically significant reductions in travel time and delay. These results are a good sign that the consolidated intersection design maintains and improves all routes that do not have to travel additional distances due to the proposed design.

It is difficult to make clear-cut conclusions about how the consolidated intersection design effected the operations of the displaced routes. However, by assuming an average speed of travel within the commercial developments and assuming that displaced vehicles travel the full distance required to meet the original O-D route, an adjusted travel time can be calculated and compared to the travel times of the base design. The overall reduction in adjusted travel time, assuming a 15 mi/h speed of vehicles within commercial developments, is 16.2 s/veh, resulting in a 24.6% decrease in travel time. Even if a 10 mi/h speed is assumed, travel time is reduced by 8.3 s/veh (12.6%).

Based on the results of this research, we conclude that the consolidated intersection design improves travel time and delay for arterials that run adjacent to commercial developments. Trips that either originate or conclude in the commercial developments are also positively impacted by the consolidated intersection. Trips that both originate and conclude in the commercial developments (i.e. trips that start and end in the study area), may be displaced by a considerable distance, but more research is needed to clearly understand how this considerable displaced distance effects the travel time and delay of the routes within the commercial development.

FUTURE WORK

The 39th Street corridor was chosen as a real-world test case to verify that the consolidated intersection design could improve traffic operations for one particular location. Given the success of this trial application, the next step is to test the applicability of the consolidated intersection for various ranges of traffic volumes and varying demand on particular origin-destination routes within the study area. A sensitivity analysis is currently underway to determine the most appropriate conditions to utilize the consolidated intersection design.

The simulation models collected vehicle travel times and delays for all O-D routes in the study area that were observed to have demand. The data collection on these routes started 240 feet of the first intersection traversed and ended downstream of the final intersection traversed. For trips starting or ending in the commercial developments, it is unknown how much travel time and delay were incurred due to travel between the study area and the desired parking space within the commercial development. This unknown travel time and delay are a function of the traffic control and layout within the commercial development and parking choice made by the individual vehicle.

For routes that became displaced due to the consolidated intersection design, it is difficult to make a clear-cut conclusion on how the proposed design affected travel time and delay for vehicles on these displaced routes. This study did not attempt to make reasonable assumptions or approximations on what these extra travel times may be; however, an additional study should be conducted to investigate how displaced routes are affected in more detail to include travel time and delay within commercial developments.

This study analyzed the operational effects of the consolidated intersection design in an isolated setting. Additional research should be conducted to understand the operational effects of deploying this proposed design within a larger signalized arterial network. Because the signals in the consolidated intersection design are two-phased, it is practical to consider half-cycling these intersections in relation to adjacent signalized intersections on the arterial.

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