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A Performance Assessment of the Elimination of Left-turn at Selected Intersections

Author
Cao, Xinyun

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A Performance Assessment of the Elimination of Left-Turns at Selected Intersections

THESIS

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for the degree of

MASTER OF SCIENCE

in Civil Engineering

by

Xinyun Cao

Thesis Committee:
Professor Michael McNally, Chair
Professor Jean-Daniel Saphores
Professor R.(Jay) Jayakrishnan

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Abstract of the Thesis

A Performance Assessment of the Elimination of Left-Turns at Selected Intersections

by

Xinyun Cao

Master of Science in Civil Engineering

University of California, Irvine 2014

Professor Michael McNally, Chair

For most signalized intersections, left-turn movements are considered as a primary contributor to intersection delay. The concept of eliminating left-turn movements is now feasible with the rise of GPS-based routing which will allow the active routing of vehicles in networks with reduced left turns. This research seeks to assess the impacts of left turn reductions on overall travel time and left turn delays at intersections via validation and sensitivity analyses of prior work.

The research objective is to evaluate the effect of left turn movement elimination in a hypothetical network. The type of network considered is a grid network defined by the roadway hierarchy defined by capacity and speeds. The sample network utilized was used in prior research and was loosely based on real world networks to better reflect realistic volumes, travel times, and delays. The analysis approach is to eliminate left turn movements in three types of intersections by applying turn prohibitions and adjusting cycle lengths and turn penalties on other movements. Network performance is then assessed based on delay reduction, total travel time, and fuel consumption. The results validated prior research and concluded that selective reduction of left turn movements can improve network performance.

Chapter 1 Introduction

1.1 Background

This research seeks to assess the impacts of left turn reductions on overall travel time and left turn delays at intersections via validation and sensitivity analyses of prior work. The work is part of a research proposal (McNally, 2011) which provided the research justification:

> “Over the past century, the automobile has evolved to dominate transportation not only from a behavioral perspective but also from an infrastructure perspective. Thoroughfares that evolved over millennia to serve many users were transformed in decades to the near exclusive use by motor vehicles. The reasons for this evolution are well documented; alternatives to the behavioral dominance, while numerous in terms of proposals and promise, are nevertheless constrained by the infrastructural dominance. One option that has not been systematically studied but that has the cost advantage of maintaining current infrastructure while addressing associated performance impacts is a significant reduction in allowed arterial left turns. For current arterial infrastructure, left turns consume a disproportion share of intersection capacity, pose the greatest restrictions on non-automotive movements (pedestrians, in particular), and can cause excessive delay in low volume operation. Driver behavior has already become habitual, with the ability to turn left assumed at every intersection, thus limiting the potential to remove left turns, even at problematic locations. The evolving technology that accommodates this proposal is the growing presence of GPS devices in automobiles and the growing familiarity of drivers with communication technology. The question to be addressed is to assess the potential for performance improvements, direct and indirect, from the systematic elimination of left turns.” (McNally, 2011)

The first phase of this study was summarized by Mi (2013) who applied an algorithm linking a travel forecasting model and a traffic operations model. The second phase of this research, reported here in, was to further validate the initial analysis by Mi and to perform a sensitivity analysis of those results.

1.2 Proposed Network

This study utilizes a hypothetical grid network loosely based on a real-world grid network with the intent of reflecting a real-world traffic volumes and operations but in a simulated environment to facilitate manipulation of turn phasing, prohibitions, and penalties. The grid selected reflects a road hierarchy based on half-mile long links (Figure 1). The model network, the same as used by Mi (2013), is a six by six grid with the termini of each of the six roadways serving as external stations for demand and with two internal centroids. Links are defined with a three-level hierarchy according to geometry, capacity, traffic volumes, and other performance characteristics. The characters of each level is summarized as following:

- Level 1 (Primary Arterial): three (3) through lanes in each direction; a 45 mph speed limit; raised median and no street parking; potential connection to freeway ramps; and link volumes in the range of 1600-2000 vehicles per hour.
- Level 2 (Major Arterial): two (2) through lanes in each direction; a 40 mph speed limit; raised median; potential connection to freeway ramps; and link volumes in the range of 800-1200 vehicles per hour.
- Level 3 (Secondary Arterial): two (2) through lanes in each direction; a 40 mph speed limit; no raised medians; street parking and no freeway access); and link volumes in the range of 500-800 vehicles per hour.

In horizontal or vertical order, the grid comprises the following roadways by level: 3rd - 2nd - 3rd - 1st - 3rd - 2nd. There is freeway access every mile (but not from level 3 facilities). In the existing network, every half-mile spaced intersection is signalized with 8-phase operation, which means all movements are allowed at any intersection and that all left turn movements are protected. Figure 1 is the proposed network, S represents Secondary Arterials, M represents Major Arterials, and P represents Primary Arterials.

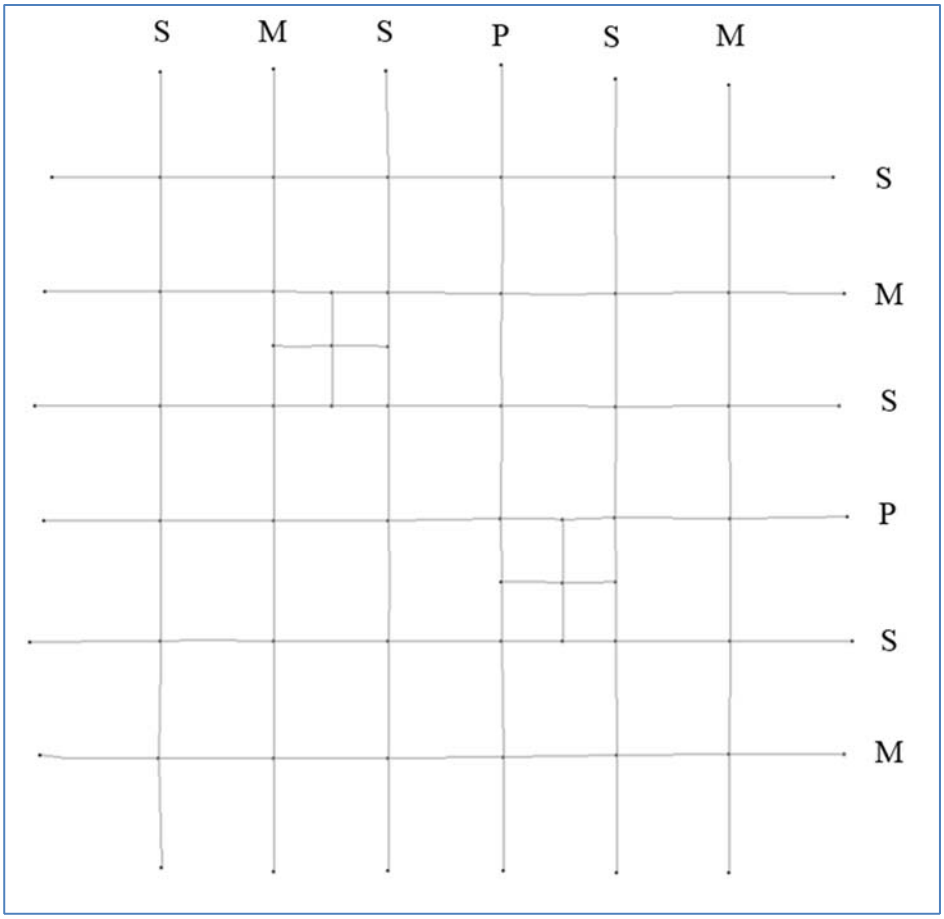

Figure 1. Proposed Network in the Study (based on Mi, 2013)

1.3 Problem Statement

At a signalized intersection that has heavy through traffic but has left-turn traffic that is light, the effectiveness of accommodating full eight phase movements is questionable, particularly in the case where GPS-based navigation systems (or autonomous vehicles) are present. Intersection delay is often driven by accommodating left-turn movements that may be better accommodated on alternate network paths. In this situation, left-turn elimination may be reasonable.

The prior study (Mi, 2013) has shown that eliminating left turns in an alternating fashion along a grid can reduce intersection delay. The estimated reduction in intersection delay caused by left-turn elimination was shown to be consistent and convergent with turn penalties applied in travel forecasting models. In this study, the research objective is to improve the transportation network performance by eliminating the left turn in special intersections. These intersections are defined by different levels of roads; the selected intersections are chosen by the relative higher original delays: Primary-Primary, Secondary-Secondary, and Primary-Secondary.

As before, delay results for the selected treatments were based on analysis using travel forecasting (TransCAD) and traffic signal analysis (Synchro) models, evaluating the delay results in different network configurations. Network performance was evaluated using total travel time and fuel consumption. Considering the relative factors, the relative improvements due to turn restrictions can be determined for the defined network.

Chapter 2. Literature Review

2.1 Conventional Intersection

At a typical intersection of two, two-way streets, there are 12 legal vehicular movements (left turn, thru, and right turn from each of four approaches) as well as four legal pedestrian crossing movements. As indicated in Figure 2, these movements create a total of 16 potential vehicular crossing conflicts. To ensure safe and efficient movement through the intersection, the signalized intersection is essential.

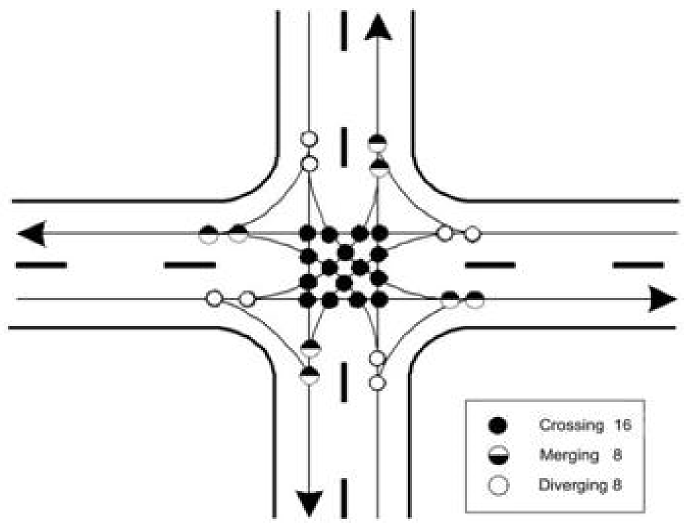

Figure 2. Typical Conflicts at a Four-Leg Intersection (FHWA, 2010)

2.1.1 Signal Operation

For a signalized intersection, three types of signal operation can be used:

1. *Pre-timed Operation*. In this operation, the cycle length, phase sequence, and timing of each interval are constant. Each cycle of the signal follows the same predetermined plan. An internal clock is used to active the appropriate timing for each defined time period.
2. *Semi-actuated Operation.* In this operation, detectors are placed on the minor approaches to the intersection; there are no detectors on the major street. The light is green for the

major street at all times except when a “call” or actuation is noted on one of the minor approaches. The green returns to the major street when detector senses there is no further demand on the minor street. Semi-actuated operation is often used where the primary reason for signalized is “interruption of continuous traffic”.

3. *Fully-actuated Operation.* In this operation, every lane of every approach must be monitored by a detector. Green time is allocated in accordance with information from the detector and programmed “rules” established in the controller for capturing and retaining the green. In this operation, cycle length, sequence of phases, and green time split may vary from cycle to cycle.

In most urban and suburban settings, signalized intersections along arterials and in arterial network are close enough to have a significant impact on adjacent signalized intersection operations. Therefore, it is common to coordinate signals into a signal system. When coordinated, such systems could keep vehicles moving through sequences of individual signalized intersections without stopping for as long as possible; the allocation of green times among the defined phases can significantly reduce delay. This system must operate on a common cycle length.

2.1.2 Signalized Intersection Delay

Signalized intersections, represented as point locations within a surface street network, can be characterized by measuring the operation quality, often via the measurement of delay. Delay refers to the amount of time consumed in traversing the intersection — the difference between vehicle arrival time and departure time. Measuring delay accurately is important for operating traffic control systems. Delay at signalized intersection is defined and used in many different ways.

1. *Control delay*. Defined as the total delay due to the signalized intersection, and includes the deceleration delay, stopped delay and acceleration delay. Delay measures can be stated for a single vehicle or as an average for all vehicles over a specified time period.
2. *Stopped time delay.* Defined as the time a vehicle is stopped in queue while waiting to pass through the intersection. This delay begins when the vehicle is fully stopped and ends when the vehicle begins to accelerate.
3. *Approach delay*. Defined as stopped time delay plus the time loss due to deceleration from the approach delay to a stop and the time loss due to reacceleration back to the desired speed. Approach delay is the time difference between the hypothetical extension of the approaching slope and the departure slope after full acceleration.

A diagram shown in Figure 3 (Quiroga and Bullock, 1999) is useful to define the three types of delay. Aggregate delay is measured in total vehicle-seconds, vehicle-minutes, or vehicle-hours for all vehicles in the specified time period. Average individual delay is generally stated in terms of second per vehicle for a specified time period.

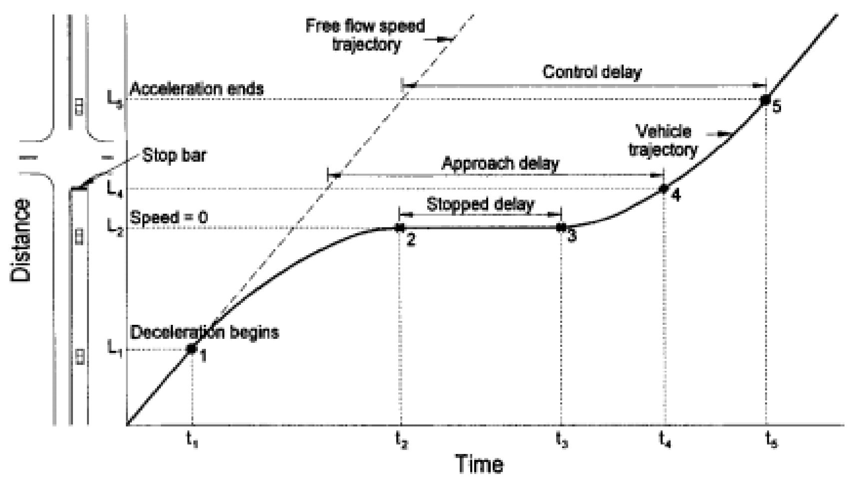

Figure 3. Delay Terms at Signalized Intersections

2.1.3 Left-Turn Operation

Left-turn operation has significant impact on the safety and efficient operation of a signalized intersection. The appropriate type of left-turn phasing will result in reducing the traffic delay, improving traffic flow, and decreasing accident rates. The Manual on Uniform Traffic Control Devices (MUTCD) defines three types of left-turn controls:

- Permissive-Only left-turn control: Left turns do not have dedicated right-of-way and can be made when an acceptable exists in the opposing through movement;
- Protected-Only left-turn control (PO): Left turns have dedicated right-of-way with a green arrow indication; and
- Protected/Permissive left-turn control (PPLT): This is a combination of the above two left-turn controls. Left turns have a dedicated right-of –way during the protected interval. In other part of the cycle, left turns may be made when an acceptable gap exists in the opposing through movement.

There are four warrants provided by MUCTD that refer to protected left turns: collisions, delay, volume, and miscellaneous. These warrants are for addressing two concerns: safety and efficiency, as identified in Mi (2013). One of the standards used to justify the safety of an intersection is the accident rate. Accidents may be cause by conflict movements, or limited sight distance. Therefore, when it not safe for a driver to make a left turn or pedestrians to cross the street, the protected left is necessary.

Another concern is efficiency. Again, as explained in Mi(2013), if a signalized intersection has heavy through traffic with relatively light left-turn traffic, it may not be efficient to allow all intersection movements to experience greater average delay for that limited left-turn volumes, particularly where alternative routes are available to accommodate left-turns. In such a situation, left-turn elimination is a potentially means to reduce average delays.

To be able to mitigate the delay caused by left turns, some challenges must be addressed. In consideration of the coordination, one issue is the inefficiency of large cycle lengths. Consider the example identified by Mi (2013). For a large intersection with pedestrian crossings, such as many major intersections throughout urban areas, with a pedestrian speed of 3.5 feet per second, a Flashing Don't Walk (FDW) time can easily reach 35 seconds. This would result in a: 7 s (Walk) + 35s (FDW) + 4 s (Yellow) + 1 s (AR) equals 47 second minimum split per thru phase. For a full 8-phase intersection, a cycle length of as great as 150 seconds could result. However, a 150 second cycle length is unnecessary for a small street intersection with major corridor where the left turn phase would have longest delay. A lower cycle length would provide less pedestrian crossing time, thus, eliminating left-turn movements for one or both streets would change an 8-phase operation to 6 or 4 phases. As a result, a larger cycle length can be reduced by the left-turn phase eliminations.

As mentioned in Mi 92013), an issue with corridor coordination is that some intersections have very high volume/capacity ratios and poor performance while others may have lower V/C ratios and high performance. Thus the Intersection Capacity Utilitzation (ICU) is not balanced. Potential balance could be achieved by selectively eliminating left-turns for some heavy traffic intersections and accommodating the demand at other corridor intersections, and this might improve overall corridor performance.

2.2 Alternative Intersection Types

Today's transportation professionals, with limited resources available to them, are challenged to meet the mobility needs of a growing population. At many highway junctions, congestion continues to worsen, and drivers, pedestrians, and bicyclists experience increasing delay and heightened exposure to risk. Due to traffic volumes and travel demands leading to safety and delay problems, many engineers have considered alternative treatments to improve mobility several studies have been completed to assess the mitigation excess delay associated with left turns. A short summary and review of these alternative intersections is presented below.

Continuous Flow Intersection, also known as Displaced Left-turn Intersection (DLT), have been implemented at several locations to reduce congestion. The main feature of this alternative intersection is the relocation of the left-turn movement on an approach on the other side of the road's opposing direction, which consequently eliminates the left turn phase for this approach at the main intersection.

Compared to conventional intersections, DLT intersections have fewer conflict points; but the DLT intersection has internal conflict points at the left-turn crossover points. Since left-turn traffic does not have to cross on-coming traffic, using this type of intersection will increase the amount of "green" time on the main-line route. At most volume scenarios, DLT intersections have the potential to considerably reduce average intersection delays. However, constructing a DLT intersection need additional right-of-way for ramps and need extra signals. In addition, there is no minimum traffic volume requirement for the application of DLT.

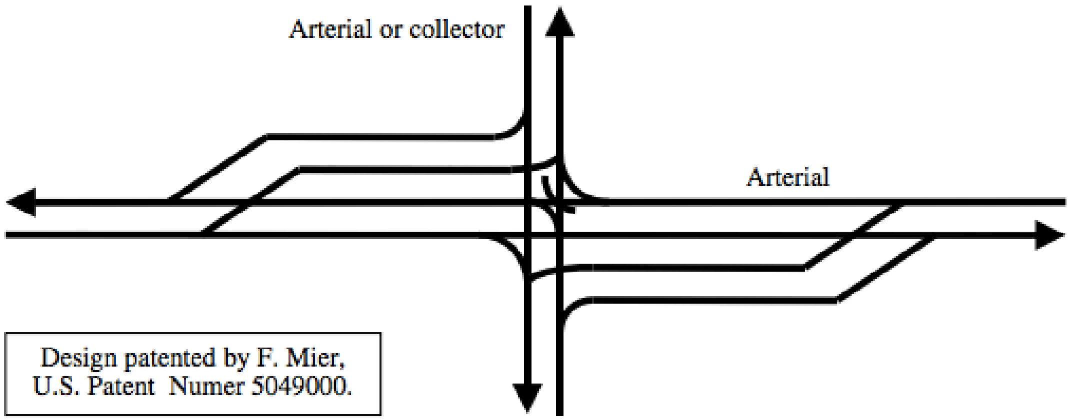

Figure 4. Full Continuous Flow Intersection

Median U-turn Intersection (MUT), which is a potential treatment to balance the intersection congestion and safety problems. This intersection involves the elimination of direct left turn from the major road and/or minor approaches. Drivers turn left from the major road onto an intersecting street must first travel through the main intersection and then execute a U-turn at the median opening downstream of the intersection.

Compared to the conventional intersection, due to the elimination of left turns, MUT reduces the delay for through arterial traffic and reduces the risk to crossing pedestrians. Also, MUL has better progression for the through traffic on the main arterial. However, MUT may increase the delay for left-turning traffic, increase travel distances for left-turning traffic, and increase stops for left-turning traffic.

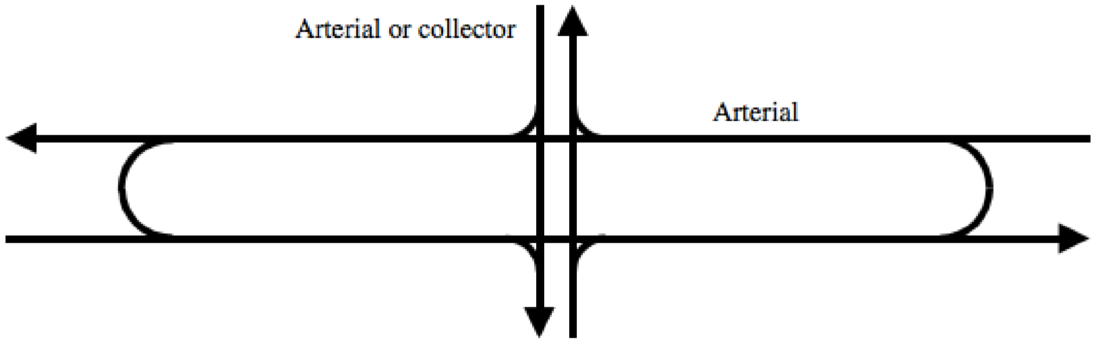

Figure 5. Median U-turn Intersection

Bowtie, is a variation of the median U-turn alternative with the median and directional crossovers on the cross street. The bowtie alternative uses roundabout on the cross street to overcome the disadvantage of requiring a wide right-of-way. The advantage of roundabout is that the traffic can continue moving without a complete stop. The left elimination only used on cross street. Same as the MUT, bowtie alternative reduces the delay and stops for through arterial traffic. However, the arterial is difficult to make a U-turn. The bowtie alternative often is considered where generally high arterial through volumes conflict with moderate or low cross street through volumes and moderate or low left turn volumes.

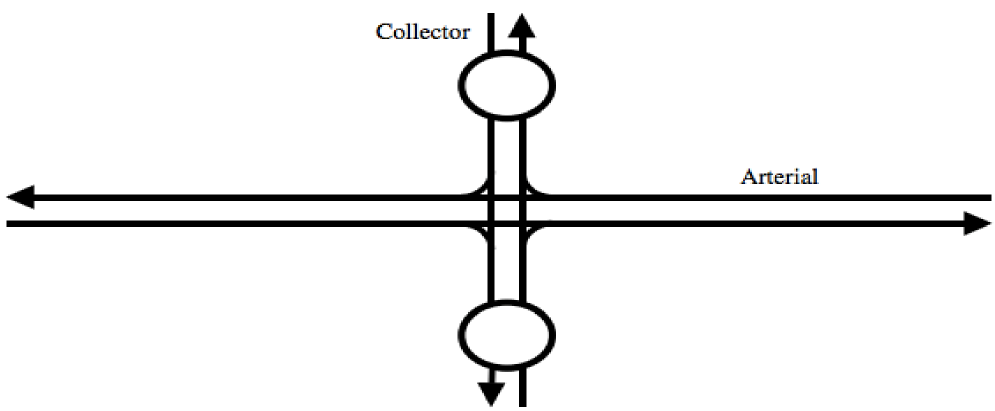

Figure 6. Bowtie Alternative

A **Jug-handle** intersection uses ramps diverging from the right side of the arterial to accommodate all turns from the arterial. For left turns, ramp terminals are stop-controlled; for channelized right turns, ramp terminal are yield-controlled. If jug-handles are used as the only way drivers can make left-turns and U-turns, all turns will be made from the right lane. This could decrease driver confusion, decrease lane changes, and increase travel speeds in the left turn.

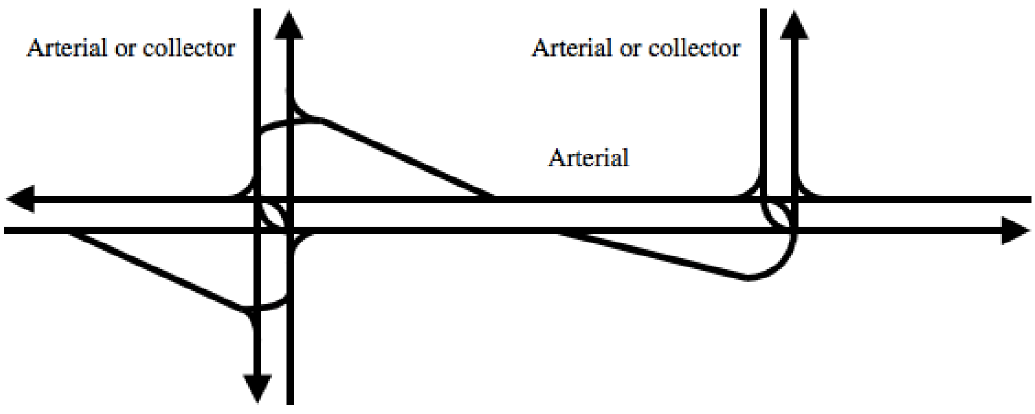

Figure 7. Jug-handle Alternatives

The following table summarized when these alternative intersections could be considered.

Table 1. Summary of Alternative Intersection types

Alternative	Arterial Left turns	Minor Left turns	Minor through	Extra right of way needed
Continuous Flow	Any	Any	Any	Two 40'by 300'retangels at int.
Median U-turn	Low-Medium	Low-Medium	Any	30' wide along arterial
Bowtie	Low-Medium	Low-Medium	Low-Medium	2 circles up to 300' diameter on minor
Jughandle	Low-Medium	Low-Medium	Any	Two 400'by 300' triangles at int.

2.3 Case Study of Right-in and Right-out Intersections

The option of Right-in and Right-out (RIRO) intersections has also been used to improve operations and safety by placing islands or devices that force drivers to enter or exit a location with a right turn movement, eliminating left turns. The RIRO reduces the frequency and severity of conflicts by reducing the basic conflicts points. It is worth to mentioning that the case of RIRO is a success application of left turn elimination.

Chapter 3. Methodology

The methodology in this work is the same as used earlier by Mi (2013). A crucial requirement in left-turn elimination is that alternative routes must be available to drivers so that they can easily re-route and not add unnecessary congestion to the network. The objective of eliminating left turns is to decrease intersection delay and improve network performance. Each of these analyses utilize TransCAD and Synchro software.

3.1 Basic Assumptions

All model results will reflect the following assumptions:

1. No U-turns are allowed at intersections.
2. GPS devices are available to route drivers to real time shortest paths.
3. Re-routing occurs when a left-turn movement is permanently prohibited.
4. In shortest paths, the difference in control and turn movement delay is reflected.
5. The trip assignment results are based on User Equilibrium.
6. Turn Penalties are used in routing before and after turn elimination.

3.2 Analysis Model

In this study, one needs to evaluate the function of left turn elimination in a proposed transportation network based on a set of observed approaching and turning movement flows. Once turning movements are obtained, use Synchro software to estimate the control delay of each intersection. Then, comparing the delay results with the reductions of turn penalties, process convergence can be assessed. The general model process is summarized in the flow chart shown in Figure 9.

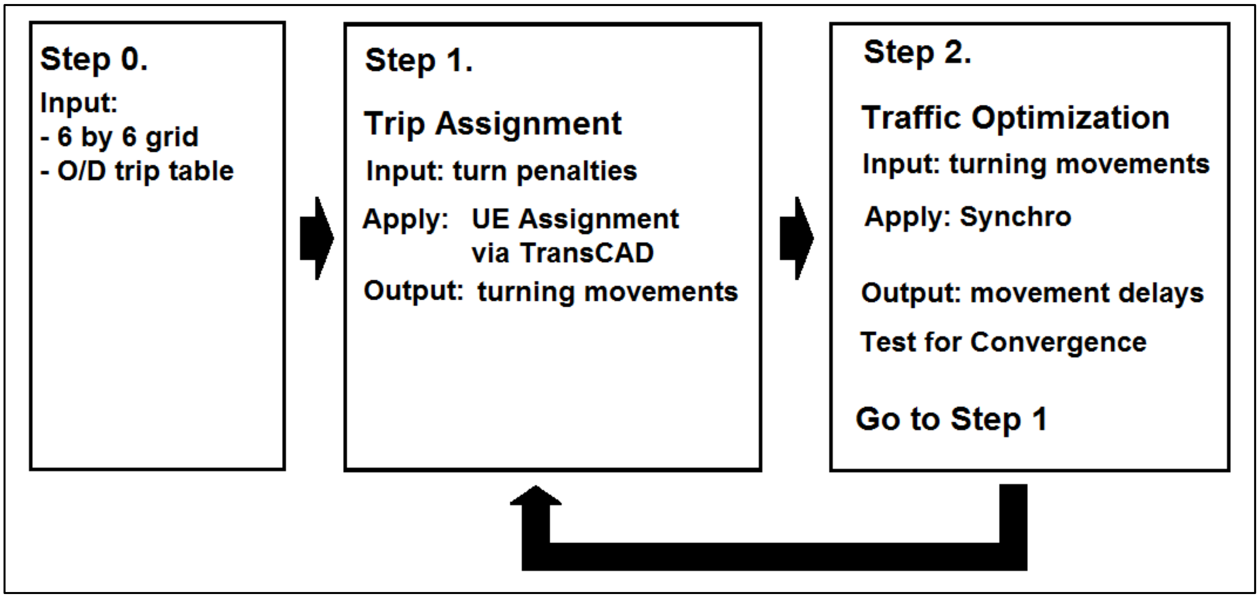

Figure 9. Model Flow Chart

As the algorithm depicts, a trip assignment model is used to estimate turning movements on the hypothetical network and the assumed origin and destination trip table. To facilitate comparisons with prior results (Mi, 2013), the same network and O/D table will be utilized (see Table 2). The algorithm process iterates until hourly link volumes converge.

Table 2. Hypothetical Peak Hour Origin-Destination (OD) Matrix (from Mi, 2013)

OD-Matrix	1	2	3	4	5	6	11	22	33	44	55	66	101	102	103	104	105	106	107	108	109	110	111	112	6001	6005
1	0	0	0	0	0	0	21	27	18	31	15	14	34	40	22	52	19	28	18	24	18	32	13	13	64	46
2	0	0	0	0	0	0	24	37	22	48	21	24	37	47	25	59	22	31	24	32	22	49	21	19	91	63
3	0	0	0	0	0	0	15	21	16	31	16	17	22	27	15	34	12	20	17	22	16	31	17	16	58	43
4	0	0	0	0	0	0	32	51	34	88	39	51	48	60	32	81	30	42	43	58	40	81	40	47	128	112
5	0	0	0	0	0	0	9	14	12	26	15	18	16	20	10	26	9	12	15	20	15	31	15	17	42	40
6	0	0	0	0	0	0	14	23	21	56	30	43	31	38	22	51	16	18	38	51	33	68	33	36	84	79
11	15	22	15	29	9	10	0	0	0	0	0	0	18	27	17	45	18	33	7	14	13	33	17	23	48	45
22	22	39	24	53	17	24	0	0	0	0	0	0	26	39	25	69	28	47	15	28	24	58	31	41	85	80
33	17	27	20	40	16	23	0	0	0	0	0	0	20	27	17	48	21	33	15	24	18	48	26	34	65	66
44	25	50	33	88	29	47	0	0	0	0	0	0	29	50	29	81	35	60	31	48	40	88	51	66	109	128
55	9	17	14	32	14	20	0	0	0	0	0	0	10	17	12	32	14	24	13	21	17	41	24	30	43	55
66	11	24	18	50	20	36	0	0	0	0	0	0	13	21	16	50	20	35	23	36	30	71	41	55	63	76
101	22	31	20	43	16	24	18	23	15	30	12	12	0	0	0	0	0	0	15	20	15	27	12	11	58	43
102	31	47	31	64	23	34	31	40	24	53	25	26	0	0	0	0	0	0	22	35	24	53	23	24	99	68
103	19	31	19	39	14	23	23	29	18	39	19	22	0	0	0	0	0	0	15	21	18	36	19	18	66	50
104	43	64	39	79	32	41	54	71	44	94	46	55	0	0	0	0	0	0	30	48	36	95	42	51	138	120
105	21	31	19	42	13	16	31	40	25	50	24	29	0	0	0	0	0	0	12	20	19	42	25	27	68	64
106	23	34	23	40	12	16	42	52	32	65	32	39	0	0	0	0	0	0	11	21	18	50	27	36	75	71
107	20	36	26	62	27	49	11	18	16	44	23	31	24	30	17	40	12	14	0	0	0	0	0	0	66	62
108	23	40	29	70	30	49	16	30	25	53	31	45	27	40	21	54	17	24	0	0	0	0	0	0	87	82
109	17	28	20	49	21	37	16	28	19	45	26	37	21	28	18	41	17	21	0	0	0	0	0	0	66	67
110	29	53	39	94	37	66	38	54	39	93	53	76	31	53	31	94	31	50	0	0	0	0	0	0	117	137
111	11	22	17	40	16	28	18	27	20	47	25	35	13	20	14	36	16	23	0	0	0	0	0	0	50	64
112	10	23	20	49	20	35	26	40	29	68	36	54	12	23	15	49	20	34	0	0	0	0	0	0	61	80
6001	58	100	67	137	51	76	58	87	58	116	57	68	64	100	58	137	51	75	49	77	58	118	58	63	0	160
6005	44	72	52	125	50	75	56	86	62	143	76	94	48	72	45	125	50	73	48	75	61	144	77	80	167	0

3.2.1 Trip Assignment Model

Usually, the classic travel forecasting modeling system comprises four steps:

Trip Generation: measures the trip frequency of Origins and Destinations, or more commonly, Productions and Attractions for each traffic analysis zone (TAZs) by trip purpose.

Trip Distribution: matches the distribution of trip productions and attractions and reflects underlying travel impedance, often using a gravity model.

Mode Choice: computes the proportions of trips between each Origin and Destinations that use different transportation modes.

Trip Assignment: allocates estimated trips between an origin and destination by a particular mode to a route, often using Wardrop's principle of User Equilibrium.

In this study, only trip assignment is considered. TransCAD's User Equilibrium procedure was utilized. The proposed grid network was built to create the network file and find the shortest path trees (skims) for all network centroids (2 internal centroids and 22 external nodes). In this network, turn penalties are to be applied for the following situations:

1. Turns that are physically or legally prohibited;
2. Signalized intersections which have traffic delays in one or more directions;
3. Delay that occurs with link transitions (by facility type).

The application of turn penalties will help calculate the delay at each intersection. When all the intersections are in full 8-phase mode (the Before scenario), the turn penalties values selected are 45, 30, and 30 seconds for left turns, thru , and right turn movements. When selected left-turn movements are eliminated, movement delay reductions are expected. After reduction, the estimate penalty delays are assumed to be 45, 25, and 25 seconds for left turn, thru, and right turn movements. These reduced delays are used as turn penalty for intersections that have left turn elimination applied; other intersections remain the same turn penalties used in the Before case.

After the initial procedure was completed, the final PM-peak hour (5-6 PM) vehicle-trip O-D matrix (Table 2) was assigned to the propose network via User Equilibrium. The User Equilibrium trip assignment starts with an All-or-Nothing (AON) Assignment using initial skim trees. An optimal weight is determined via Frank-Wolfe for averaging the AON link-volume vector with the current solution. The final link-volume vector was based on a threshold relative gap to closely approximate user equilibrium conditions. Final turning movements for each intersection were the primary objective of the user equilibrium solution.

3.2.2 Synchro Model

The turning movement results from TransCAD's assignment algorithm were input to Synchro for intersection analysis and optimization. The objective of Synchro is to estimate intersection delay after optimizing signal timing.

Basic Data Entry

Following Table 3, enter the basic information for each intersection, such as the volumes, lanes, speed, and detector locations.

Table 3. Grid Characteristics for Synchro Analysis

Type	Speed (mph)	Lane and Sharing			Control Type	Left Turn Type
		Left Turns	Through	Right Turns		
Primary Street	45	2	3	1	Actuated-uncoordinated	Protected
Major Street	40	1	2	1	Actuated-uncoordinated	Protected
Secondary Street	40	1	2	Share with 1 through lane	Actuated-uncoordinated	Protected

In the proposed analysis, pedestrian volumes are not considered. For the controller type, Actuated-Uncoordinated control was chosen, under which the cycle length is allowed to vary with each signal cycle to avoid potential delay created by a large cycle length at a smaller intersection. The setting of protected left turns is a method to decrease the unnecessary delay. Directional volumes at each intersection follow the input turning movement data. As with the preceding analysis by Mi (2013), the width of each lane is 12 feet, the yellow time of each phase is 4 seconds, the all-red time of each phase is 1 second, the maximum cycle length is 150 seconds, and right-turn movements are allowed when the light is red.

Optimization

After all the settings were made, optimization was performed to provide comparable delay statistics. There are two major steps for optimizing. The first step is optimizing the intersection splits. This step will provide enough green time to serve the 90th percentile lane group flows; this optimization would give lower volumes/capacity ratios for low lane group flow approaches. In addition, Synchro will also balance the volumes/capacity rations for each phase to keep all at a minimum.

The second step is optimizing the intersection cycle length, which will set the intersection to the natural cycle length. The natural cycle length can be considered as the shortest cycle length that clears the critical percentile traffic. By optimizing each intersection, the intersection will obtain the appropriate cycle length, which can ensure the minimum delay in each intersection. The control delay would be calculated by the natural cycle length.

Control Delay Calculation

The methodology used in estimating the control delay is from the US Highway Capacity Manual (HCM) which recommends methods for computing the delays at a signalized intersection. The core delay calculation is called The Percentile Delay Method. The percentile delay calculation considers five levels of traffic arrivals so that actuated signals can be evaluated under varying traffic loads.

Compared with HCM (using Webster's formula), which added capabilities for calculating delays of actuated signals and for congested movements, the percentile delay is more accurate than HCM 2000 delay estimation. The percentile method uses five sets of green times, by using five level of traffic; a weighted average is taken when calculating the delay. While, HCM only use a single set of green times, which is an average of actual green time. For the coordination, the percentile method calculates the affect by actual arrivals from adjacent intersections. HCM calculates the effect by using a Progression Factor, which is calculated by estimating the percentage of vehicles arriving on green; this calculation process is an approximation. Therefore, in this study, the percentile method is used to calculate the intersection delay.

The basic premise of the Percentile Delay Method is traffic arrivals will vary according to a Poisson distribution. The five scenarios used are the 10th, 30th, 50th, 70th, and 90th percentiles. Because the signal in this network is actuated, to determine the green times for each scenario, the skipping and gap out behavior are used. The basic delay calculation is shown as following:

Step 1: Calculate the uniform delay per vehicle, for scenario p (s).

$$Dp = 0.5 * C * \frac{[1 - \left(\frac{g}{C}\right)]^2}{[1 - X * \frac{g}{C}]}$$

Step 2: Calculate average percentile delay (Uniform Delay).

$$D_1 = \frac{VD10 + VD30 + VD50 + VD70 + VD90}{(v10 + v30 + v50 + v70 + v90) * C/3600}$$

Where: volume for percentile P: $vP = v + \left[z * \sqrt{v * \frac{C}{3600}}\right] * \frac{3600}{C}$

P percentile vehicle-delay per hour: $VDP = 0.5 * \frac{vP}{\left(1 - \frac{vP}{s}\right)} * \frac{R^2}{C} * 3600$

Step 3: Calculate Incremental Delay.

$$D_2 = 900 * T * [(x - 1) + \sqrt{(x - 1)^2 + \frac{8 * k * I * X}{c * T}}]$$

Step 4: Calculate total Percentile Delay

$$D = D_1 + D_2$$

Where:
R=Red time (s)
C=Cycle Length(s)
T=duration of analysis in hours, default 0.25
g=Effective green time (s)
X=Volume to Capacity Ratio (v/c)
c=Capacity
k=incremental delay factor, 0.5
I=upstream filtering factor, 1.0

3.3 Network Evaluation

The purpose of eliminating the left turn movements is to decrease the intersection control delay and enhance the performance of network. The method to evaluate the delay results after eliminating left turns is to compare the results with the original one. For the network performance, because the eliminated left-turn movements have to re-rout with a new path that may with longer travel distance; a total vehicle mile traveled (VMT) may increase slightly in term of the whole network. However, VMT is expected to decrease due to the reduction in delay at intersection for the rest of movements. Therefore, to evaluate the network performance, by utilizing the Federal Highway Administration (FHWA) fuel consumption equation provided by Wagner (1980), the fuel consumption equation is based on vehicle mile traveled and vehicle hour traveled.

$$\text{Total Fuel Consumption} = 0.0425*\text{VMT}+0.6*\text{VHT}$$

Here, the VHT is equal to the network total travel time. The travel time can be estimated by a total of the link travel time (from TransCAD) and the intersection control delay time (from Synchro).

$$\text{Travel Time}=\text{Link Travel Time}+ \text{Intersection Control Delay}$$

Another method is to evaluate the total travel cost. The total travel cost can be estimated by a summation of vehicle mile traveled (VMT) and vehicle hour traveled (VHT):

$$\text{Total Cost}= \text{VMT}+\text{VHT}$$

In order to evaluate the performance of the network, the travel demand (OD matrix) should remain the same before and after the left-turn elimination applied.

Chapter 4 Case Study

4.1 Base Model with Left Turns

This research utilized the hypothetical 6 by 6 grid network and associated trip table from Mi (2013). For the base network, global turn penalties were selected as 45, 30, and 30 seconds for left turn, thru, and right turn movements, respectively. The network's external intersections act as buffer zones and remain in 8-phase operations, thus, no left-turn elimination is introduced for these intersections. The internal centroid connectors have no turn penalties and the flow capacities are defined as sufficiently large to eliminate delay into the internal zone land uses. Figure 10 is the trip assignment result for model with left turns. By design, this corresponds to Mi's (2013) base case (Before Turn Elimination). The assignment results were deemed reasonable.

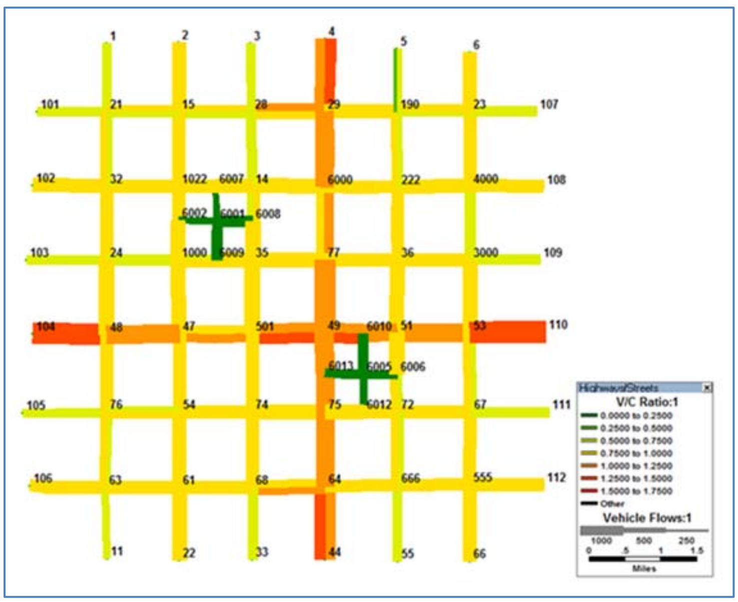

Figure 10. TransCAD Assignment Results: Before Case (same as Mi, 2013)

The turning movements produced by trip assignment are used to estimate intersection delay via Synchro. The results for the internal links (excluding the outside buffer links), corresponding to the inner 4 by 4 network grid are shown in Table 4. Based on these delay results, it appears that larger control delays appear on centralized intersections (near node 49). What would be the relative impacts of eliminating left turn movements as a function of location within the network hierarchy?

Table 4. Synchro Before Model Control Delay

Model	Before	
Node ID	Natural Cycle	Control Delay
14	100	23.2
35	100	28.0
36	100	28.6
47	100	25.4
49	100	25.5
51	100	26.7
54	100	26.9
72	100	25.9
74	100	29.3
75	100	27.3
77	100	26.8
222	100	25.7
501	100	31.0
1000	100	23.6
1022	100	20.5
6000	100	24.6
Average		26.2

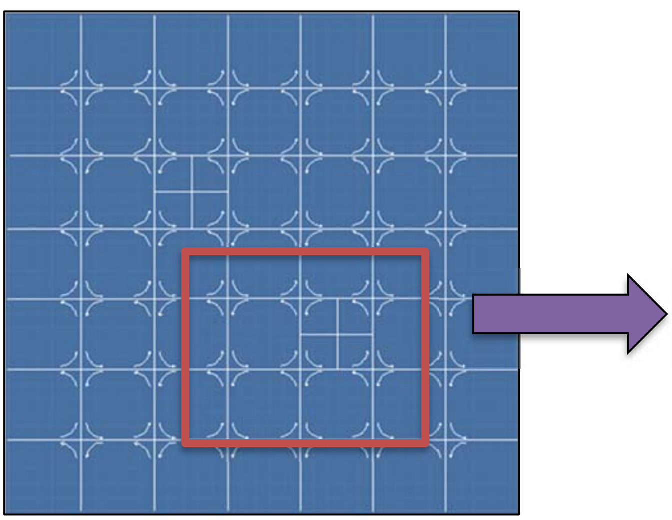

Figure 11. Network 2 (6*6 nodes)

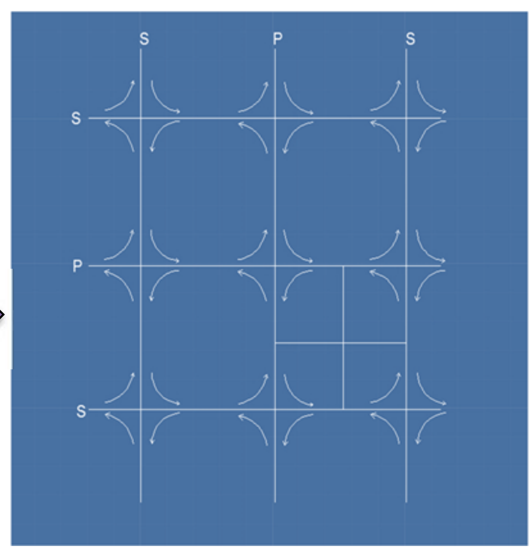

Figure 12. Network 2 (3*3 nodes)

4.2 Left-turn Elimination at Primary-Primary (P-P) intersection

A set of reduced turn penalty is assumed and applied to the TransCAD model assignment. Left-turn movement penalty remain the same value of 45 seconds, and through and right-turn movements have penalty reduction of 5 seconds, which is 25 seconds. These turn penalties are only applied to the intersection with left-turn elimination. The nodes without left-turn elimination apply the same global turn penalties as before.

In this model, deemed After Case 1 model, left-turn elimination is only imposed at node 49, the Primary-Primary intersection. Due to the same level of street, and high volumes on each approach, what would happen if left turns were eliminated on both arterials? By eliminating the left turn movements in both arterials, the P-P intersection only requires 4 phase operation. Figure 13 represents the proposed left-turn elimination layout.

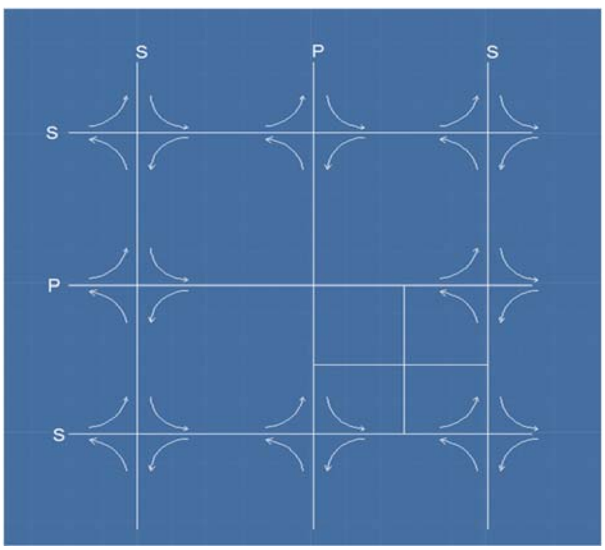

Figure 13. Primary-Primary Intersection Left-turn Elimination

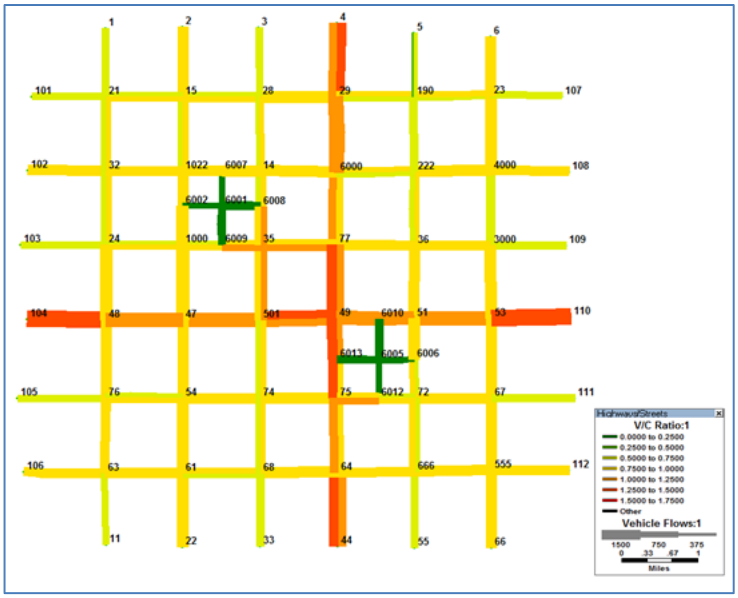

Figure 14. TransCAD Assignment Results: After Case 1 (based on Mi, 2013)

Figure 14 depicts the assignment results, deemed After Case 1. These assignment results are similar to but slightly different from those of Mi (2013) likely due to transcription errors in data flows between Synchro and TransCAD. Traffic on the outside links and nodes appear shifted to inner links in the After Case 1 than in the Before Case (and in Mi's 2013 After Case 1). Mi offers a potential explanation that the turn penalty applied to the fixed intersection, though only 5 seconds, is sufficient to reduce after left turns at this intersection, thus, some trips may have changed the shortest path in favor of using the internal links and nodes around the P-P intersection.

Table 5 and Table 6 show the intersection delays result in two different areas (Network 1 and Network 2), where Network 1 contains Network 2. Comparing cycle lengths, eliminating 4 left-turn phases in the fixed intersection would achieve a reduction in cycle length from 100 to 85 seconds. A smaller natural cycle length means it will take less time to clear critical lane traffic in all directions, so the average delay per intersection should be reduced. The results shown in both tables are consistent with this expectation. The reduction at the eliminated turn intersections is the highest. While, the average delay reduction in Network 2 is greater than it in Network 1; it suggests that the impact of the P-P left elimination in the inner area is more significant.

The assumption that turn penalty would reduce 5 seconds at the intersection with left-turn elimination has been supported by the Synchro results. The reduction of control delay in the inside area is 7.5 seconds; which is a little higher than the assumption. It can be concluded that the reduction in turn penalty in After Case at the left-turn eliminated intersection has converged.

Table 5. Synchro Model Before & After 1 Cycle and Delay (Network 2)

Model	**Before**		**After 1**			
Node ID	Natural Cycle(s)	Control Delay(s/veh)	**Node ID**	Natural Cycle(s)	Control Delay(s/veh)	Delay Difference(s)
35	100	28	**35**	85	20.7	-7.3
36	100	28.6	**36**	85	19.3	-9.3
49	100	25.5	**49**	75	12.6	-12.9
51	100	26.7	**51**	85	20.5	-6.2
72	100	25.9	**72**	85	17.3	-8.6
74	100	29.3	**74**	85	20.7	-8.6
75	100	27.3	**75**	85	19.7	-7.6
77	100	26.8	**77**	85	22.1	-4.7
501	100	31	**501**	85	24.9	-6.1
Average		27.7			19.8	-7.9

These results are again similar to but slightly different from Mi's (2013) analysis.

Table 6. Synchro Model Before & After 1 Cycle and Delay (Network 1)

Model	Before		After 1			
Node ID	Natural Cycle(s)	Control Delay(s/veh)	**Node ID**	Natural Cycle(s)	Control Delay(s/veh)	Delay Difference(s)
14	100	23.2	**14**	85	17.3	-5.9
35	100	28.0	**35**	85	20.7	-7.3
36	100	28.6	**36**	85	19.3	-9.3
47	100	25.4	**47**	85	18.4	-7
49	100	25.5	**49**	75	12.6	-12.9
51	100	26.7	**51**	85	20.5	-6.2
54	100	26.9	**54**	85	18.2	-8.7
72	100	25.9	**72**	85	17.3	-8.6
74	100	29.3	**74**	85	20.7	-8.6
75	100	27.3	**75**	85	19.7	-7.6
77	100	26.8	**77**	85	22.1	-4.7
222	100	25.7	**222**	85	15.6	-10.1
501	100	31.0	**501**	85	24.9	-6.1
1000	100	23.6	**1000**	85	18.3	-5.3
1022	100	20.5	1022	85	15	-5.5
6000	100	24.6	6000	85	18.8	-5.8
Average		26.2			18.7	-7.5

4.3 Left-turn Elimination at Secondary-Secondary (S-S) intersection

In the Network 2, there are two other types of intersections where left-turn elimination could be implemented. In addition to the P-P intersection, there are four S-S intersections in Network 4. Would the result be better than those for only one intersection elimination?

In this model, deemed After Case 2, the turn penalty reduction remains the same as it in the After Case 1 when left turns are eliminated. The left-turn elimination would occur in four S-S intersections; the elimination would apply to both arterials. Then, as for the After Case 1 P-P intersection, the S-S intersections would have only four phases per cycle. Figure 15 represents the proposed left-turn elimination layout.

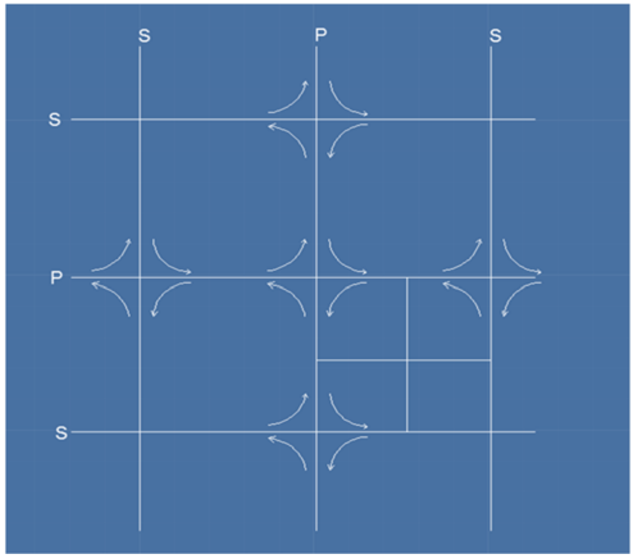

Figure 15. Secondary-Secondary Intersections Left-turn Elimination

With same peak hour demand OD matrix, the traffic assignment results are shown in Figure 16.

Figure 16. Trip Assignment Results: After Case 2 (based on Mi, 2013)

Compared with the Before Case, the After Case 2 trip assignment result is similar with the After Case 1 result: more traffic is attracted to the area around inner Network 2, and the outer traffic is slightly relieved. Again, flow differences are noted with the results of Mi (2013), possibly reflecting transcription errors and assignment model convergence. While, due to a different left-turn elimination strategy, the affected area is a little difference from After Case 1; the traffic volume/capacity ratios increase on the secondary streets and decrease slightly at the primary street.

Similar as the delay result of the After Case 1, the average intersection delay result in the Network 2 reduces more than the result in the Network 1. However, comparing the Network 2 results in After Case 1 and After Case 2, there is a greater reduction in delay in the After Case 2 model. The explanation may be of the more left-turn elimination intersections. The result shown in Table 7 shows the greater reduction in the natural cycle length of intersection and increased delay reduction at the corresponding intersections.

Then, returning to Network 1, the average delay reduction in After Case 2 is 7.5 seconds, which is almost same as the reduction in After Case 1. The result also can be considered as a converged result, when the reduction of turn penalty is five seconds. It is difficult to judge which left-turn elimination is more effective in Network 1, because of varying numbers of eliminated intersections. Therefore, by eliminating the same left-turns at different level of street, what would happen? Whether the elimination applied in Primary Street is more effective than left elimination applied in Secondary Street.

Table 7. Synchro Model Before & After 2 Cycle and Delay (Network 2)

Model	Before		After 2			
Node ID	Natural Cycle(s)	Control Delay(s/veh)	**Node ID**	Natural Cycle(s)	Control Delay(s/veh)	Delay Difference(s)
35	100	28	**35**	75	17.4	-10.6
36	100	28.6	**36**	75	17.4	-11.2
49	100	25.5	**49**	85	17.6	-7.9
51	100	26.7	**51**	85	22	-4.7
72	100	25.9	**72**	75	14.2	-11.7
74	100	29.3	**74**	75	13.3	-16
75	100	27.3	**75**	85	23.7	-3.6
77	100	26.8	**77**	85	22.5	-4.3
501	100	31	**501**	85	23.1	-7.9
Average		27.7			19	-8.7

Table 8. Synchro Model Before & After 2 Cycle and Delay (Network 1)

Model	Before		After 2			
Node ID	Natural Cycle(s)	Control Delay(s/veh)	**Node ID**	Natural Cycle(s)	Control Delay(s/veh)	Delay Difference(s)
14	100	23.2	**14**	85	17.7	-5.5
35	100	28.0	**35**	75	17.4	-10.6
36	100	28.6	**36**	75	17.4	-11.2
47	100	25.4	**47**	85	19.8	-5.6
49	100	25.5	**49**	85	17.6	-7.9
51	100	26.7	**51**	85	22	-4.7
54	100	26.9	**54**	85	18	-8.9
72	100	25.9	**72**	75	14.2	-11.7
74	100	29.3	**74**	75	13.3	-16
75	100	27.3	**75**	85	23.7	-3.6
77	100	26.8	**77**	85	22.5	-4.3
222	100	25.7	**222**	85	21.1	-4.6
501	100	31.0	**501**	85	23.1	-7.9
1000	100	23.6	**1000**	85	18.9	-4.7
1022	100	20.5	**1022**	85	14.6	-5.9
6000	100	24.6	**6000**	85	17.7	-6.9
Average		26.2			18.7	-7.5

4.4 Left-turn Elimination at Primary-Secondary (P-S) intersections

Based on the Previous Study, it is difficult to judge the delay reduction effects that caused by P-P intersection left-turn elimination and S-S intersection left-turn elimination. It is worthwhile studying what would happen with the elimination applied at the Primary-Secondary (P-S) intersection. From Table 4, the highest delay happens at the P-S intersection, without left turn elimination. To better evaluate the effect of left turn elimination applied on varying road, the study of P-S intersections would be divided into two parts: 1) eliminate left turns only on Primary Street; and 2) eliminate left turns only on Secondary Street.

4.4.1 Eliminating Secondary Street Left turns at P-S Intersections

Using the same turn penalty reduction as before, the left turn elimination layout depicted in Figure 17. These results are deemed After Case 3.

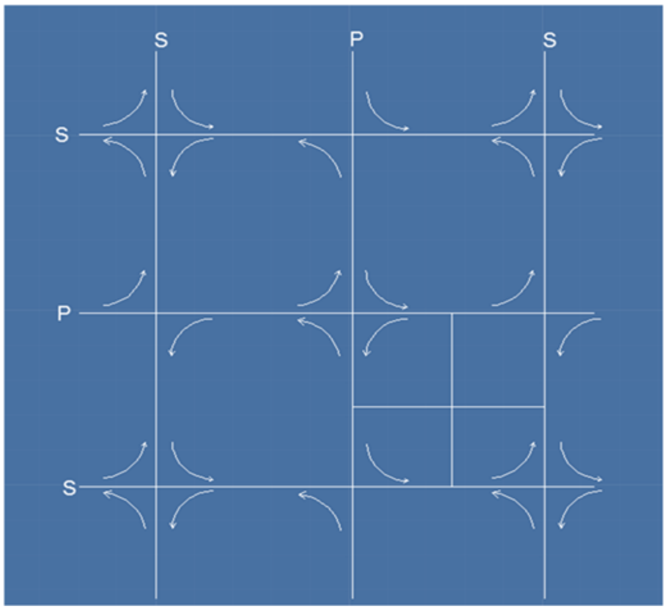

Figure 17. Left-turn Elimination of Secondary at Primary-Secondary Intersections

Based on the TransCAD trip assignment result (Figure 18), the comment can be made is that more traffic volumes are attracted to the vertical Primary Street. The result makes sense, because of the secondary left turn elimination; drivers should find the relatively shorter path to their destinations, where the Primary- Primary intersection maybe the best choice.

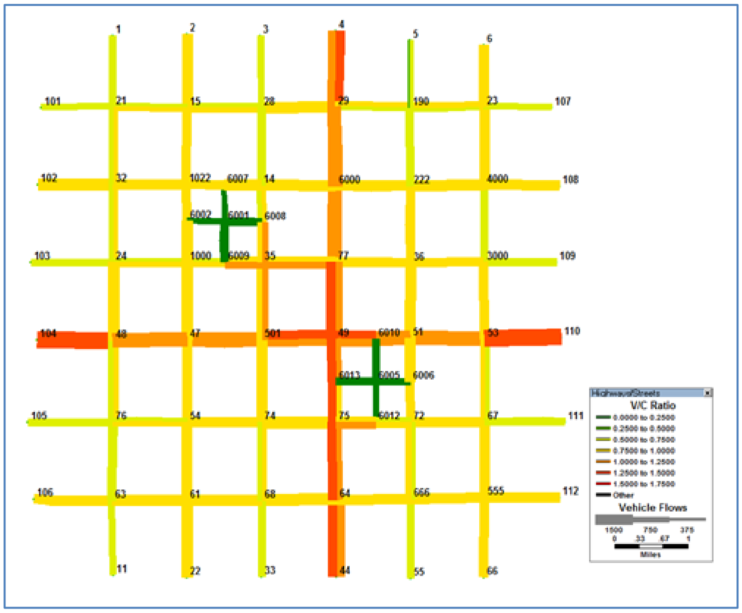

Figure 18. Trip Assignment Results: After Case 3

Now, check the delay result in the Network 1 and Network 2, and also check the convergence of Synchro delay and turn penalty applied (see Table 9 and Table 10 below that compare the intersection control delay with Before Case). With the same turn penalty reduction, the overall average intersection delay would be around five seconds reduction per intersection. While, the result of Synchro delay reduction in the Network 1 and Network 2 is 0.4 seconds and 1.1 seconds, respectively, it cannot be concluded that the model converged. Because of the delay reduction is relatively small, and the cycle length is only reduced at eliminated intersections (From 100 seconds to 85 seconds); it can be concluded that the elimination of left turns on the secondary street for P-S intersections is not effective.

Table 9. Synchro Model Before and After 3 Cycle and Delay (Network 2)

Model	Before		After 3			
Node ID	Natural Cycle(s)	Control Delay(s/veh)	Node ID	Natural Cycle(s)	Control Delay(s/veh)	Delay Difference(s)
35	100	28	35	100	33.8	5.8
36	100	28.6	36	100	32.6	4
49	100	25.5	49	100	30.1	4.6
51	100	26.7	51	85	19.1	-7.6
72	100	25.9	72	100	28.5	2.6
74	100	29.3	74	100	36.2	6.9
75	100	27.3	75	85	18.8	-8.5
77	100	26.8	77	85	20.8	-6
501	100	31	501	85	18.6	-12.4
Average		27.7			26.6	-1.1

Table 10. Synchro Model Before and After 3 Cycle and Delay (Network 1)

Model	Before		After 3			
Node ID	Natural Cycle(s)	Control Delay(s/veh)	Node ID	Natural Cycle(s)	Control Delay(s/veh)	Delay Difference(s)
14	100	23.2	14	100	22.5	-0.7
35	100	28.0	35	100	33.8	5.8
36	100	28.6	36	100	32.6	4
47	100	25.4	47	100	27.3	1.9
49	100	25.5	49	100	30.1	4.6
51	100	26.7	51	85	19.1	-7.6
54	100	26.9	54	100	25.9	-1
72	100	25.9	72	100	28.5	2.6
74	100	29.3	74	100	36.2	6.9
75	100	27.3	75	85	18.8	-8.5
77	100	26.8	77	85	20.8	-6
222	100	25.7	222	100	25.2	-0.5
501	100	31.0	501	85	18.6	-12.4
1000	100	23.6	1000	100	25	1.4
1022	100	20.5	1022	100	22.7	2.2
6000	100	24.6	6000	100	25.9	1.3
Average		26.2			25.8	-0.4

4.4.2 Eliminating Primary Street Left Turns at P-S Intersections

The second method to test the elimination effect at P-S intersections is eliminating left turns on Primary Street, using the same turn penalty reductions. The left turn elimination layout is depicted in Figure 19.

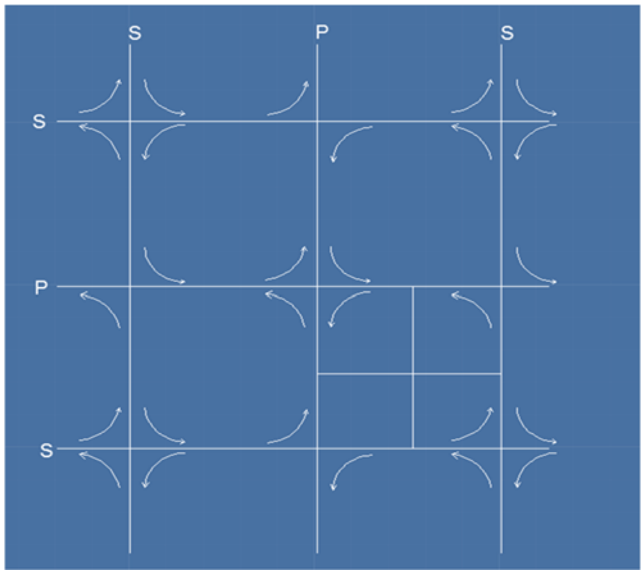

Figure 19. Left-turn elimination of Primary Street at Primary-Secondary Intersections

The difference between these two elimination methods is eliminate the left turns on different arterials, while the trip assignment result is totally varying between these two arterials. The model that eliminates Primary left turns is called After Case 4. The trip assignment result is a little similar with the After Case 1 model; with greater traffic volumes attracted to the area around Network 2. Due to Primary left turn eliminations, the volumes/capacity ratios on the secondary street is relatively higher than before, which implies that the utility of the secondary street improved with the left turn elimination. Node 49 remains the highest volume intersection.

Figure 20. Trip Assignment Results: After Case 4

Then, according to the trip assignment result, Before Case and After Case 4 network intersection delays are estimated by Synchro Model and shown in Tables 11 and 12. Delay reduction is almost same as After Case 1 model, the average delay of 6.6 seconds in the Network 1 can be conclude that it converged with the turn penalty reduction. However, unlike three other after models, the reduction delay in the Network 2 is less than reduction delay in the Network 1. It is difficult to determine the reason caused this result; maybe because this elimination improve the v/c ratios of secondary streets. Possibly, the larger intersection delay reductions do not happen at the eliminated intersection; while in other after models, the larger reductions did happen at the eliminated intersections.

Table 11. Synchro Model Before and After 4 Cycle and Delay (Network 2)

Model	Before		After 4			
Node ID	Natural Cycle(s)	Control Delay(s/beh)	Node ID	Natural Cycle(s)	Control Delay(s/veh)	Delay Difference(s)
35	100	28	35	85	24	-4
36	100	28.6	36	85	24.2	-4.4
49	100	25.5	49	85	27	1.5
51	100	26.7	51	85	24.2	-2.5
72	100	25.9	72	85	20.7	-5.2
74	100	29.3	74	85	25.5	-3.8
75	100	27.3	75	75	17.9	-9.4
77	100	26.8	77	75	14.4	-12.4
501	100	31	501	85	19.2	-11.8
		27.7			21.9	-5.8

Table 12. Synchro Model Before and After 4 Cycle and Delay (Network 1)

Model	Before		After 4			
Node ID	Natural Cycle(s)	Control Delay(s/veh)	Node ID	Natural Cycle(s)	Control Delay(s/veh)	Delay Difference(s)
14	100	23.2	14	85	16.9	-6.3
35	100	28.0	35	85	24	-4
36	100	28.6	36	85	24.2	-4.4
47	100	25.4	47	85	15.3	-10.1
49	100	25.5	49	85	27	1.5
51	100	26.7	51	85	24.2	-2.5
54	100	26.9	54	85	16.5	-10.4
72	100	25.9	72	85	20.7	-5.2
74	100	29.3	74	85	25.5	-3.8
75	100	27.3	75	75	17.9	-9.4
77	100	26.8	77	75	14.4	-12.4
222	100	25.7	222	85	15.7	-10
501	100	31.0	501	85	19.2	-11.8
1000	100	23.6	1000	85	19	-4.6
1022	100	20.5	1022	85	15.3	-5.2
6000	100	24.6	6000	85	17.5	-7.1
Average		26.2			19.6	-6.6

4.5 Delay Comparison

4.5.1 Comparing Four After Cases

In this study, four different results are compared to judge the effective of left turn elimination. Table 13 summarizes the average delay and average delay reduction in three networks. These three networks are relatively to each other.

Table 13. Summary of the Average Intersection Delay in Three Network

Model	Before	After 1	Difference 1	After 2	Difference 2	After 3	Difference 3	After 4	Difference 4
Network 2	27.7	19.8	-7.9	19	-8.7	26.6	-1.1	21.9	-5.8
Network 1	26.2	18.7	-7.5	18.7	-7.5	25.8	-0.4	19.6	-6.6
Network	28.2	25.4	-2.8	25.6	-2.6	28.1	-0.1	25.5	-2.7

From the above table, the results can be conclude that:

1. According to the network size, the smaller the network is, the more reduction will result in the intersection delay;
2. The left elimination applied on the Secondary Street at P-S intersection is not work for the delay reduction. Oppositely, the elimination on the Primary Street has the significant effect. This conclusion is consistent by prior results that show that left turn elimination is only effective for heavy traffic roads.
3. It is difficult to judge the effects of left turn elimination at the intersection that the two arterials have the same level (P-P and S-S). In other word, when the two arterials are at the same level, and thus it is difficult to determine which arterial should eliminate the left-turn movements.
4. For the whole network, when the outside buffers are considered, the result of delay reduction is almost the same, which means that the left turn elimination is more

effective in the relative small area that around it. For the whole network, it does not matter which intersection eliminates the left-turn movements.

4.5.2 Comparison with the Previous Study Results

The results of the preceding study completed by Mi (2013) are shown in Table 13. Note that the current study only considers peak hour flows, while Mi considered both peak and off-peak flows. Also not that an additional after peak case was considered herein and is not comparable to Mi's work. However, since the primary research objective was to validate the proposed approach to assessing the elimination of left turn movements, this current analysis uses the same turn penalty reductions, the same OD matrix, and the same assumptions. Thus, direct comparison with the two sets of model results is straightforward.

Table 14. Synchro Model Before and After Cycle and Delay (Network 1)

Model	**Before**		**After**			
Node ID	Natural Cycle(s)	Control Delay(s/veh.)	**Node ID**	Natural Cycle(s)	Control Delay(s/veh.)	Delay Difference(s)
14	100	23.2	**14**	85	19.1	-4.1
35	100	28.0	**35**	85	25.9	-2.1
36	100	28.6	**36**	85	28.6	0
47	100	25.4	**47**	85	18.5	-6.9
49	100	25.5	**49**	85	19.9	-5.6
51	100	26.7	**51**	85	21.9	-4.8
54	100	26.9	**54**	85	18.4	-8.5
72	100	25.9	**72**	85	17.7	-8.2
74	100	29.3	**74**	85	22.5	-6.8
75	100	27.3	**75**	85	22.3	-5
77	100	26.8	**77**	85	24.4	-2.4
222	100	25.7	**222**	85	17.1	-8.6
501	100	31.0	**501**	85	25	-6
1000	100	23.6	**1000**	85	23.1	-0.5
1022	100	20.5	**1022**	85	17.5	-3
6000	100	24.6	**6000**	85	18.9	-5.7
Average		26.2			21	-5.2

With the same turn penalty reduction, the result in this previous study converges. While compared with the 4 after model, the average reduction of intersection delay is not as larger as expected. It implies that there is not a strong relationship between delay reduction and the number of left-turn movements eliminated. This also suggests that left turn elimination may depend on specific network topography.

4.6 Network Performance Evaluation

The network performance can be evaluated using total travel time and total fuel consumption. The methods have been introduced in chapter 3.

4.6.1 Total Travel Time Evaluation

Total travel time can be calculated as the sum of intersection control delay time and the calculated link travel time. The volume is the sum of all link movements. The control delay is the average intersection delay. The result of total travel reduction in each model is shown in the Table 14.

From this table, the conclusion can be draw is that except for the left-turn elimination applied on the secondary streets at P-S intersections, the total travel time of all the other models decrease. Even though, the delay reduction is the same in After Case 1 and After Case 2 model, the reduction of total travel time is varying due to the different value of VMT. The total travel time reduction in eliminated only one P-P intersection is the largest. It can be concluded that the network performance is improved, due to the reduction in travel time.

Table 15. Network 1 (4 by 4 nodes) Peak One Hour Performance Summary (based on Mi, 2013)

Model Information		TransCAD Output			Synchro Delay			Comparison	
Peak OD	Turn Penalty(s)	VMT	VHT	Volume	Control Delay(s)	Network Delay (veh-hr)	Network TT=VHT+Dealy(veh-hr)	VMT change (%)	TT change (%)
Before	Global (45.30.30)	33120	902	79771	26.2	581	1482	N/A	N/A
After	Global &Reduced (45,25,25)	34295	965	82497	21.0	481	1445	3.5%	-2.5%
After 1	Global &Reduced (45,25,25)	35060	960	87517	18.7	455	1415	5.8%	-4.5%
After 2	Global &Reduced (45,25,25)	35485	971	88530	18.7	460	1431	7.1%	-3.4%
After 3	Global &Reduced (45,25,25)	35376	975	88246	25.8	632	1607	6.8%	8.4%
After 4	Global &Reduced (45,25,25)	35397	971	88268	19.6	481	1452	6.9%	-2.0%

4.6.2 Fuel Consumption Evaluation

In addition to the evaluation of total travel time, estimated fuel consumption also can be considered as a factor to evaluate network performance, along the same lines as in Mi (2013). Utilizing the Federal Highway Administration (FHWA) fuel consumption analysis of Wagner (1980), the fuel consumption is based on vehicle mile traveled and vehicle hour traveled.

$$\text{Total Fuel Consumption} = 0.0425*\text{VMT}+0.6*\text{VHT}$$

Here, VHT is equal to the network total travel time. The travel time can be estimated by a total of the link travel time (from TransCAD) and the intersection control delay time (from Synchro).

One improvement of a network performance is to save the fuel consumption. From the equation above, the fuel can be saved by decreasing the value of VMT and network TT. Table 14 summarizes the after models improvement in Total Travel Time changes and Fuel Consumption changes, comparing with the before model. Except After 3 model, the other after models have saved some vehicle hours in the Peak Hour operation, however, the fuel consumptions increase in some degree at the same time. The After 3 model shows the increase in both Total Travel Time and Fuel Consumptions. It can be concluded that even the travel time is reduced; the fuel consumption is difficult to save due to re-routing. The re-routing of some trips may increase the consumptions of fuel.

Table 16. Network 1 (4 by 4 nodes) Peak One Hour Performance Measure in Fuel Consumption (based on Mi, 2013)

Model Information		**Network Performance**			**Fuel Consumption (Gallon)**				
Peak OD	Turn Penalty(s)	VMT	Network TT (veh-hr)	TT Difference(veh-hr)	By VMT	By TT	Total	Difference	Change (%)
Before	Global (45.30.30)	33120	1482	N/A	1408	889	2297	N/A	N/A
After	Global &Reduced (45,25,25)	34295	1445	-37	1458	867	2325	28	1.2%
After 1	Global &Reduced (45,25,25)	35060	1415	-67	1490	849	2339	42	1.8%
After 2	Global &Reduced (45,25,25)	35485	1431	-51	1508	858	2366	69	3.0%
After 3	Global &Reduced (45,25,25)	35376	1607	125	1503	964	2467	170	7.4%
After 4	Global &Reduced (45,25,25)	35397	1452	-30	1504	871	2375	78	3.4%

Chapter 5. Summary and Conclusions

Based on the results presented, a conclusion can be drawn that the selected elimination of left-turn movements can be an effective way to reduce intersection delay. This study was designed to both validate the results produced by Mi (2013) and to perform sensitivity tests on those results. In both studies, the primary objective was to assess the types of intersection, based on geometry and flow characteristics, for which left-turn elimination is most effective. The judgment criteria are the evaluation of delay reduction, total travel time, and fuel consumption on the network. Overall, this study validated Mi's earlier research, although deviations in the two sets of results suggest that further sensitivity analysis is required. A source of error may be the manual data transcription used by Mi when porting data between TransCAD and Syncro. The current study attempted to better automate this transcription process but the results, while slightly different, were similar in magnitude for the common network treatments considered. There still exist some limitations in this study:

1. Estimating turn movements from a link-based trip assignment is an approximation.
2. The porting turn movement data and turning movement penalties between TransCAD and Synchro is not automated (future software improvements may correct this)
3. Intersection delay is affected by many factors, not only the left-turn movements.
4. This study only focused on two roadway classifications: primary and secondary arterials; other facility types should be taken into consideration. The conclusions drawn in this study are only one aspect of the left-turn elimination.
5. The assumption is that using turn penalties in trip assignment improves the accuracy of the turning movement estimation; different turn penalties may result in different conclusions.

It is recommended that the elimination of left-turn movement be tested in real world networks. The grid network is easily for driver to re-route, while in the real world, other intersection types should be considered.

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Appendix

Table A. Trip Assignment Result from TransCAD: After 1 Model

ID	AB_Flow	BA_Flow	Tot_Flow	AB_Time	BA_Time	AB_VOC	BA_VOC	AB_VMT	BA_VMT	Tot_VMT	AB_VHT	BA_VHT	Tot_VHT
1	777.00	779.00	1556.00	0.81	0.81	0.86	0.87	388.50	389.50	778.00	10.52	10.56	21.08
6	784.83	541.03	1325.86	0.82	0.76	0.87	0.60	392.42	270.51	662.93	10.66	6.90	17.56
7	538.00	461.00	999.00	0.76	0.76	0.60	0.51	269.00	230.50	499.50	6.85	5.82	12.68
8	622.00	535.00	1157.00	0.78	0.76	0.69	0.59	311.00	267.50	578.50	8.04	6.81	14.85
9	764.46	612.18	1376.64	0.40	0.39	0.85	0.68	191.12	153.04	344.16	5.15	3.95	9.10
11	793.28	854.61	1647.89	0.41	0.42	0.88	0.95	198.32	213.65	411.97	5.41	5.99	11.40
13	590.69	625.00	1215.69	0.77	0.78	0.66	0.69	295.34	312.50	607.85	7.59	8.09	15.67
14	733.19	708.08	1441.28	0.80	0.79	0.81	0.79	366.60	354.04	720.64	9.77	9.36	19.13
17	832.39	880.45	1712.85	0.83	0.85	0.92	0.98	416.20	440.23	856.42	11.55	12.52	24.06
18	674.89	827.38	1502.27	0.79	0.83	0.75	0.92	337.44	413.69	751.13	8.84	11.45	20.29
19	812.19	855.07	1667.26	0.82	0.84	0.90	0.95	406.09	427.54	833.63	11.16	11.99	23.16
20	695.00	793.00	1488.00	0.79	0.82	0.77	0.88	347.50	396.50	744.00	9.15	10.81	19.96
21	743.18	674.82	1418.00	0.80	0.79	0.83	0.75	371.59	337.41	709.00	9.94	8.84	18.77
22	682.35	571.07	1253.42	0.79	0.77	0.76	0.63	341.18	285.53	626.71	8.95	7.31	16.26
23	590.81	654.05	1244.85	0.77	0.78	0.66	0.73	295.40	327.02	622.43	7.59	8.52	16.11
24	721.99	634.40	1356.39	0.80	0.78	0.80	0.70	360.99	317.20	678.20	9.59	8.22	17.81
25	742.60	659.66	1402.26	0.80	0.78	0.83	0.73	371.30	329.83	701.13	9.93	8.60	18.53
26	893.73	778.50	1672.23	0.86	0.81	0.99	0.87	446.86	389.25	836.12	12.80	10.55	23.35
29	923.41	1150.64	2074.05	0.76	0.88	0.97	1.21	461.70	575.32	1037.02	11.63	16.91	28.55
32	922.76	766.40	1689.16	0.87	0.81	1.03	0.85	461.38	383.20	844.58	13.45	10.34	23.78
33	671.00	766.57	1437.57	0.78	0.81	0.75	0.85	335.50	383.28	718.78	8.78	10.34	19.11
34	1104.71	981.92	2086.63	0.85	0.78	1.16	1.03	552.36	490.96	1043.32	15.64	12.78	28.42
35	694.26	712.62	1406.88	0.79	0.79	0.77	0.79	347.13	356.31	703.44	9.14	9.43	18.57
36	664.72	711.09	1375.80	0.78	0.79	0.74	0.79	332.36	355.54	687.90	8.68	9.41	18.09

37	741.96	762.76	1504.72	0.80	0.81	0.82	0.85	370.98	381.38	752.36	9.92	10.27	20.19
38	702.31	610.35	1312.67	0.79	0.77	0.78	0.68	351.16	305.18	656.33	9.27	7.87	17.14
39	627.39	712.98	1340.37	0.78	0.79	0.70	0.79	313.70	356.49	670.19	8.12	9.44	17.56
40	630.91	743.61	1374.52	0.78	0.80	0.70	0.83	315.46	371.80	687.26	8.17	9.94	18.12
41	760.08	887.73	1647.81	0.81	0.86	0.84	0.99	380.04	443.86	823.90	10.23	12.67	22.90
42	864.26	863.26	1727.52	0.85	0.85	0.96	0.96	432.13	431.63	863.76	12.18	12.16	24.34
43	783.27	952.14	1735.41	0.81	0.89	0.87	1.06	391.63	476.07	867.71	10.63	14.14	24.77
44	1356.80	1020.73	2377.52	1.08	0.80	1.43	1.07	678.40	510.36	1188.76	24.48	13.61	38.09
46	816.80	797.29	1614.09	0.83	0.82	0.91	0.89	408.40	398.64	807.04	11.25	10.89	22.14
47	862.95	760.00	1622.94	0.85	0.81	0.96	0.84	431.47	380.00	811.47	12.15	10.22	22.38
48	1222.00	1204.00	2426.00	0.94	0.92	1.29	1.27	611.00	602.00	1213.00	19.15	18.55	37.71
49	618.00	458.00	1076.00	0.78	0.76	0.69	0.51	309.00	229.00	538.00	7.98	5.78	13.77
50	704.00	707.00	1411.00	0.79	0.79	0.78	0.79	352.00	353.50	705.50	9.29	9.34	18.64
52	1023.26	1064.88	2088.14	0.80	0.82	1.08	1.12	511.63	532.44	1044.07	13.67	14.63	28.30
53	705.22	773.25	1478.46	0.79	0.81	0.78	0.86	352.61	386.62	739.23	9.31	10.46	19.77
54	984.99	998.24	1983.22	0.78	0.79	1.04	1.05	492.49	499.12	991.61	12.84	13.12	25.96
56	1122.34	1201.99	2324.33	0.86	0.92	1.18	1.27	561.17	600.99	1162.16	16.11	18.49	34.60
58	1042.18	1177.78	2219.95	0.41	0.51	1.10	1.24	260.54	294.44	554.99	7.05	10.10	17.15
59	1347.39	955.36	2302.75	0.54	0.44	1.42	1.01	336.85	238.84	575.69	12.03	6.98	19.01
60	839.05	772.53	1611.58	0.42	0.41	0.93	0.86	209.76	193.13	402.89	5.84	5.22	11.06
61	1027.03	1037.35	2064.38	0.80	0.81	1.08	1.09	513.52	518.67	1032.19	13.75	13.98	27.73
62	1196.00	1215.00	2411.00	0.92	0.93	1.26	1.28	598.00	607.50	1205.50	18.30	18.92	37.21
63	792.86	681.22	1474.08	0.82	0.79	0.88	0.76	396.43	340.61	737.04	10.81	8.93	19.74
64	740.45	703.56	1444.02	0.80	0.79	0.82	0.78	370.23	351.78	722.01	9.89	9.29	19.18
65	788.88	751.91	1540.79	0.82	0.80	0.88	0.84	394.44	375.96	770.40	10.73	10.09	20.82
66	790.00	709.00	1499.00	0.82	0.79	0.88	0.79	395.00	354.50	749.50	10.75	9.37	20.13
67	761.47	772.77	1534.24	0.81	0.81	0.85	0.86	380.74	386.39	767.12	10.25	10.45	20.70
80	798.00	775.00	1573.00	0.82	0.81	0.89	0.86	399.00	387.50	786.50	10.90	10.49	21.39
81	759.95	677.69	1437.64	0.81	0.79	0.84	0.75	379.98	338.85	718.82	10.22	8.88	19.10
82	553.00	458.00	1011.00	0.77	0.76	0.61	0.51	276.50	229.00	505.50	7.06	5.78	12.84

83	697.00	719.00	1416.00	0.79	0.80	0.77	0.80	348.50	359.50	708.00	9.18	9.54	18.72
84	1220.00	1117.00	2337.00	0.94	0.86	1.28	1.18	610.00	558.50	1168.50	19.09	15.97	35.06
85	880.70	815.24	1695.94	0.85	0.83	0.98	0.91	440.35	407.62	847.97	12.52	11.22	23.74
86	621.00	459.00	1080.00	0.78	0.76	0.69	0.51	310.50	229.50	540.00	8.03	5.80	13.82
87	720.77	778.09	1498.86	0.80	0.81	0.80	0.86	360.38	389.05	749.43	9.57	10.54	20.11
88	549.00	605.00	1154.00	0.77	0.77	0.61	0.67	274.50	302.50	577.00	7.01	7.79	14.80
89	739.78	671.48	1411.27	0.80	0.78	0.82	0.75	369.89	335.74	705.63	9.88	8.78	18.66
90	1156.23	930.45	2086.68	0.89	0.76	1.22	0.98	578.12	465.22	1043.34	17.08	11.77	28.84
91	928.31	742.39	1670.70	0.44	0.40	1.03	0.82	232.08	185.60	417.67	6.79	4.96	11.75
92	741.01	625.03	1366.04	0.80	0.78	0.82	0.69	370.50	312.52	683.02	9.90	8.09	17.99
93	741.72	710.66	1452.38	0.80	0.79	0.82	0.79	370.86	355.33	726.19	9.91	9.40	19.31
94	673.54	726.70	1400.25	0.79	0.80	0.75	0.81	336.77	363.35	700.12	8.82	9.66	18.48
95	832.53	844.97	1677.50	0.83	0.84	0.93	0.94	416.27	422.48	838.75	11.55	11.79	23.34
96	701.28	710.55	1411.83	0.79	0.79	0.78	0.79	350.64	355.27	705.91	9.25	9.40	18.65
97	742.56	641.33	1383.88	0.80	0.78	0.83	0.71	371.28	320.66	691.94	9.93	8.33	18.25
98	808.06	735.36	1543.42	0.82	0.80	0.90	0.82	404.03	367.68	771.71	11.09	9.81	20.89
99	612.00	542.00	1154.00	0.77	0.76	0.68	0.60	306.00	271.00	577.00	7.90	6.91	14.80
100	791.00	718.00	1509.00	0.82	0.80	0.88	0.80	395.50	359.00	754.50	10.77	9.52	20.29
101	470.00	549.00	1019.00	0.76	0.77	0.52	0.61	235.00	274.50	509.50	5.94	7.01	12.95
102	544.00	467.00	1011.00	0.77	0.76	0.60	0.52	272.00	233.50	505.50	6.94	5.90	12.84
103	545.00	466.00	1011.00	0.77	0.76	0.61	0.52	272.50	233.00	505.50	6.95	5.89	12.84
104	1225.00	1137.00	2362.00	0.94	0.87	1.29	1.20	612.50	568.50	1181.00	19.26	16.52	35.78
105	467.00	382.00	849.00	0.76	0.75	0.52	0.42	233.50	191.00	424.50	5.90	4.80	10.70
106	729.00	785.00	1514.00	0.80	0.82	0.81	0.87	364.50	392.50	757.00	9.70	10.66	20.37
107	461.00	628.00	1089.00	0.76	0.78	0.51	0.70	230.50	314.00	544.50	5.82	8.13	13.95
108	753.10	713.51	1466.60	0.40	0.40	0.84	0.79	188.27	178.38	366.65	5.05	4.72	9.78
109	437.94	337.03	774.97	0.38	0.38	0.05	0.04	109.49	84.26	193.74	2.74	2.11	4.84
112	685.11	642.01	1327.11	0.39	0.39	0.76	0.71	171.28	160.50	331.78	4.50	4.17	8.67
113	449.09	472.50	921.59	0.38	0.38	0.05	0.05	112.27	118.13	230.40	2.81	2.95	5.76
116	733.99	737.65	1471.63	0.40	0.40	0.82	0.82	183.50	184.41	367.91	4.89	4.92	9.81

120	627.46	781.86	1409.32	0.39	0.41	0.70	0.87	156.87	195.46	352.33	4.06	5.30	9.36
124	737.77	690.25	1428.02	0.80	0.79	0.82	0.77	368.89	345.13	714.01	9.85	9.08	18.92
128	709.54	736.92	1446.46	0.79	0.80	0.79	0.82	354.77	368.46	723.23	9.38	9.83	19.22
132	646.82	749.31	1396.13	0.78	0.80	0.72	0.83	323.41	374.65	698.07	8.41	10.04	18.45
133	757.08	848.25	1605.33	0.40	0.42	0.84	0.94	189.27	212.06	401.33	5.09	5.93	11.02
134	360.25	447.76	808.01	0.38	0.38	0.04	0.05	90.06	111.94	202.00	2.25	2.80	5.05
135	760.15	958.16	1718.31	0.40	0.45	0.84	1.06	190.04	239.54	429.58	5.11	7.14	12.26
136	583.84	627.45	1211.29	0.38	0.38	0.06	0.07	145.96	156.86	302.82	3.65	3.92	7.57
137	915.56	730.07	1645.63	0.44	0.40	1.02	0.81	228.89	182.52	411.41	6.64	4.86	11.50
138	618.97	585.77	1204.74	0.38	0.38	0.07	0.07	154.74	146.44	301.18	3.87	3.66	7.53
139	1000.49	963.81	1964.30	0.39	0.44	1.05	1.01	250.12	240.95	491.08	6.58	7.07	13.66
140	622.69	450.40	1073.09	0.38	0.38	0.07	0.05	155.67	112.60	268.27	3.89	2.82	6.71
142	546.24	514.14	1060.37	0.38	0.38	0.06	0.06	136.56	128.53	265.09	3.41	3.21	6.63
143	766.26	662.32	1428.58	0.40	0.39	0.85	0.74	191.57	165.58	357.15	5.17	4.32	9.49
144	381.99	463.96	845.95	0.38	0.38	0.04	0.05	95.50	115.99	211.49	2.39	2.90	5.29
145	1226.40	802.27	2028.67	0.47	0.41	1.29	0.84	306.60	200.57	507.17	9.65	5.47	15.12

Table B. Trip Assignment Result from TransCAD: After 2 Model

ID	AB_Flow	BA_Flow	Tot_Flow	AB_Time	BA_Time	AB_VOC	BA_VOC	AB_VMT	BA_VMT	Tot_VMT	AB_VHT	BA_VHT	Tot_VHT
1	777.00	779.00	1556.00	0.81	0.81	0.86	0.87	388.50	389.50	778.00	10.52	10.56	21.08
6	806.33	536.76	1343.09	0.82	0.76	0.90	0.60	403.16	268.38	671.54	11.05	6.84	17.89
7	538.00	461.00	999.00	0.76	0.76	0.60	0.51	269.00	230.50	499.50	6.85	5.82	12.68
8	622.00	535.00	1157.00	0.78	0.76	0.69	0.59	311.00	267.50	578.50	8.04	6.81	14.85
9	822.70	687.33	1510.03	0.41	0.39	0.91	0.76	205.68	171.83	377.51	5.68	4.51	10.20
11	750.73	829.48	1580.21	0.40	0.42	0.83	0.92	187.68	207.37	395.05	5.03	5.75	10.78
13	504.32	552.98	1057.30	0.76	0.77	0.56	0.61	252.16	276.49	528.65	6.40	7.06	13.46
14	751.18	728.37	1479.55	0.80	0.80	0.83	0.81	375.59	364.18	739.78	10.07	9.69	19.76
17	813.33	870.22	1683.54	0.83	0.85	0.90	0.97	406.66	435.11	841.77	11.18	12.30	23.49
18	707.68	787.38	1495.06	0.79	0.82	0.79	0.87	353.84	393.69	747.53	9.35	10.71	20.06
19	804.32	807.10	1611.41	0.82	0.82	0.89	0.90	402.16	403.55	805.71	11.02	11.07	22.08
20	695.00	793.00	1488.00	0.79	0.82	0.77	0.88	347.50	396.50	744.00	9.15	10.81	19.96
21	726.76	645.81	1372.57	0.80	0.78	0.81	0.72	363.38	322.90	686.29	9.66	8.39	18.06
22	664.11	574.44	1238.55	0.78	0.77	0.74	0.64	332.05	287.22	619.27	8.67	7.36	16.03
23	635.38	690.68	1326.07	0.78	0.79	0.71	0.77	317.69	345.34	663.03	8.24	9.08	17.32
24	682.57	660.55	1343.12	0.79	0.78	0.76	0.73	341.29	330.28	671.56	8.96	8.62	17.57
25	695.21	665.24	1360.45	0.79	0.78	0.77	0.74	347.61	332.62	680.22	9.15	8.69	17.84
26	868.66	828.03	1696.69	0.85	0.83	0.97	0.92	434.33	414.01	848.35	12.27	11.46	23.73
29	999.22	1103.94	2103.16	0.79	0.85	1.05	1.16	499.61	551.97	1051.58	13.14	15.62	28.76
32	975.38	920.96	1896.34	0.91	0.87	1.08	1.02	487.69	460.48	948.17	14.72	13.41	28.12
33	655.12	784.38	1439.49	0.78	0.81	0.73	0.87	327.56	392.19	719.75	8.53	10.65	19.19
34	1134.96	1053.05	2188.01	0.87	0.82	1.19	1.11	567.48	526.53	1094.01	16.46	14.35	30.81
35	714.79	809.51	1524.31	0.79	0.82	0.79	0.90	357.40	404.76	762.15	9.47	11.11	20.58
36	779.81	801.44	1581.25	0.81	0.82	0.87	0.89	389.91	400.72	790.63	10.57	10.96	21.53
37	701.08	747.64	1448.72	0.79	0.80	0.78	0.83	350.54	373.82	724.36	9.25	10.01	19.26
38	743.58	637.21	1380.79	0.80	0.78	0.83	0.71	371.79	318.60	690.40	9.94	8.27	18.21
39	627.03	647.05	1274.08	0.78	0.78	0.70	0.72	313.52	323.53	637.04	8.11	8.41	16.53

40	632.50	677.34	1309.85	0.78	0.79	0.70	0.75	316.25	338.67	654.92	8.20	8.87	17.07
41	765.33	839.55	1604.88	0.81	0.84	0.85	0.93	382.67	419.77	802.44	10.32	11.69	22.00
42	843.75	794.00	1637.75	0.84	0.82	0.94	0.88	421.87	397.00	818.88	11.77	10.83	22.60
43	793.46	879.16	1672.62	0.82	0.85	0.88	0.98	396.73	439.58	836.31	10.82	12.49	23.31
44	1290.20	1118.57	2408.77	1.01	0.86	1.36	1.18	645.10	559.28	1204.38	21.65	16.01	37.66
46	919.36	858.76	1778.13	0.87	0.84	1.02	0.95	459.68	429.38	889.06	13.37	12.07	25.44
47	829.72	788.78	1618.50	0.83	0.82	0.92	0.88	414.86	394.39	809.25	11.50	10.73	22.23
48	1222.00	1204.00	2426.00	0.94	0.92	1.29	1.27	611.00	602.00	1213.00	19.15	18.55	37.71
49	618.00	458.00	1076.00	0.78	0.76	0.69	0.51	309.00	229.00	538.00	7.98	5.78	13.77
50	704.00	707.00	1411.00	0.79	0.79	0.78	0.79	352.00	353.50	705.50	9.29	9.34	18.64
52	981.25	1034.00	2015.25	0.78	0.81	1.03	1.09	490.62	517.00	1007.63	12.76	13.91	26.67
53	702.17	705.62	1407.79	0.79	0.79	0.78	0.78	351.08	352.81	703.90	9.26	9.32	18.59
54	880.79	941.91	1822.70	0.74	0.76	0.93	0.99	440.39	470.96	911.35	10.87	11.98	22.85
56	1003.57	1082.55	2086.12	0.79	0.84	1.06	1.14	501.78	541.27	1043.06	13.23	15.07	28.30
58	908.53	1049.92	1958.45	0.38	0.47	0.96	1.11	227.13	262.48	489.61	5.68	8.14	13.82
59	1275.49	1041.45	2316.94	0.50	0.46	1.34	1.10	318.87	260.36	579.24	10.54	8.02	18.56
60	905.17	808.66	1713.82	0.43	0.41	1.01	0.90	226.29	202.16	428.46	6.53	5.55	12.07
61	982.90	1021.20	2004.11	0.78	0.80	1.03	1.07	491.45	510.60	1002.05	12.80	13.62	26.42
62	1196.00	1215.00	2411.00	0.92	0.93	1.26	1.28	598.00	607.50	1205.50	18.30	18.92	37.21
63	733.55	711.92	1445.47	0.80	0.79	0.82	0.79	366.78	355.96	722.74	9.78	9.42	19.20
64	839.63	645.89	1485.52	0.84	0.78	0.93	0.72	419.81	322.95	742.76	11.69	8.39	20.08
65	728.61	735.87	1464.49	0.80	0.80	0.81	0.82	364.31	367.94	732.24	9.69	9.82	19.51
66	790.00	709.00	1499.00	0.82	0.79	0.88	0.79	395.00	354.50	749.50	10.75	9.37	20.13
67	727.12	692.76	1419.88	0.80	0.79	0.81	0.77	363.56	346.38	709.94	9.67	9.12	18.79
80	798.00	775.00	1573.00	0.82	0.81	0.89	0.86	399.00	387.50	786.50	10.90	10.49	21.39
81	750.12	705.31	1455.43	0.80	0.79	0.83	0.78	375.06	352.65	727.72	10.06	9.32	19.37
82	553.00	458.00	1011.00	0.77	0.76	0.61	0.51	276.50	229.00	505.50	7.06	5.78	12.84
83	697.00	719.00	1416.00	0.79	0.80	0.77	0.80	348.50	359.50	708.00	9.18	9.54	18.72
84	1220.00	1117.00	2337.00	0.94	0.86	1.28	1.18	610.00	558.50	1168.50	19.09	15.97	35.06
85	866.68	810.98	1677.67	0.85	0.82	0.96	0.90	433.34	405.49	838.83	12.23	11.14	23.37

86	621.00	459.00	1080.00	0.78	0.76	0.69	0.51	310.50	229.50	540.00	8.03	5.80	13.82
87	699.55	707.66	1407.21	0.79	0.79	0.78	0.79	349.77	353.83	703.60	9.22	9.35	18.58
88	549.00	605.00	1154.00	0.77	0.77	0.61	0.67	274.50	302.50	577.00	7.01	7.79	14.80
89	744.43	669.35	1413.78	0.80	0.78	0.83	0.74	372.21	334.67	706.89	9.96	8.75	18.71
90	1176.06	1009.25	2185.30	0.90	0.79	1.24	1.06	588.03	504.62	1092.65	17.67	13.36	31.03
91	1008.11	721.03	1729.15	0.46	0.40	1.12	0.80	252.03	180.26	432.29	7.79	4.78	12.57
92	807.63	688.09	1495.72	0.82	0.79	0.90	0.76	403.81	344.05	747.86	11.08	9.04	20.12
93	857.47	690.74	1548.21	0.84	0.79	0.95	0.77	428.73	345.37	774.11	12.04	9.08	21.13
94	694.26	730.88	1425.13	0.79	0.80	0.77	0.81	347.13	365.44	712.57	9.14	9.73	18.87
95	956.27	793.76	1750.03	0.89	0.82	1.06	0.88	478.14	396.88	875.02	14.24	10.82	25.06
96	658.13	629.95	1288.08	0.78	0.78	0.73	0.70	329.07	314.97	644.04	8.58	8.16	16.74
97	737.10	608.74	1345.85	0.80	0.77	0.82	0.68	368.55	304.37	672.92	9.84	7.85	17.68
98	804.31	685.96	1490.27	0.82	0.79	0.89	0.76	402.16	342.98	745.14	11.02	9.01	20.02
99	612.00	542.00	1154.00	0.77	0.76	0.68	0.60	306.00	271.00	577.00	7.90	6.91	14.80
100	791.00	718.00	1509.00	0.82	0.80	0.88	0.80	395.50	359.00	754.50	10.77	9.52	20.29
101	470.00	549.00	1019.00	0.76	0.77	0.52	0.61	235.00	274.50	509.50	5.94	7.01	12.95
102	544.00	467.00	1011.00	0.77	0.76	0.60	0.52	272.00	233.50	505.50	6.94	5.90	12.84
103	545.00	466.00	1011.00	0.77	0.76	0.61	0.52	272.50	233.00	505.50	6.95	5.89	12.84
104	1225.00	1137.00	2362.00	0.94	0.87	1.29	1.20	612.50	568.50	1181.00	19.26	16.52	35.78
105	467.00	382.00	849.00	0.76	0.75	0.52	0.42	233.50	191.00	424.50	5.90	4.80	10.70
106	729.00	785.00	1514.00	0.80	0.82	0.81	0.87	364.50	392.50	757.00	9.70	10.66	20.37
107	461.00	628.00	1089.00	0.76	0.78	0.51	0.70	230.50	314.00	544.50	5.82	8.13	13.95
108	711.51	708.60	1420.11	0.40	0.40	0.79	0.79	177.88	177.15	355.03	4.71	4.68	9.39
109	451.85	370.19	822.04	0.38	0.38	0.05	0.04	112.96	92.55	205.51	2.82	2.31	5.14
112	775.27	729.07	1504.35	0.41	0.40	0.86	0.81	193.82	182.27	376.09	5.25	4.85	10.10
113	418.83	469.13	887.96	0.38	0.38	0.05	0.05	104.71	117.28	221.99	2.62	2.93	5.55
116	697.13	752.36	1449.49	0.40	0.40	0.77	0.84	174.28	188.09	362.37	4.59	5.05	9.64
120	675.80	768.14	1443.94	0.39	0.40	0.75	0.85	168.95	192.03	360.98	4.43	5.18	9.61
124	793.00	805.49	1598.49	0.82	0.82	0.88	0.89	396.50	402.75	799.25	10.81	11.04	21.85
128	710.92	652.80	1363.72	0.79	0.78	0.79	0.73	355.46	326.40	681.86	9.41	8.50	17.90

132	686.03	753.87	1439.90	0.79	0.81	0.76	0.84	343.01	376.94	719.95	9.01	10.12	19.13
133	796.13	855.69	1651.83	0.41	0.42	0.88	0.95	199.03	213.92	412.96	5.43	6.00	11.44
134	402.03	406.37	808.40	0.38	0.38	0.04	0.05	100.51	101.59	202.10	2.51	2.54	5.05
135	749.02	932.76	1681.78	0.40	0.44	0.83	1.04	187.25	233.19	420.44	5.02	6.84	11.86
136	489.85	581.25	1071.10	0.38	0.38	0.05	0.06	122.46	145.31	267.78	3.06	3.63	6.69
137	1025.05	872.58	1897.63	0.47	0.42	1.14	0.97	256.26	218.15	474.41	8.02	6.18	14.20
138	657.27	640.19	1297.46	0.38	0.38	0.07	0.07	164.32	160.05	324.36	4.11	4.00	8.11
139	873.60	875.99	1749.58	0.37	0.42	0.92	0.92	218.40	219.00	437.40	5.37	6.15	11.52
140	614.61	475.61	1090.21	0.38	0.38	0.07	0.05	153.65	118.90	272.55	3.84	2.97	6.81
142	612.24	554.91	1167.14	0.38	0.38	0.07	0.06	153.06	138.73	291.79	3.83	3.47	7.29
143	890.94	650.89	1541.83	0.43	0.39	0.99	0.72	222.74	162.72	385.46	6.37	4.23	10.61
144	354.33	401.35	755.68	0.38	0.38	0.04	0.04	88.58	100.34	188.92	2.21	2.51	4.72
145	1182.08	890.70	2072.77	0.45	0.42	1.24	0.94	295.52	222.67	518.19	8.93	6.29	15.22

Table C. Trip Assignment Result From TransCAD: After 3 Model

ID	AB_Flow	BA_Flow	Tot_Flow	AB_Time	BA_Time	AB_VOC	BA_VOC	AB_VMT	BA_VMT	Tot_VMT	AB_VHT	BA_VHT	Tot_VHT
1	777.00	779.00	1556.00	0.81	0.81	0.86	0.87	388.50	389.50	778.00	10.52	10.56	21.08
6	778.78	527.80	1306.57	0.81	0.76	0.87	0.59	389.39	263.90	653.29	10.55	6.71	17.27
7	538.00	461.00	999.00	0.76	0.76	0.60	0.51	269.00	230.50	499.50	6.85	5.82	12.68
8	622.00	535.00	1157.00	0.78	0.76	0.69	0.59	311.00	267.50	578.50	8.04	6.81	14.85
9	727.56	627.54	1355.11	0.40	0.39	0.81	0.70	181.89	156.89	338.78	4.84	4.06	8.90
11	794.85	845.47	1640.32	0.41	0.42	0.88	0.94	198.71	211.37	410.08	5.42	5.90	11.32
13	574.88	592.68	1167.56	0.77	0.77	0.64	0.66	287.44	296.34	583.78	7.37	7.62	14.98
14	719.53	713.80	1433.33	0.80	0.79	0.80	0.79	359.76	356.90	716.66	9.55	9.45	19.00
17	800.14	865.27	1665.41	0.82	0.85	0.89	0.96	400.07	432.64	832.71	10.94	12.20	23.14
18	683.30	799.95	1483.25	0.79	0.82	0.76	0.89	341.65	399.97	741.62	8.97	10.94	19.90
19	797.90	850.12	1648.01	0.82	0.84	0.89	0.94	398.95	425.06	824.01	10.90	11.90	22.79
20	695.00	793.00	1488.00	0.79	0.82	0.77	0.88	347.50	396.50	744.00	9.15	10.81	19.96
21	743.15	682.58	1425.73	0.80	0.79	0.83	0.76	371.57	341.29	712.86	9.94	8.96	18.89
22	672.68	582.43	1255.11	0.79	0.77	0.75	0.65	336.34	291.22	627.56	8.80	7.47	16.27
23	611.69	649.53	1261.23	0.77	0.78	0.68	0.72	305.85	324.77	630.61	7.89	8.45	16.34
24	722.32	611.65	1333.96	0.80	0.77	0.80	0.68	361.16	305.82	666.98	9.59	7.89	17.48
25	743.11	644.86	1387.97	0.80	0.78	0.83	0.72	371.55	322.43	693.99	9.94	8.38	18.32
26	892.74	783.25	1675.99	0.86	0.81	0.99	0.87	446.37	391.62	837.99	12.78	10.63	23.41
29	956.69	1157.84	2114.52	0.77	0.89	1.01	1.22	478.34	578.92	1057.26	12.27	17.12	29.39
32	954.42	810.31	1764.73	0.89	0.82	1.06	0.90	477.21	405.15	882.37	14.19	11.13	25.32
33	630.37	758.51	1388.88	0.78	0.81	0.70	0.84	315.18	379.26	694.44	8.16	10.20	18.36
34	1121.03	971.39	2092.42	0.86	0.78	1.18	1.02	560.51	485.70	1046.21	16.08	12.56	28.64
35	728.13	699.41	1427.54	0.80	0.79	0.81	0.78	364.06	349.71	713.77	9.69	9.22	18.91
36	678.39	704.98	1383.37	0.79	0.79	0.75	0.78	339.19	352.49	691.68	8.89	9.31	18.20
37	722.54	750.53	1473.07	0.80	0.80	0.80	0.83	361.27	375.26	736.54	9.59	10.06	19.66

38	699.46	603.86	1303.32	0.79	0.77	0.78	0.67	349.73	301.93	651.66	9.22	7.78	17.00
39	615.89	724.56	1340.45	0.77	0.80	0.68	0.81	307.94	362.28	670.22	7.95	9.63	17.58
40	628.65	745.05	1373.70	0.78	0.80	0.70	0.83	314.33	372.52	686.85	8.14	9.97	18.11
41	744.04	879.05	1623.09	0.80	0.85	0.83	0.98	372.02	439.53	811.55	9.95	12.49	22.44
42	862.66	816.45	1679.11	0.84	0.83	0.96	0.91	431.33	408.22	839.56	12.15	11.24	23.39
43	787.87	959.55	1747.42	0.82	0.90	0.88	1.07	393.93	479.77	873.71	10.72	14.32	25.03
44	1383.30	1037.77	2421.08	1.12	0.81	1.46	1.09	691.65	518.89	1210.54	25.73	13.99	39.73
46	818.58	874.15	1692.73	0.83	0.85	0.91	0.97	409.29	437.08	846.37	11.28	12.39	23.67
47	846.05	712.54	1558.59	0.84	0.79	0.94	0.79	423.03	356.27	779.29	11.81	9.43	21.25
48	1222.00	1204.00	2426.00	0.94	0.92	1.29	1.27	611.00	602.00	1213.00	19.15	18.55	37.71
49	618.00	458.00	1076.00	0.78	0.76	0.69	0.51	309.00	229.00	538.00	7.98	5.78	13.77
50	704.00	707.00	1411.00	0.79	0.79	0.78	0.79	352.00	353.50	705.50	9.29	9.34	18.64
52	1049.82	1085.40	2135.22	0.82	0.84	1.11	1.14	524.91	542.70	1067.61	14.27	15.14	29.42
53	669.03	750.46	1419.49	0.78	0.80	0.74	0.83	334.51	375.23	709.74	8.75	10.06	18.81
54	1046.60	1026.66	2073.26	0.81	0.80	1.10	1.08	523.30	513.33	1036.63	14.20	13.74	27.94
56	1091.98	1214.83	2306.80	0.84	0.93	1.15	1.28	545.99	607.41	1153.40	15.31	18.91	34.22
58	1091.75	1196.54	2288.29	0.42	0.52	1.15	1.26	272.94	299.14	572.07	7.65	10.44	18.09
59	1301.47	974.00	2275.48	0.51	0.44	1.37	1.03	325.37	243.50	568.87	11.05	7.19	18.24
60	852.34	832.81	1685.15	0.42	0.42	0.95	0.93	213.08	208.20	421.29	5.97	5.78	11.75
61	1045.75	1095.10	2140.85	0.81	0.84	1.10	1.15	522.87	547.55	1070.43	14.18	15.39	29.57
62	1196.00	1215.00	2411.00	0.92	0.93	1.26	1.28	598.00	607.50	1205.50	18.30	18.92	37.21
63	739.87	636.71	1376.57	0.80	0.78	0.82	0.71	369.93	318.35	688.29	9.88	8.26	18.14
64	724.37	677.45	1401.83	0.80	0.79	0.80	0.75	362.19	338.73	700.91	9.62	8.88	18.50
65	761.83	743.80	1505.63	0.81	0.80	0.85	0.83	380.92	371.90	752.81	10.26	9.95	20.20
66	790.00	709.00	1499.00	0.82	0.79	0.88	0.79	395.00	354.50	749.50	10.75	9.37	20.13
67	747.11	757.31	1504.43	0.80	0.81	0.83	0.84	373.56	378.66	752.21	10.00	10.18	20.18
80	798.00	775.00	1573.00	0.82	0.81	0.89	0.86	399.00	387.50	786.50	10.90	10.49	21.39
81	772.33	703.64	1475.97	0.81	0.79	0.86	0.78	386.16	351.82	737.98	10.44	9.29	19.73
82	553.00	458.00	1011.00	0.77	0.76	0.61	0.51	276.50	229.00	505.50	7.06	5.78	12.84
83	697.00	719.00	1416.00	0.79	0.80	0.77	0.80	348.50	359.50	708.00	9.18	9.54	18.72

84	1220.00	1117.00	2337.00	0.94	0.86	1.28	1.18	610.00	558.50	1168.50	19.09	15.97	35.06
85	872.70	796.79	1669.49	0.85	0.82	0.97	0.89	436.35	398.39	834.74	12.36	10.88	23.23
86	621.00	459.00	1080.00	0.78	0.76	0.69	0.51	310.50	229.50	540.00	8.03	5.80	13.82
87	694.16	761.20	1455.36	0.79	0.81	0.77	0.85	347.08	380.60	727.68	9.14	10.25	19.38
88	549.00	605.00	1154.00	0.77	0.77	0.61	0.67	274.50	302.50	577.00	7.01	7.79	14.80
89	759.24	685.59	1444.83	0.81	0.79	0.84	0.76	379.62	342.79	722.41	10.21	9.00	19.21
90	1211.25	965.30	2176.55	0.93	0.77	1.28	1.02	605.63	482.65	1088.28	18.79	12.44	31.23
91	965.92	768.27	1734.19	0.45	0.40	1.07	0.85	241.48	192.07	433.55	7.24	5.18	12.42
92	775.04	669.87	1444.91	0.81	0.78	0.86	0.74	387.52	334.94	722.45	10.49	8.76	19.25
93	732.11	691.48	1423.59	0.80	0.79	0.81	0.77	366.06	345.74	711.80	9.75	9.10	18.85
94	669.24	727.50	1396.74	0.78	0.80	0.74	0.81	334.62	363.75	698.37	8.75	9.68	18.43
95	892.77	816.48	1709.26	0.86	0.83	0.99	0.91	446.39	408.24	854.63	12.78	11.24	24.02
96	668.13	663.81	1331.94	0.78	0.78	0.74	0.74	334.06	331.91	665.97	8.73	8.67	17.40
97	706.23	631.97	1338.20	0.79	0.78	0.78	0.70	353.11	315.99	669.10	9.33	8.19	17.52
98	783.51	709.71	1493.23	0.81	0.79	0.87	0.79	391.76	354.86	746.61	10.64	9.39	20.02
99	612.00	542.00	1154.00	0.77	0.76	0.68	0.60	306.00	271.00	577.00	7.90	6.91	14.80
100	791.00	718.00	1509.00	0.82	0.80	0.88	0.80	395.50	359.00	754.50	10.77	9.52	20.29
101	470.00	549.00	1019.00	0.76	0.77	0.52	0.61	235.00	274.50	509.50	5.94	7.01	12.95
102	544.00	467.00	1011.00	0.77	0.76	0.60	0.52	272.00	233.50	505.50	6.94	5.90	12.84
103	545.00	466.00	1011.00	0.77	0.76	0.61	0.52	272.50	233.00	505.50	6.95	5.89	12.84
104	1225.00	1137.00	2362.00	0.94	0.87	1.29	1.20	612.50	568.50	1181.00	19.26	16.52	35.78
105	467.00	382.00	849.00	0.76	0.75	0.52	0.42	233.50	191.00	424.50	5.90	4.80	10.70
106	729.00	785.00	1514.00	0.80	0.82	0.81	0.87	364.50	392.50	757.00	9.70	10.66	20.37
107	461.00	628.00	1089.00	0.76	0.78	0.51	0.70	230.50	314.00	544.50	5.82	8.13	13.95
108	746.50	730.09	1476.59	0.40	0.40	0.83	0.81	186.62	182.52	369.15	5.00	4.86	9.86
109	424.89	357.86	782.74	0.38	0.38	0.05	0.04	106.22	89.46	195.69	2.66	2.24	4.89
112	703.00	682.10	1385.10	0.40	0.39	0.78	0.76	175.75	170.52	346.27	4.64	4.47	9.11
113	470.30	468.92	939.22	0.38	0.38	0.05	0.05	117.57	117.23	234.80	2.94	2.93	5.87
116	689.91	728.35	1418.26	0.39	0.40	0.77	0.81	172.48	182.09	354.57	4.54	4.85	9.38
120	636.96	760.04	1397.00	0.39	0.40	0.71	0.84	159.24	190.01	349.25	4.13	5.11	9.24

124	709.80	710.06	1419.86	0.79	0.79	0.79	0.79	354.90	355.03	709.93	9.39	9.39	18.78
128	705.05	714.35	1419.40	0.79	0.79	0.78	0.79	352.53	357.17	709.70	9.31	9.46	18.77
132	768.54	797.43	1565.97	0.81	0.82	0.85	0.89	384.27	398.72	782.99	10.37	10.89	21.26
133	741.28	839.26	1580.54	0.40	0.42	0.82	0.93	185.32	209.81	395.13	4.95	5.84	10.79
134	375.86	435.40	811.26	0.38	0.38	0.04	0.05	93.97	108.85	202.82	2.35	2.72	5.07
135	727.81	930.94	1658.75	0.40	0.44	0.81	1.03	181.95	232.73	414.69	4.84	6.82	11.66
136	526.09	606.13	1132.22	0.38	0.38	0.06	0.07	131.52	151.53	283.05	3.29	3.79	7.08
137	928.96	753.40	1682.36	0.44	0.40	1.03	0.84	232.24	188.35	420.59	6.79	5.06	11.85
138	674.16	598.62	1272.78	0.38	0.38	0.07	0.07	168.54	149.65	318.19	4.21	3.74	7.95
139	1037.07	1011.33	2048.40	0.40	0.45	1.09	1.06	259.27	252.83	512.10	6.99	7.64	14.63
140	583.86	453.32	1037.18	0.38	0.38	0.06	0.05	145.96	113.33	259.30	3.65	2.83	6.48
142	542.34	502.50	1044.84	0.38	0.38	0.06	0.06	135.58	125.62	261.21	3.39	3.14	6.53
143	788.07	663.17	1451.24	0.41	0.39	0.88	0.74	197.02	165.79	362.81	5.36	4.33	9.69
144	403.50	476.26	879.76	0.38	0.38	0.04	0.05	100.88	119.06	219.94	2.52	2.98	5.50
145	1190.03	822.72	2012.75	0.46	0.41	1.25	0.87	297.51	205.68	503.19	9.05	5.65	14.70

Table D. Trip Assignment Result from TransCAD: After 4 Model

ID	AB_Flow	BA_Flow	Tot_Flow	AB_Time	BA_Time	AB_VOC	BA_VOC	AB_VMT	BA_VMT	Tot_VMT	AB_VHT	BA_VHT	Tot_VHT
1	777.00	779.00	1556.00	0.81	0.81	0.86	0.87	388.50	389.50	778.00	10.52	10.56	21.08
6	787.33	532.70	1320.03	0.82	0.76	0.87	0.59	393.67	266.35	660.01	10.71	6.78	17.49
7	538.00	461.00	999.00	0.76	0.76	0.60	0.51	269.00	230.50	499.50	6.85	5.82	12.68
8	622.00	535.00	1157.00	0.78	0.76	0.69	0.59	311.00	267.50	578.50	8.04	6.81	14.85
9	796.97	670.12	1467.09	0.41	0.39	0.89	0.74	199.24	167.53	366.77	5.44	4.38	9.82
11	783.19	846.90	1630.10	0.41	0.42	0.87	0.94	195.80	211.73	407.52	5.32	5.92	11.23
13	535.31	591.54	1126.84	0.76	0.77	0.59	0.66	267.65	295.77	563.42	6.82	7.60	14.42
14	735.33	702.82	1438.15	0.80	0.79	0.82	0.78	367.66	351.41	719.07	9.81	9.28	19.08
17	810.76	867.27	1678.03	0.82	0.85	0.90	0.96	405.38	433.64	839.02	11.14	12.24	23.38
18	708.08	787.23	1495.30	0.79	0.82	0.79	0.87	354.04	393.61	747.65	9.36	10.70	20.06
19	817.15	827.29	1644.44	0.83	0.83	0.91	0.92	408.58	413.64	822.22	11.26	11.45	22.70
20	695.00	793.00	1488.00	0.79	0.82	0.77	0.88	347.50	396.50	744.00	9.15	10.81	19.96
21	747.44	691.87	1439.32	0.80	0.79	0.83	0.77	373.72	345.94	719.66	10.01	9.10	19.11
22	652.35	631.21	1283.56	0.78	0.78	0.72	0.70	326.17	315.60	641.78	8.49	8.18	16.67
23	626.64	637.50	1264.13	0.78	0.78	0.70	0.71	313.32	318.75	632.07	8.11	8.27	16.38
24	735.36	621.90	1357.26	0.80	0.78	0.82	0.69	367.68	310.95	678.63	9.81	8.04	17.85
25	739.34	643.32	1382.67	0.80	0.78	0.82	0.71	369.67	321.66	691.33	9.87	8.36	18.23
26	836.28	798.11	1634.39	0.83	0.82	0.93	0.89	418.14	399.06	817.20	11.62	10.90	22.52
29	993.34	1124.91	2118.25	0.79	0.86	1.05	1.18	496.67	562.46	1059.13	13.02	16.19	29.20
32	1017.50	796.64	1814.15	0.93	0.82	1.13	0.89	508.75	398.32	907.07	15.84	10.87	26.71
33	644.96	803.73	1448.69	0.78	0.82	0.72	0.89	322.48	401.87	724.35	8.38	11.01	19.39
34	1067.59	958.66	2026.26	0.83	0.77	1.12	1.01	533.80	479.33	1013.13	14.70	12.31	27.01
35	690.49	702.87	1393.36	0.79	0.79	0.77	0.78	345.24	351.44	696.68	9.08	9.28	18.36
36	683.50	741.66	1425.15	0.79	0.80	0.76	0.82	341.75	370.83	712.58	8.97	9.91	18.88
37	729.85	761.48	1491.33	0.80	0.81	0.81	0.85	364.92	380.74	745.66	9.71	10.25	19.97

38	720.85	631.47	1352.32	0.80	0.78	0.80	0.70	360.43	315.73	676.16	9.57	8.18	17.75
39	615.98	727.43	1343.41	0.77	0.80	0.68	0.81	307.99	363.72	671.70	7.95	9.67	17.63
40	622.62	768.58	1391.20	0.78	0.81	0.69	0.85	311.31	384.29	695.60	8.05	10.37	18.42
41	751.78	910.12	1661.90	0.80	0.87	0.84	1.01	375.89	455.06	830.95	10.08	13.16	23.24
42	846.19	819.94	1666.13	0.84	0.83	0.94	0.91	423.09	409.97	833.07	11.82	11.31	23.13
43	826.16	968.57	1794.72	0.83	0.90	0.92	1.08	413.08	484.28	897.36	11.43	14.54	25.97
44	1352.86	981.92	2334.78	1.08	0.78	1.42	1.03	676.43	490.96	1167.39	24.30	12.78	37.08
46	853.09	917.38	1770.47	0.84	0.87	0.95	1.02	426.55	458.69	885.23	11.95	13.32	25.28
47	813.19	682.34	1495.53	0.82	0.79	0.90	0.76	406.60	341.17	747.76	11.18	8.95	20.13
48	1222.00	1204.00	2426.00	0.94	0.92	1.29	1.27	611.00	602.00	1213.00	19.15	18.55	37.71
49	618.00	458.00	1076.00	0.78	0.76	0.69	0.51	309.00	229.00	538.00	7.98	5.78	13.77
50	704.00	707.00	1411.00	0.79	0.79	0.78	0.79	352.00	353.50	705.50	9.29	9.34	18.64
52	980.13	1090.38	2070.51	0.78	0.84	1.03	1.15	490.06	545.19	1035.26	12.74	15.27	28.01
53	697.66	727.75	1425.41	0.79	0.80	0.78	0.81	348.83	363.87	712.70	9.19	9.68	18.87
54	936.12	1053.95	1990.06	0.76	0.82	0.99	1.11	468.06	526.97	995.03	11.87	14.37	26.24
56	1058.93	1250.13	2309.05	0.82	0.97	1.11	1.32	529.46	625.06	1154.53	14.49	20.14	34.63
58	1010.80	1164.39	2175.19	0.40	0.51	1.06	1.23	252.70	291.10	543.80	6.70	9.87	16.57
59	1243.93	910.59	2154.52	0.48	0.43	1.31	0.96	310.98	227.65	538.63	9.96	6.50	16.46
60	850.84	886.36	1737.20	0.42	0.43	0.95	0.98	212.71	221.59	434.30	5.95	6.32	12.28
61	1025.15	1087.13	2112.29	0.80	0.84	1.08	1.14	512.58	543.57	1056.14	13.71	15.19	28.89
62	1196.00	1215.00	2411.00	0.92	0.93	1.26	1.28	598.00	607.50	1205.50	18.30	18.92	37.21
63	794.67	706.80	1501.46	0.82	0.79	0.88	0.79	397.33	353.40	750.73	10.84	9.34	20.18
64	779.10	672.33	1451.43	0.81	0.79	0.87	0.75	389.55	336.16	725.71	10.56	8.80	19.36
65	781.83	731.96	1513.79	0.81	0.80	0.87	0.81	390.92	365.98	756.90	10.61	9.75	20.36
66	790.00	709.00	1499.00	0.82	0.79	0.88	0.79	395.00	354.50	749.50	10.75	9.37	20.13
67	766.32	747.14	1513.46	0.81	0.80	0.85	0.83	383.16	373.57	756.73	10.33	10.00	20.34
80	798.00	775.00	1573.00	0.82	0.81	0.89	0.86	399.00	387.50	786.50	10.90	10.49	21.39
81	738.84	672.92	1411.76	0.80	0.79	0.82	0.75	369.42	336.46	705.88	9.86	8.81	18.67
82	553.00	458.00	1011.00	0.77	0.76	0.61	0.51	276.50	229.00	505.50	7.06	5.78	12.84
83	697.00	719.00	1416.00	0.79	0.80	0.77	0.80	348.50	359.50	708.00	9.18	9.54	18.72

84	1220.00	1117.00	2337.00	0.94	0.86	1.28	1.18	610.00	558.50	1168.50	19.09	15.97	35.06
85	843.06	801.01	1644.07	0.84	0.82	0.94	0.89	421.53	400.50	822.03	11.76	10.95	22.71
86	621.00	459.00	1080.00	0.78	0.76	0.69	0.51	310.50	229.50	540.00	8.03	5.80	13.82
87	677.64	729.92	1407.56	0.79	0.80	0.75	0.81	338.82	364.96	703.78	8.88	9.72	18.60
88	549.00	605.00	1154.00	0.77	0.77	0.61	0.67	274.50	302.50	577.00	7.01	7.79	14.80
89	694.59	655.55	1350.14	0.79	0.78	0.77	0.73	347.30	327.77	675.07	9.14	8.54	17.68
90	1145.97	948.64	2094.61	0.88	0.77	1.21	1.00	572.98	474.32	1047.30	16.78	12.11	28.89
91	961.18	752.25	1713.43	0.45	0.40	1.07	0.84	240.29	188.06	428.36	7.18	5.05	12.23
92	755.03	664.48	1419.52	0.81	0.78	0.84	0.74	377.52	332.24	709.76	10.14	8.68	18.82
93	776.36	691.06	1467.42	0.81	0.79	0.86	0.77	388.18	345.53	733.71	10.51	9.09	19.60
94	696.26	755.26	1451.52	0.79	0.81	0.77	0.84	348.13	377.63	725.76	9.17	10.14	19.31
95	905.07	808.33	1713.41	0.87	0.82	1.01	0.90	452.54	404.17	856.70	13.05	11.09	24.14
96	696.60	689.52	1386.12	0.79	0.79	0.77	0.77	348.30	344.76	693.06	9.18	9.06	18.24
97	756.41	633.58	1390.00	0.81	0.78	0.84	0.70	378.21	316.79	695.00	10.16	8.21	18.37
98	793.31	690.14	1483.45	0.82	0.79	0.88	0.77	396.66	345.07	741.73	10.81	9.07	19.89
99	612.00	542.00	1154.00	0.77	0.76	0.68	0.60	306.00	271.00	577.00	7.90	6.91	14.80
100	791.00	718.00	1509.00	0.82	0.80	0.88	0.80	395.50	359.00	754.50	10.77	9.52	20.29
101	470.00	549.00	1019.00	0.76	0.77	0.52	0.61	235.00	274.50	509.50	5.94	7.01	12.95
102	544.00	467.00	1011.00	0.77	0.76	0.60	0.52	272.00	233.50	505.50	6.94	5.90	12.84
103	545.00	466.00	1011.00	0.77	0.76	0.61	0.52	272.50	233.00	505.50	6.95	5.89	12.84
104	1225.00	1137.00	2362.00	0.94	0.87	1.29	1.20	612.50	568.50	1181.00	19.26	16.52	35.78
105	467.00	382.00	849.00	0.76	0.75	0.52	0.42	233.50	191.00	424.50	5.90	4.80	10.70
106	729.00	785.00	1514.00	0.80	0.82	0.81	0.87	364.50	392.50	757.00	9.70	10.66	20.37
107	461.00	628.00	1089.00	0.76	0.78	0.51	0.70	230.50	314.00	544.50	5.82	8.13	13.95
108	760.53	700.25	1460.78	0.40	0.40	0.85	0.78	190.13	175.06	365.20	5.12	4.62	9.73
109	446.40	322.41	768.81	0.38	0.38	0.05	0.04	111.60	80.60	192.20	2.79	2.02	4.81
112	728.46	742.92	1471.39	0.40	0.40	0.81	0.83	182.12	185.73	367.85	4.85	4.97	9.81
113	456.89	435.83	892.72	0.38	0.38	0.05	0.05	114.22	108.96	223.18	2.86	2.72	5.58
116	745.51	708.29	1453.80	0.40	0.40	0.83	0.79	186.38	177.07	363.45	4.99	4.68	9.67
120	659.41	729.71	1389.12	0.39	0.40	0.73	0.81	164.85	182.43	347.28	4.30	4.86	9.16

124	766.89	785.40	1552.29	0.81	0.82	0.85	0.87	383.45	392.70	776.15	10.34	10.67	21.02
128	708.36	674.54	1382.89	0.79	0.79	0.79	0.75	354.18	337.27	691.45	9.36	8.83	18.19
132	696.80	765.84	1462.64	0.79	0.81	0.77	0.85	348.40	382.92	731.32	9.18	10.33	19.51
133	746.13	851.81	1597.94	0.40	0.42	0.83	0.95	186.53	212.95	399.48	4.99	5.96	10.96
134	334.88	477.77	812.65	0.38	0.38	0.04	0.05	83.72	119.44	203.16	2.09	2.99	5.08
135	769.31	942.35	1711.66	0.41	0.44	0.85	1.05	192.33	235.59	427.91	5.19	6.95	12.14
136	553.50	656.25	1209.75	0.38	0.38	0.06	0.07	138.38	164.06	302.44	3.46	4.10	7.56
137	986.25	734.76	1721.01	0.46	0.40	1.10	0.82	246.56	183.69	430.25	7.50	4.90	12.40
138	666.22	541.57	1207.79	0.38	0.38	0.07	0.06	166.56	135.39	301.95	4.16	3.38	7.55
139	938.74	971.96	1910.70	0.38	0.44	0.99	1.02	234.69	242.99	477.68	5.96	7.17	13.13
140	618.52	498.14	1116.66	0.38	0.38	0.07	0.06	154.63	124.54	279.16	3.87	3.11	6.98
142	499.90	523.72	1023.63	0.38	0.38	0.06	0.06	124.98	130.93	255.91	3.12	3.27	6.40
143	823.56	633.25	1456.81	0.41	0.39	0.92	0.70	205.89	158.31	364.20	5.69	4.10	9.79
144	424.69	443.31	867.99	0.38	0.38	0.05	0.05	106.17	110.83	217.00	2.65	2.77	5.42
145	1153.83	844.31	1998.14	0.44	0.42	1.21	0.89	288.46	211.08	499.53	8.50	5.85	14.35

Table E. Control Delay Results from Synchro: After 1-4 Models

Model	**Before**		**After 1**			**After 2**			**After 3**			**After 4**		
Node	Natural Cycle	Control Delay	Natural Ccycle	Control Delay	Difference 1	Natural Cycle	Control Delay	Difference 2	Natural Cycle	Control Delay	Difference 3	Natural Cycle	Control Delay	Difference 4
14	100	23.2	85	17.3	-5.9	85	17.7	-5.5	85	16.9	-6.3	100	22.5	-0.7
15	95	28.7	95	28.6	-0.1	95	23.6	-5.1	95	29.6	0.9	95	30.4	1.7
21	100	30.5	100	26.8	-3.7	100	28.9	-1.6	100	27.9	-2.6	100	28.9	-1.6
23	100	23.2	100	24.5	1.3	100	20.7	-2.5	100	22.6	-0.6	100	21.5	-1.7
24	100	28.2	100	28.9	0.7	100	30.7	2.5	100	30.7	2.5	100	28.7	0.5
28	100	27.5	100	29	1.5	100	33.1	5.6	100	27.9	0.4	100	31.5	4
29	100	34.5	100	41.5	7	100	33.8	-0.7	110	37.8	3.3	100	39.8	5.3
32	100	28.1	100	31.9	3.8	100	30.4	2.3	100	29.9	1.8	100	27.2	-0.9
35	100	28	85	20.7	-7.3	75	17.4	-10.6	85	24	-4	100	33.8	5.8
36	100	28.6	85	19.3	-9.3	75	17.4	-11.2	85	24.2	-4.4	100	32.6	4
47	100	25.4	85	18.4	-7	85	19.8	-5.6	85	15.3	-10.1	100	27.3	1.9
48	100	33.8	100	32.8	-1	100	31.8	-2	100	34.8	1	100	32.8	-1
49	100	25.5	75	12.6	-12.9	85	17.6	-7.9	85	27	1.5	100	30.1	4.6
51	100	26.7	85	20.5	-6.2	85	22	-4.7	85	24.2	-2.5	85	19.1	-7.6
53	100	27.9	100	35	7.1	100	26.7	-1.2	100	34.8	6.9	100	33.1	5.2
54	100	26.9	85	18.2	-8.7	85	18	-8.9	85	16.5	-10.4	100	25.9	-1
61	100	27.3	100	27.7	0.4	100	27.9	0.6	100	27.1	-0.2	100	27.7	0.4
63	100	29.3	100	30.9	1.6	100	26.1	-3.2	100	29	-0.3	100	28.7	-0.6
64	100	31.5	100	36.7	5.2	100	25.9	-5.6	100	35	3.5	100	30.3	-1.2
67	100	27.1	100	28.4	1.3	100	32.8	5.7	100	28.3	1.2	100	28.2	1.1
68	100	30.7	100	29.4	-1.3	100	44.3	13.6	100	27.2	-3.5	100	29.6	-1.1

72	100	25.9	85	17.3	-8.6	75	14.2	-11.7	85	20.7	-5.2	100	28.5	2.6
74	100	29.3	85	20.7	-8.6	75	13.3	-16	85	25.5	-3.8	100	36.2	6.9
75	100	27.3	85	19.7	-7.6	85	23.7	-3.6	75	17.9	-9.4	85	18.8	-8.5
76	100	28.3	100	30.6	2.3	100	32.8	4.5	100	31.9	3.6	100	30	1.7
77	100	26.8	85	22.1	-4.7	85	22.5	-4.3	75	14.4	-12.4	85	20.8	-6
190	100	30.2	100	28.5	-1.7	100	34.7	4.5	100	30.8	0.6	100	30.7	0.5
222	100	25.7	85	15.6	-10.1	85	21.1	-4.6	85	15.7	-10	100	25.2	-0.5
501	100	31	85	24.9	-6.1	85	23.1	-7.9	85	19.2	-11.8	85	18.6	-12.4
555	100	27	100	27.7	0.7	100	25.8	-1.2	100	27.3	0.3	100	27.9	0.9
666	100	28.4	100	26.1	-2.3	100	30.7	2.3	100	25.7	-2.7	100	24.9	-3.5
1000	100	23.6	85	18.3	-5.3	85	18.9	-4.7	85	19	-4.6	100	25	1.4
1022	100	20.5	85	15	-5.5	85	14.6	-5.9	85	15.3	-5.2	100	22.7	2.2
3000	100	34.4	100	29.5	-4.9	120	41.9	7.5	100	28.8	-5.6	100	28.1	-6.3
4000	100	38.6	110	40.3	1.7	120	37.5	-1.1	100	37.6	-1	120	36.7	-1.9
6000	100	24.6	85	18.8	-5.8	85	17.7	-6.9	85	17.5	-7.1	100	25.9	1.3