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Analysis of methods for assigning capacity in a transportation planning network

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ANALYSIS OF METHODS FOR ASSIGNING CAPACITY IN A TRANSPORTATION PLANNING NETWORK

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ABSTRACT

The objective of the research was to analyze the current practice of assigning capacity values to links of a network and to determine how capacity can be assigned more accurately without greatly increasing time, effort and costs.

Currently in most planning networks, the link capacities are assigned based on the number of lanes and a gross facility and area type considerations (LSU, 1997). This practice might have affected the results of travel demand modeling performed using the network. To test this hypothesis, the current practice was compared to the practice of assigning capacities link-by-link using the Highway Capacity Manual (HCM) methodology. Significant differences were found in travel volumes, travel times, travel speeds and volume to capacity ratios, which resulted from travel demand modeling. It was therefore concluded that the current practice of assigning capacity values was not accurate because it affected the results of modeling.

Calculating and assigning capacities link-by-link would involve time, effort and costs if all HCM adjustment factors were to be estimated. Therefore, the thesis attempted to determine if the effects of some or all adjustment factors could be ignored while assigning capacities link-by-link to reduce data collection effort. However, when the results of travel demand modeling with these capacity values was compared to corresponding results where capacity was calculated using all HCM adjustment factors, significant differences were observed. Therefore, the study failed to make any conclusions on whether the effects of adjustment factors could be ignored to reduce data collection effort, without greatly affecting the accuracy of modeling. The results of this study provided insights on how capacities could be assigned more accurately to links of a

planning network. It could also provide insights to further studies on how data collection effort could be reduced for estimating and assigning capacity values to links.

CHAPTER 1. INTRODUCTION

1.1 Background

The process of travel demand modeling is one of the key components in the planning and development of transportation systems for cities in the Unites States (US). This is also referred to as the Urban Transportation Planning Process (UTPP). UTPP traditionally incorporates four steps: trip generation, trip distribution, mode-choice and traffic assignment. The output from the modeling process is a future forecast of directional traffic volumes and travel times on each street in a planning area. Recent advances in computer technologies like Geographic Information Systems (GIS) have allowed planners to conduct travel demand modeling forecasts with increasing levels of speed, accuracy, and repeatability.

Travel demand modeling in Baton Rouge, Louisiana is conducted using GIS techniques by the Baton Rouge Metropolitan Planning Organization (MPO). They worked with a local consultant, to develop a digital representation of the network of streets and highways in the city. They have also divided the Baton Rouge area into zones called Travel Analysis Zones (TAZ) and represented them in the form of another digital map. The GIS used for modeling comprises of the Baton Rouge network, Baton Rouge TAZs and the TranPlan software for the four step modeling process. The significant advantage of using a GIS is that it allows the storage, retrieval, manipulation and display of spatial information on networks and zones.

The street network is modeled as a system of nodes and links. Nodes typically represent junctions of roads and links represent homogenous segments of roads between the nodes (Ortuzar and Willumsen, 1994). Each link stores data such as distance, directional travel speed and time, facility type, capacity etc. This data is used as input for modeling. However, despite the advantages that the network brings to the modeling process, it suffers from a major drawback because of the way capacity values are assigned to it.

1.2 Problem Statement

Presently, the network link capacities are average values that have been assigned to the links based on just the number of lanes and a gross facility type consideration (LSU, 1997). For example, all two–lane undivided arterial links were assigned capacities of 550 vehicles per hour (vph) and all four-lane undivided arterial links 1,150 vph in each direction. The capacity values were not assigned on a link-by-link basis because of the enormous data collection effort required. The practice of assigning average capacity values is also common to other networks and is considered inaccurate, for a number of reasons described below.

Past research has shown that the capacity of a link depends on several factors including geometric conditions, traffic conditions and signalization parameters in addition to just the facility type (TRB, 2000). Also the network of an urban area consists of primarily arterial links and the capacity of an arterial link in most cases is determined by the capacity of the intersection approach at the end of the link. A field observation of the links in the network revealed that the intersections at the end of the arterial links were either signalized or unsignalized. Therefore, different methodologies should be applied to estimate capacities of signalized and unsignalized links, even though they are of the same facility type.

The current practice of assigning average values may also affect the accuracy of the results of the traffic assignment procedure performed. This is because the common methods like User Equilibrium, incorporate link capacity restraint effects while computing link flows and travel times (Caliper Corporation, 1998). Therefore, it was believed that capacities should be estimated and assigned on a link-by-link basis.

A planning network would consist of several thousands of links. Assigning capacities link-by-link would require time, effort and resources and would not be justified unless it was more accurate than the current practice of assigning average capacity values. Therefore, there was a need to examine whether assigning capacities link-by-link would produce significant differences in the results of travel demand modeling.

The effects of some factors like the number of lanes and proportion of green time are more critical for calculating link capacities than other factors like parking, grades etc. Therefore, it was worthwhile to examine whether there could be a compromise in calculating capacities link-by-link by ignoring the effects of some factors to reduce data collection effort, without significantly affecting the results of modeling.

1.3 Research Objective

The objective of the research was to analyze the current practice of assigning capacity values to a network and to determine how capacity values can be assigned more accurately without greatly increasing time, effort and costs.

1.3.1 Hypothesis

The following two hypotheses were made and tested to achieve the objectives. Assigning capacities on link-by-link basis to the network would produce significantly different results in travel demand modeling when compared to the current practice of assigning average capacity values based on just the number of lanes and facility type.

The effect of some factors can be ignored while assigning capacity values without significantly affecting the results of modeling.

1.4 Organization of the Thesis

Chapter Two provides background information for the research. It discusses the current methodologies used for capacity estimation of roadway facilities, the Baton Rouge street network and the current practices used to assign capacity to links of various networks. Chapter Three describes the methodology used in the thesis. It discusses the selection of study sites, data collection, capacity calculations, travel demand modeling with the calculated capacity values and comparison of modeling results. Chapter Four discusses the data required for the thesis, data collection method used and presents a summary of capacity calculations. Chapter Five discusses the statistical methods used to compare the results of travel demand modeling and results of comparisons. Chapter Six presents the final conclusion made from the study.

CHAPTER 2. LITERATURE REVIEW

A literature review was undertaken to review the existing methodologies to estimate capacity, the Baton Rouge street network and the current practices used by some planning organizations for assigning link capacities to their networks. The literature review was conducted in the following areas.

1. The Transport Road Research Laboratory (TRRL) capacity estimation methodology
2. The Highway Capacity Manual (HCM) capacity estimation methodology
3. The Baton Rouge street network
4. Current practices for assigning link capacities

2.1 The TRRL Capacity Estimation Methodologies

The TRRL method is the result of research conducted in the United Kingdom (U.K) for the capacity estimation of roadway facilities. Prior to the development of this method, formulae developed by Webster and Cobbe (Webster and Cobbe, 1966) were used to estimate capacity. Since then a number of factors like vehicle performance, road markings, layout practice, signal-optimizing methods etc. had changed (Kimber, McDonald and Hounsell, 1986). Several studies were conducted by researchers, under contract from TRRL to develop saturation flow and capacity estimation methodologies for signalized road junctions and major/minor priority junctions. Results of the studies have been reviewed in this section.

2.1.1 Signalized Road Junctions

The methodology for signalized road junctions estimated the saturation flow rate of a signalized intersection based on several geometric and traffic conditions. It accounted for effect of heavy vehicles using weighing factors called passenger car units (pcu). The pcu values used were obtained from a study conducted by Kimber et all (Kimber, Semmens and Shewey, 1982). Buses, heavy commercial vehicles and motorcycles had pcu's of 2, 2.3 and 0.4 respectively. The effect of wet conditions on the roadway was accounted by reducing the saturation flow rate by six percent.

The effect of turning movements on saturation flow rates was estimated using Equation (2-1).

$$S(r, f) = \frac{2080 - 140d_n}{1 + 1.5 \, f/r} \qquad (2-1)$$

Where,

f = proportion of turning vehicles

r = path radius in meters

n = nearside (left-turn) lane

δ_n= 1 for nearside lanes and 0 otherwise

S (r,f) = saturation flow rate as a function of r and f.

It was found that saturation flow rate decreased when uphill gradient increased (Kimber, McDonald and Hounsell, 1986). No significant effects were noticed for downhill gradients. To investigate the effect of lane widths, researchers regressed saturation flow rate with the difference between lane width (w_l) and an average lane width of 3.25 meters. The final equation developed to estimate saturation flow rate was Equation (2-2).

$$S(r, f, n, G, w_l) = \frac{(2080 - 140d_n - 42d_G G + 100(w_l - 3.25))}{1 + 1.5 \, f/r} \qquad (2-2)$$

Where,

G = grade in percent

δ_G = 1 for uphill sites and 0 otherwise

w_l = lane width

$S(r, f, n, G, w_l)$ = saturation flow rate as a function of r, f, n, G and w_l.

2.1.2 Major/Minor Priority Junctions

Studies were conducted (Kimber and Coobe, 1980) to estimate capacities of non-priority streams at major/minor priority junctions. It was found that the capacities depended on flow in the relevant priority streams of the major road, lane width available to the non-priority stream, visibility available to drivers on the non-priority stream and width of the major road. At dual carriage ways width of the central reserve also affected capacities. Researchers developed a set of equations to estimate capacities for three legged junctions for minor road right-turning vehicles (B-A), minor road left-turning vehicles (B-C) and major road-right turning vehicles (C-B). The flows and notations are shown in Figure 2-1 (Source: Kimber and Coombe 1980, pp29).

$$q^s_{B-A} = X_1\left[627 + 14W_{CR} - Y\left(0.364\,q_{A-C} + 0.114\,q_{A-B} + 0.229\,q_{C-A} + 0.520\,q_{C-B}\right)\right] \qquad (2-3)$$

$$q^s_{B-C} = X_2\left[745 - Y\left(0.364 q_{A-C} + 0.114 q_{A-B}\right)\right] \qquad (2-4)$$

$$q^s_{C-B} = X'_2\left[745 - 0.364Y\left(q_{A-C} + q_{A-B}\right)\right] \qquad (2-5)$$

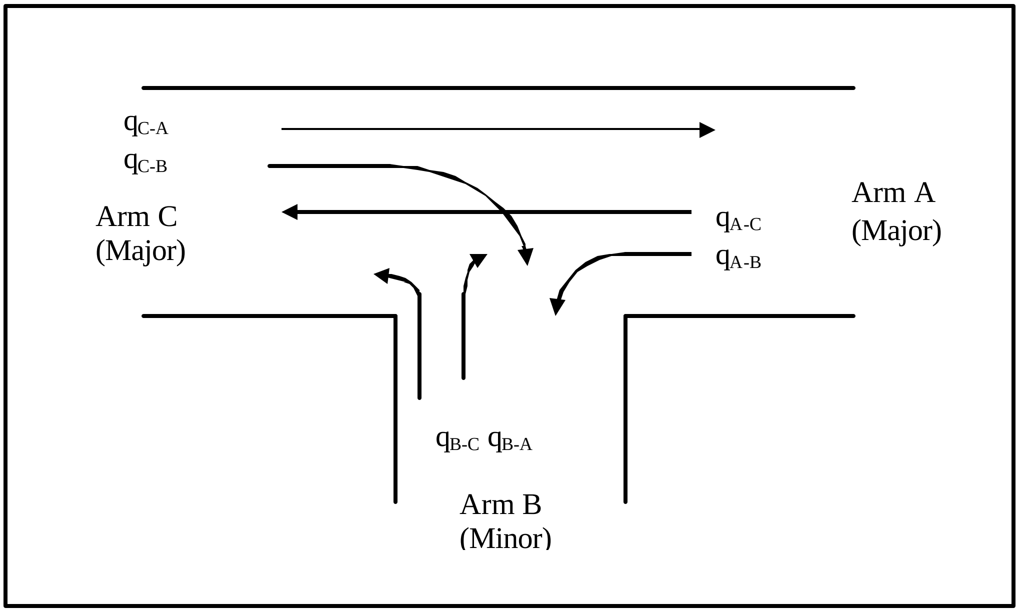

Figure 2-1. Flows and Notations for TRRL Methodology

$$Y = (1 - 0.0345W) \qquad (2-6)$$

$$X_1 = [1 + 0.094(w_{B=A} - 3.65)] \quad [1 + 0.0009(V_{rB-A} - 120)] \quad [1 + 0.0006(V_{lB-A} - 150)] \qquad (2-7)$$

$$X_2 = [1 + 0.094(w_{B=C} - 3.65)] \quad [1 + 0.0009(V_{rB-C} - 120)] \qquad (2-8)$$

$$X_2' = [1 + 0.094(w_{C=B} - 3.65)] \quad [1 + 0.0009(V_{rC-B} - 120)] \qquad (2-9)$$

Where,

q^s_{B-A}, q^s_{B-C}, q^s_{C-B} = capacities of minor road right, minor road left and major road right-turning vehicles respectively

$q_{A-C}, q_{A-B}, q_{C-A}, q_{C-B}$ = flow volumes of streams A-C, A-B, C-A and C-B respectively

W = width of the major road

w_{B-A}, w_{B-C}, w_{C-B} = lane width of streams B-A, B-C and C-B respectively

W_{CR} = width of the central reserve

V_{rB-A}, V_{rB-C}, V_{rC-B} = visibility distances to the right corresponding to points 10 meters back of the stop line

V_{lB-A} = visibility distance to the left corresponding to a point 10 meters back of the stop line.

These results are can be applied to four-arm cross roads using the methods described in another study (Kimber, R M, 1976).

2.2 HCM Methodology

The HCM provides a set of methodologies widely used in the U.S for the estimation of capacities of various transportation facilities. The HCM methodologies for signalized intersections, unsignalized intersections and freeways are of relevance to this thesis and are reviewed.

2.2.1 Signalized Streets

In the HCM method, capacity of an arterial is estimated by the capacity of the intersection approach at the end of the arterial segment. For calculating the capacity of a signalized intersection approach the lane groups were first established for the sake of analysis. All exclusive left-turn and right-turn lanes were designated as separate lane groups and all through and shared through-lanes were designated as a single lane group. The saturation flow rate of each lane group is determined from an ideal saturation flow rate s_o using Equation (2-10). The ideal saturation flow rate is taken to be 1900 passenger cars per hour of green time per lane (pcphgpl) (TRB, 2000).

$$s = s_o n f_w f_{HV} f_g f_p f_{bb} f_a f_{LU} f_{RT} f_{LT} \qquad (2-10)$$

Where,

s = saturation flow rate for the lane group in vehicles per hour green.

s_o = ideal saturation flow rate in pcphgpl

n = number of lanes in the lane group

f_w = adjustment factor for lane width

f_{HV} = adjustment factor for heavy vehicles

f_g = adjustment factor for approach grade

f_p = adjustment factor for parking characteristics

f_{bb} = adjustment factor for blocking effect of local buses that halt within the intersection area

f_a = adjustment factor for area type (Central business district or other areas)

f_{LU}= adjustment factor for lane utilization

f_{RT} = adjustment factors for right-turns in the lane group

f_{LT} = adjustment factors for left-turns in the lane group.

The capacity of the lane group is determined from the saturation flow rate using Equation (2-11).

$$c = s\left(\frac{g}{C}\right) \qquad (2-11)$$

Where,

c = capacity of the given lane group in vehicles per hour

s = saturation flow rate of the given lane group in vehicles per hour of green g/C = effective green to signal cycle ratio for the given lane group.

2.2.2 Unsignalized Streets

For calculating the capacity of an unsignalized intersection approach the priority of right-of-way is first determined for each movement. The major-street movements have a higher priority than minor-street movements. Capacity is then determined by the gap acceptance of drivers on the minor-street approach who wait for an acceptable gap between vehicles on the major-street approach (TRB, 2000). The gap acceptance method computes the potential capacity of each minor-traffic movement according to Equation (2-12) (TRB, 2000).

$$c_{p,x} = v_{c,x} \frac{\exp(-v_{c,x} t_c / 3600)}{1 - \exp(-v_{c,x} t_f / 3600)} \qquad (2-12)$$

Where,

$c_{p,x}$ = potential capacity of minor movement x vehicles per hour (veh/hr)

$v_{c,x}$ = conflicting flow rate for movement x

t_c = critical gap or minimum time interval that allows intersection entry to one minor stream vehicle (seconds) for minor movement x

t_f = follow-up time or headway between departure of one vehicle from the minor-street and departure of next vehicle under continuous queue conditions (seconds) for minor movement x.

When several movements share the same lane, the capacity of the shared lane is given by Equation (2-13).

$$c_{SH} = \frac{v_l + v_t + v_r}{(\frac{v_l}{c_{m,l}}) + (\frac{v_t}{c_{m,t}}) + (\frac{v_r}{c_{m,r}})} \qquad (2-13)$$

Where,

c_{SH} = capacity of shared lane (veh/hr)

v_l = volume of left-turning vehicles in the shared lane (veh/hr)

v_t = volume of through vehicles in the shared lane (veh/hr)

v_r = volume of right-turning vehicles in the shared lane (veh/hr)

$c_{m,l}$ = movement capacity of left-turn movement in shared lane (veh/hr)

$c_{m,t}$ = movement capacity of through movement in shared lane (veh/hr)

$c_{m,r}$ = movement capacity of right-turn movement in shared lane (veh/hr).

2.2.3 Freeway Segments

The capacity of a freeway facility varies with the free-flow speed (TRB, 1998). The capacity values for different free-flow speeds are summarized in Table 2-1.

Table 2-1. HCM Capacity Values for Freeway Segments

Free-Flow Speed (mph)	Capacity (pcphpl)
70	2400
65	2350
60	2300
55	2250

The free-flow speeds of a freeway facility are obtained using Equation (2-14).

$$FFS = BFFS - f_{LW} - f_{LC} - f_N - f_{ID} \qquad (2-14)$$

Where,

FFS = free-flow speed in miles per hour (mph)

BFFS = base free-flow speed (70 mph for urban freeways)

f_{LW} = adjustment for lane width

f_{LC} = adjustment for right shoulder lateral clearance

f_N = adjustment for the number of lanes

f_{ID} = adjustment for interchange density.

The capacity of the freeway facility can be obtained in vehicles per hour by multiplying the capacity in pcphpl and the heavy vehicles adjustment factor f_{HV}, which is given by

$$f_{HV} = \frac{1}{1 + P_T (E_T - 1) + P_R (E_R - 1)} \qquad (2-15)$$

Where,

E_T, E_R = passenger car equivalents for trucks/buses and recreational vehicles

P_T, P_R = proportion of trucks/buses and recreational vehicles in the traffic stream.

2.3 The Baton Rouge Street Network

The Baton Rouge street network is a digital map, which represented the major highways and streets in the Baton Rouge area. The network was initially developed by a local consultant for the purpose of travel demand modeling using the TranPlan software (LSU, 1997). The streets were represented on the network as lines called links and the intersections as points called nodes. Each link has a starting node called A-node and an ending node called B-node. Information on each link such as ID, length, free-flow speed, travel time, capacity, facility type etc. are available in a Geographic Information System (GIS) database. Each link consisted of two directions AB and BA. Where the links represented two-way facilities, two capacities namely the AB_capacity and BA_capacity were coded for the AB and BA directions respectively. Where the links represented a one-way facility, only the AB_capacity was coded.

For the purpose of travel demand modeling the Baton Rouge area was divided into Travel Analysis Zones (TAZs). Each TAZ contained information like area, population, number of households, employment etc. This information can be used to predict the number of trips produced from and attracted to a TAZ.

2.4 Current Practices for Capacity Estimation of Links

The capacity values currently assigned to the Baton Rouge network are average values that depend only on facility type and number of lanes. The values are based on 50 percent of the 24-hour capacity from the 1985 HCM for each facility type (LSU, 1997). The values assigned to the links were the hourly capacities, factored by 10 to produce peak-period volume/capacity ratios (LSU, 1997). The capacity values are for Level of Service E (LOS E) and are summarized in Table 2-2.

Table 2-2. Capacity Values for Baton Rouge Network

Facility Type	Factored Capacity Value	Capacity (vph)
2-lane undivided	5,500	550
2-lane with left-turn lane	7,500	750
4 lane undivided	11,500	1,150
4 lane divided	13,500	1,350
6 lane undivided	16,000	1,600
6 lane divided	19,500	1,950
Ramps	7500	750
4-lane freeways	34,000	3,400
6-lane freeways	51,000	5,100

The capacity values assigned to the Dallas-Fort Worth (DFW) network depended on area type, functional class, whether the facility type was divided or undivided and the number of lanes (NCTOG, 2001). The area types were divided into central business district (CBD), fringe, urban-residential, suburban-residential and rural areas. The functional classes were divided into freeways, principal arterials, minor arterials, collectors, locals, ramps, frontage roads and HOV lanes. The capacity values were for LOS E and are based on the 1994 HCM.

The capacity values assigned to the Phoenix network depended on the facility type, area type and the number of lanes (Maricopa, 1999). The area types were divided into rural, suburban, mixed urban outlying CBDs and CBDs. The facility types were divided into freeways, expressways, collectors, six-legged arterials, major arterials, freeway ramps, freeway ramp meters, uniform time links and freeway high-occupancy vehicle lanes. Also in the State of Florida networks were assigned capacity values based on the facility type, area type and the number of lanes. The MPO's in Florida however divided the area types and facility types into more than ten and twenty classifications respectively (Florida Department of Transportation, 1997).

The practice of using average values based on a gross classification was not accurate because it did not account for various link specific factors such as traffic signal presence and timing, lane widths, presence of parking, proportion of heavy vehicles etc.

In the State of Ohio a computer program was developed for use by all MPO's for the calculation of link capacities (Giaimo, 2001). The program used the HCM methodology to calculate capacities. The input used by the program were the lane configuration, total roadway width, functional class, area type, presence of parking, percent heavy vehicles, terrain type (grade), intersection type, signal timing, directional split, peak-hour factor etc. It obtained the proportion of green time depending on the street/cross street combination shown in Table 2.3. The percentage green time affected the capacity of a link greatly and the use of average values by the method might have affected the accuracy of capacity calculations.

Table 2.3 Proportion Green Time for Networks in Ohio

Street	Cross Street	Proportion Green Time
Arterial	Arterial	.45
Arterial	Collector	.5
Arterial (2 Lane)	Local	.55
Arterial (Else)	Local	.55
Collector	Arterial	.4
Collector (2 Lane)	Collector	.45
Collector (Else)	Collector	.45
Collector	Local	.5
Local	Arterial	.35
Local	Collector	.4
Local	Local	.45

The Oregon Department of Transportation (ODOT) employed a method, which assigned capacities link-by-link to the street network of Salem and Keizer. ODOT and the Metropolitan Planning Organizations (MPO's) worked on a program to improve travel demand modeling methods. As part of this program, a standard methodology for the estimation of network capacity was used (Parsons Brinkerhoff Quade & Douglas, 1995). Capacities were calculated for arterial links using Equation (2-16).

$$c = n \times 1900 \times \left(\frac{g}{C} \right) \qquad (2-16)$$

Where,

c= capacity (vph)

n= number of lanes

g/C = green to cycle ratio.

Later to improve the accuracy of the methodology an analysis was performed to calibrate Equation (2-16) based on area type (Kimley-Horn and Associates Inc, 1997). As part of the analysis, field measurements of saturation flow rates were conducted on urban arterial roadway intersections in a variety of area types and these values were correlated with area type data. The study assumed that area type could be defined by the population and employment density, which is available for each TAZ. An adjustment factor called the area type adjustment factor (f_{area}) was developed which takes values depending on the number of residents and employees per square mile of the study area. The study derived Equation (2-17).

$$c = n \times 1900 \times f_{area} \times \left(\frac{g}{C}\right) \qquad (2-17)$$

f_{area}= area type adjustment factor

The study derived a lookup table for f_{area} depending on the number lanes on the intersection approach and the combined population and employment density (Kimley-Horn and Associates Inc, 1997). This method used only one adjustment factor in calculating capacities and therefore may not have quantified the effects of various traffic and geometric factors accurately.

2.5 Conclusions

Between the two methodologies reviewed the HCM method was used more widely in the US and was therefore chosen for capacity calculations in this study. Also the review of current practices showed that capacity values were typically assigned depending on a gross classification of links. There was no literature available on the accuracy of the current capacity assignment practices and whether they affected the results of travel demand modeling.

CHAPTER 3. METHODOLOGY

The hypotheses of the thesis were tested by carrying out five tasks, including the selection of a subregion, data collection, capacity calculations, travel demand modeling and comparison of modeling results. To reduce data collection effort, only a part of the Baton Rouge network was selected for the study. This subregion was selected such that any conclusions made from it could be generalized for the entire network. The data required for the study was obtained by manual field observations. The HCM methodology was used for all capacity calculations. Five sets of capacity values were obtained. The set of capacity values obtained using all HCM adjustment factors, was used as a benchmark and all other sets were compared to the benchmark. Travel demand modeling was performed using each set of capacity values in three steps, including trip generation, trip distribution and traffic assignment. Mode-choice was not performed due to low transit ridership in Baton Rouge. The results of modeling obtained using each set of capacity values was compared to the corresponding results, obtained using the benchmark. The comparisons were made using t-tests and root mean square error calculations (RMSE).

3.1 Selection of a Subregion

The Baton Rouge street network has about 3200 links. Due to the large size of the network and data collection limitations, it was not feasible to include the entire network to test the hypotheses of this study. Therefore, only a subregion of the network was used. The subregion was selected according to the following criteria to improve the chances of getting significantly different traffic assignment volumes with link-by-link capacity values.

1. A high percentage of trips start and end within the subregion selected for the study.
2. Congestion is experienced on some of the links within the subregion.

From a trip distribution matrix it was observed that a subregion containing Travel Analysis Zones (TAZs) 23-27 and 41-46 had about thirty percent of the trips starting and ending within the same subregion. This subregion is part of the East Baton Rouge Parish and it had the highest such percentage compared to other regions. It was therefore selected to test the hypotheses of the study.

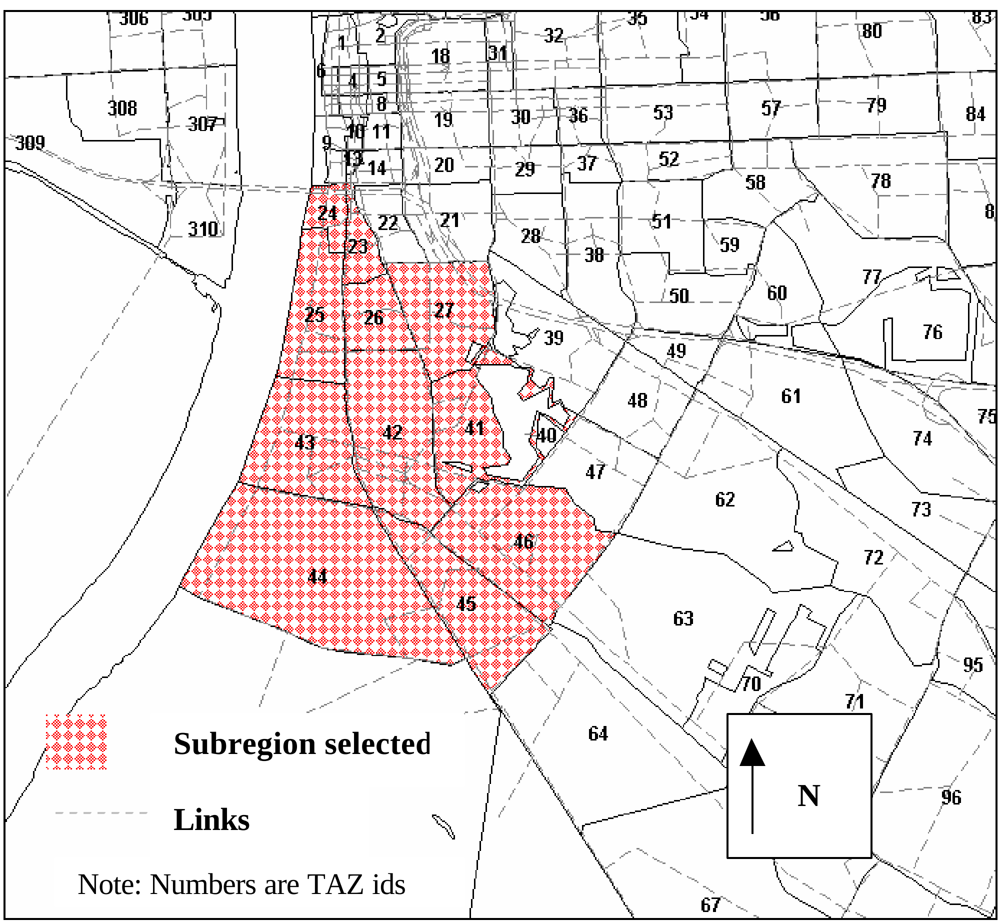

Figure 3-1. Subregion Selected for the Study

This subregion contained approximately seventy links representing two-lane undivided, two-lane with left-turn lane, four-lane divided, four-lane undivided and freeway facilities in the region. The exact location of each link on the field was determined by overlaying the network on a GIS map of streets in Baton Rouge as shown in Figure 3-2.

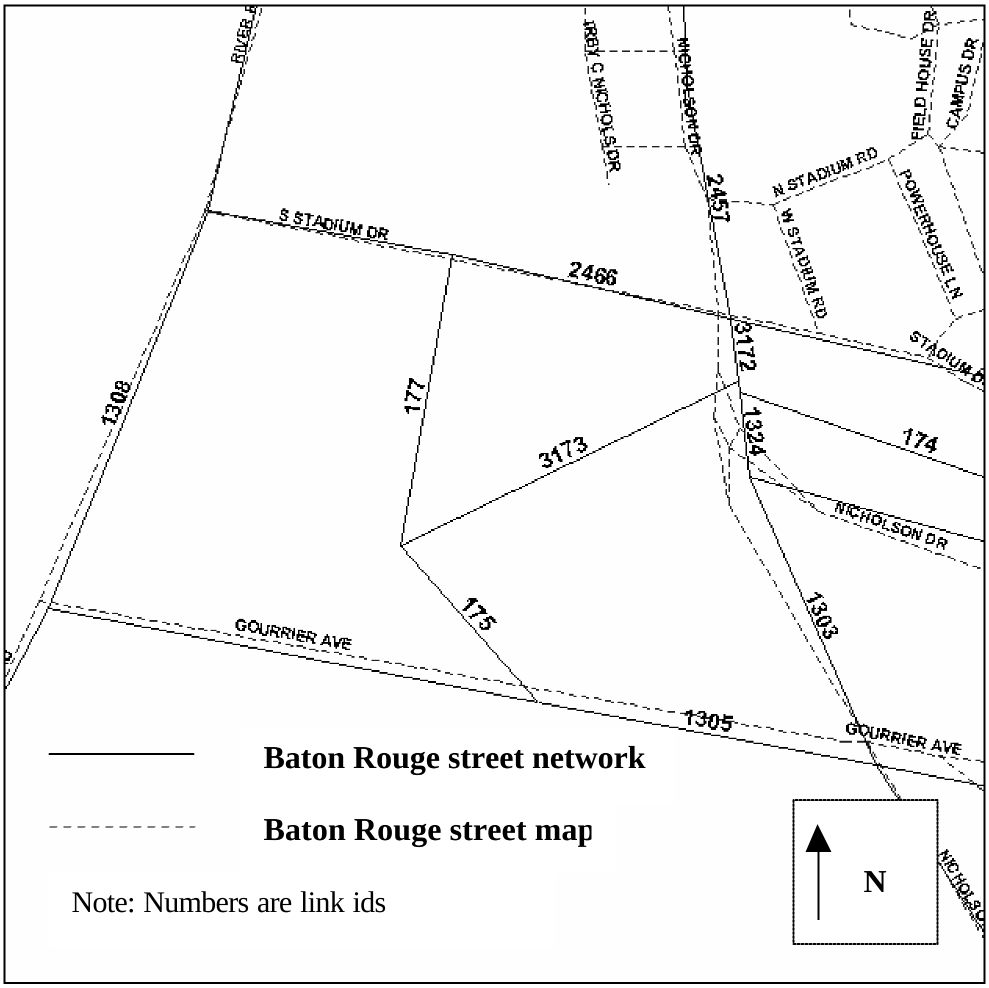

Figure 3-2. Baton Rouge Network Overlayed with a Street Map

3.2 Data Collection

The purpose of data collection was to collect data to estimate the capacity values of the arterial links using Equation (2-10) and (2-11) for signalized links, Equation (2-13) for unsignalized links and Equation (2-14) for freeway links. To estimate the adjustment factors, data such as number of lanes and their configuration, lane width, percentage of heavy vehicles, presence of parking, number of bus stops per hour, area type, and proportion of turning vehicles was collected. At sites where exclusive left-turns were absent the flow of vehicles in the opposing approach was observed to estimate the left-turn adjustment factor. Also the g/C ratio for each of the lane groups was obtained from signal timing data to calculate capacity using Equation (2-11). The required data were obtained by manual field observations using field sheets. This was because data had to be collected at several intersections for short intervals of time and so the effort and expense involved to set up and remove automated equipment was not justified. Also the kind of data required for this research could more easily be obtained by direct manual field observations. Data collection is discussed in greater detail in Chapter 4.

3.3 Capacity Calculations

Depending on the facility type and intersection at the end of the link, the appropriate HCM methodology was used to estimate capacity. For freeway links the location was determined by overlaying the network on a Baton Rouge street map. The HCM methodology for freeway segments was then used to estimate capacity.

For arterial links the location of intersections at either end was determined from the same overlay. The directional capacity of the link was then calculated as the sum of the capacities of each lane group, at the intersection approach in the direction of interest.

The intersections were mostly signalized intersections though some were unsignalized. The Highway Capacity Software (HCS) 2000 was used for capacity calculations. To calculate capacity of unsignalized intersections, lane configuration and flow at each approach was provided as input to the software. The presence of a flared intersection approach and its storage capacity were also indicated.

To calculate capacity of signalized intersections, detailed information on geometric, traffic and signalization conditions were provided as inputs to the software. The HCM method divided the lanes at the intersection into lane groups. Exclusive left-turn or right-turn lanes were treated as separate lane groups. All through lanes and shared through lanes were treated as one lane group. A base saturation flow rate of 1900 pcphgpl was used. The g/C ratio was obtained from the signal data collected from the field. In signals where the cycle lengths vary, the g/C ratio was calculated as the average for three cycles measured during the peak-period.

The average capacity values already assigned to the network were designated as Set A. Five sets of capacity values were calculated. The first set contained capacity values calculated link-by-link using all the adjustment factors in Equation (2-10). The capacities for the AB and BA directions were obtained separately. This set was considered to be the most accurate for the study and was used as a benchmark. It was designated as Set B. The second Set C contained average capacities calculated by averaging the capacity values in Set B for each facility type. Set C contained averages specific to the subregion and was therefore more accurate than the generalized averages contained in Set A. Testing this set provided insights as to whether the use of more accurate averages would suffice rather than using link-by-link capacity values, which require a lot of effort to obtain. The third Set D was calculated by ignoring the effects of all the adjustment factors in Equation (2-10). This resulted in Equation (2-16). This set was used to test whether there could be a compromise in estimating capacities link-by -

link to reduce data collection effort, without significant loss in the accuracy of travel demand modeling results. The fourth Set E, contained link-by-link capacity values calculated by ignoring adjustment factors f_{RT} and f_{LT}. Estimating these adjustment factors required detailed flow information at the intersection approach and the opposing approach. Also calculating f_{LT} was complicated and could be done easily without the use of specialized software. Therefore, it would be tedious to estimate the above two factors on a large scale for all links in the network. Testing Set E capacity values, enabled the researcher to study the loss of accuracy when the above two factors were ignored. The fifth Set F, contained capacity values calculated using the method adopted in the Salem network (Equation 2-17). This set involved less effort to calculate than Set B and E and more effort than Set D. This set was tested to analyze the capacity assignment method used in the Salem network.

3.4 Travel Demand Modeling

Travel demand modeling was performed with all six sets of capacity values. It was a four-step process consisting of trip generation, trip distribution, mode-choice and traffic assignment. However, since transit ridership was very low in Baton Rouge the third step was omitted. The modeling was performed using the TransCAD GIS software (Caliper Corporation, 1998).

The trip generation step consisted of trip production, trip attraction and balancing. The cross-classification method was used for trip production. The inputs required were a

1. Trip rate table: This table defined for each trip purpose, the classification used and the trip rates for each classification. It was in the form of a dBase file. In the trip rate table, the households were classified into three household sizes; those with 1&2, 3&4,

>5 members. The trip purposes used were home based work, home based other and non-home based trips.

2. TAZ data table: This table contained the average values of classification parameters used for each TAZ. Data such area, population, number of households for each household size, employment etc. were contained in it.

The trip production module estimated the number of trips produced by each TAZ for each trip purpose. The trip attraction module predicted the number of trips attracted to each zone. A regression model was used to estimate trip attractions. This method was preferred to cross-classification due to the difficulty in collecting disaggregate data needed to generate cross-classification tables (Caliper Corporation, 1998). The trip balancing module was used to balance the number of productions and attractions. In balancing, the number of productions was held constant and the attractions were adjusted. This was considered to be a good practice as production models are more realistic (Caliper Corporation, 1998).

The gravity model was used for trip distribution. The impedance matrix needed for the model was generated from the network using TransCAD. The friction factors were obtained using a friction factor lookup table. An origin-destination (OD) matrix, which contained the number of trips from any zone i to zone j was obtained as output of the trip distribution module.

The user equilibrium method was used for traffic assignment. This method took as input the OD matrix generated at the end of trip distribution and the Baton Rouge street network. The capacity of arterial links affected the accuracy of this step. The results of traffic assignment procedure are 24-hour link flow volumes, travel times and volume to capacity (v/c) ratios. Speed estimates were obtained from the link distance and travel time estimates. Traffic assignment was performed using the six sets of capacity values (A to F) to estimate the corresponding six sets of flow volumes, travel times, travel speeds and v/c ratios.

3.5 Analysis of Results

The adjustment factors for calculating capacities of signalized links were analyzed using t-tests to determine if they significantly impacted capacity calculations. Also capacity values and results of traffic assignment procedures were analyzed using statistical comparison tests. The modeling results obtained using Set B capacity values, was used as a benchmark. The results obtained using capacity Sets A, C, D, E and F were compared to the benchmark. Comparisons were made by pairing observations in each set with the corresponding observation in the benchmark. Absolute differences in the observations were obtained and t-tests were performed on these differences. Comparisons were also made using RMSE and RMSE percent values. The details of comparisons made and the results of the statistical tests will be described in Chapter 5.

CHAPTER 4. DATA COLLECTION

To accomplish the objectives of the study, data was collected for the purpose of calculating capacities of arterial links. This section discusses the selection of study sites, the data required to be collected, the data collection procedure and the calculation of link capacities.

4.1 Site Selection

Due to the large number of links present in the network, only a part of the network was selected for data collection. The subregion was selected using the approach described in Chapter three. All the links in the subregion were included for the purpose of capacity calculations. There were a total of 73 links excluding centroid connectors. The facility types and the number of links within each facility type, are summarized in Table 4-1.

Table 4-1. Facility Types in the Study Area

Facility Type	Number of Links
2- lane undivided	38
2-lane with left turn lane	9
4- lane undivided	7
4-lane divided	14
3-lane 1 way (same as 6-lane undivided)	1
6 lane freeways	4

The Baton Rouge street network was overlaid with a map of Baton Rouge, which was provided by Caliper Corporation. The map of Baton Rouge contained the names of all major streets and highways. By zooming in on each link the name of the street that the link represents was identified. Also the names of intersections (represented by nodes) at the end of the links were identified. The AB capacity and BA capacity of the link were the capacity of the nearest intersection approaches in the AB and BA directions respectively. The links in the subregion were mostly signalized streets. There were also some unsignalized streets and freeway links. A list of all the intersections selected for data collection is included as Appendix A.

4.2 Data Required

The data required for capacity calculations of signalized intersections were signal phases and signal timings, number of lanes and lane configuration at the intersections, lane widths, percentage of heavy vehicles, presence of parking, number of bus stops in an hour and the proportion of vehicles turning left and right. Since most intersections in the study area had flat grades the effect of grades was ignored. Almost no pedestrian movement was observed in most of the study sites. So the effect of pedestrian movement was also ignored. The data required for capacity calculations of unsignalized intersections were the traffic volumes at major and minor street approaches, lane-configuration at the approaches, percentage of heavy vehicles and presence of flared minor-street approaches. The data required for the calculation of capacities of freeway links were base free-flow speed, lane widths, shoulder widths, number of interchanges per mile (interchange density) and percentage of heavy vehicles.

4.3 Data Collection

The number of phases, vehicle movements in each phase and signal timings were observed at signalized intersections at the end of the links. The signal timings were recorded using a stopwatch. The actual green and yellow times for a phase and the total cycle time for the intersections were also recorded. Three observations were made for each phase. In most cases the differences in cycle lengths were less than two seconds. Whenever there was a difference in signal timings the average of three observations were used. The red (all red) interval was assumed to be one second in all cases. This was because of its very short duration and difficulty to measure. Also a very high level of accuracy was not needed to test the hypotheses of the thesis. Signal phase information and signal timing were used as inputs for the signalized intersection module of the Highway Capacity Software (HCS 2000). The software internally calculated the cycle length as the sum of green, yellow and all red timings that were input for each phase. The cycle lengths calculated by the software matched with the average cycle length observed in the field for almost all cases.

Each intersection approach was divided into lane groups. Exclusive right or left-turn lanes were treated as a separate lane group. All through and shared lane groups were treated as one lane group. For each approach, traffic counts were obtained for a half-hour time interval by manually counting and marking on a field tally sheet. To obtain peak hour capacities, most volume and signal timings were measured between 4 and 6 p.m. At approaches where more traffic flow occurred during the morning peak hour, observations were made between 7:30 and 9 a.m. Left-turning, right-turning and through vehicles were counted and recorded separately. All trucks, buses and large vehicles with more than four tires were recorded in separate columns. If a bus stop was present on the link, the number of bus stops was also recorded during the half-hour time interval. Other data like lane widths and parking characteristics were also obtained by direct field observations. The HCS used Equation (2-10) and (2-11) to compute the capacity of each lane group for signalized intersections.

At unsignalized intersections traffic counts were obtained from manual counts on both the major and minor-street approaches. The percentage of heavy vehicles, lane-configurations and presence of flared minor street approaches were recorded for use as input to the unsignalized intersection module of HCS 2000. The software used Equations (2-12) and (2-13) to calculate capacities.

The capacities of freeway links were calculated using Equation (2-14) and Table 2-1. The base free-flow speed was assumed to be seventy miles per hour as suggested in the HCM. The lane widths and shoulder widths were obtained from a TransCAD network file of interstates and major highways in Louisiana. The interchange density, which is the number of on ramps per mile, was observed directly on the freeway link. The number of on ramps was counted on a six-mile segment three miles upstream and three miles downstream of the link. The percentage of heavy vehicles was obtained through traffic counts for fifteen-minute intervals. The average percentage for three intervals was used.

4.4 Capacity Calculations

A sample capacity calculation for one of the links (Id No 2466) using HCS 2000 is shown below. This link represents Stadium Drive (now Skip Bertman Drive) and has the intersection of Stadium Drive and Nicholson Drive in the BA direction. The BA capacity is the approach capacity of Stadium Dr at the signalized intersection. It has a centroid connector on the other end in the AB direction. The nearest intersection in the AB direction is the stop-controlled intersection of Stadium Drive and River Road. Therefore, the AB capacity is the approach capacity of Stadium Dr at the stop-controlled intersection. The capacity calculation summary for BA capacity is shown in Figure 4-1. The approach of interest is the eastbound approach. The eastbound approach shown in

Figure 4-1 has two lane groups with capacities 367 vehicles per hour (vph) and 347 vph. Therefore, the BA capacity of the link is 714 vph.

```
HCS2000: Signalized Intersections Release 4.1

Analyst: Yogesh K Dheenadayalu          Inter.: Nicholson Dr @ S. Stadium Rd
Agency: Louisiana State University      Area Type: All other areas
Date:   7/19/01                         Jurisd:
Period: 4:30 - 5:30 P.M                 Year  : 2000
Project ID: Link Id 2466 BA_Capacity EB
E/W St: S. Stadium Rd                   N/S St: Nicholson Dr

_________________________SIGNALIZED INTERSECTION SUMMARY_______________________
            |  Eastbound     |  Westbound     |  Northbound    |  Southbound    |
            | L    T    R    | L    T    R    | L    T    R    | L    T    R    |
            |________________|________________|________________|________________|
No. Lanes   |   1    1    0  |   1    2    0  |   1    2    1  |   1    2    0  |
LGConfig    |   L   TR       |   L   TR       |   L   T    R   |   L   TR       |
Volume      |80   128  136   |188  136  156   |20   1028 92    |40   1304 60    |
Lane Width  |11.4 13.5       |10.6 11.8       |11.9 11.9 10.5  |11.7 11.5       |
RTOR Vol    |          16    |          20    |          20    |          16    |
_______________________________________________________________________________
Duration    0.25      Area Type: All other areas
______________________________Signal Operations_________________________________
Phase Combination 1     2     3     4 |            5     6     7     8
EB  Left                P     P       | NB  Left         P     P
    Thru                P             |     Thru         P     P
    Right               P             |     Right        P     P
    Peds                              |     Peds
WB  Left          P     P     P       | SB  Left   P     P
    Thru          P     P             |     Thru   P     P
    Right         P     P             |     Right  P     P
    Peds                              |     Peds
NB  Right                             | EB  Right
SB  Right                             | WB  Right
Green            7.0   23.0  9.0                 7.0   43.0  9.0
Yellow           3.0   4.0   3.0                 4.0   4.5   4.0
All Red          0.0   0.0   1.0                 0.0   0.0   1.0
                                                  Cycle Length: 122.5   secs
____________________Intersection Performance Summary___________________________
Appr/   Lane       Adj Sat     Ratios        Lane Group    Approach
Lane    Group      Flow Rate  __________     __________   ___________
Grp     Capacity     (s)      v/c    g/C     Delay LOS    Delay LOS
_______________________________________________________________________________
Eastbound
L        367       1658       0.24   0.29    35.1   D
TR       347       1850       0.79   0.19    64.3   E     57.1   E

Westbound
L        315       1545       0.66   0.38    39.8   D
TR       835       3098       0.36   0.27    37.4   D     38.4   D
```

Figure 4-1. BA Capacity Calculation Using HCS 2000

Figure 4-1 contd.

```
Northbound
L        268       1799      0.08   0.46    44.9   D
T        1601      3471      0.71   0.46    29.2   C    28.9   C
R        708       1534      0.11   0.46    19.1   B

Southbound
L        163       1787      0.27   0.44    28.5   C
TR       1513      3433      0.99   0.44    54.9   D    54.1   D

         Intersection Delay = 43.7  (sec/veh)   Intersection LOS = D
_______________________________________________________________________________
```

The capacity calculation summary for the AB capacity is shown in Figure 4-2. The approach of interest is the westbound approach. The westbound approach shown in Figure 4-2 has two lane groups with capacities 348 vph and 939 vph. Therefore the AB capacity of the link is 1287 vph.

```
HCS2000: Unsignalized Intersections Release 4.1

_______________________TWO-WAY STOP CONTROL SUMMARY___________________________

Analyst:              Yogesh K Dheenadayalu
Agency/Co.:           Louisiana State University
Date Performed:       04/25/01
Analysis Time Period: 4:45 - 5:15 P.M
Intersection:         River Rd @ S. Stadium Rd
Jurisdiction:
Analysis Year:        2001
Project ID:  Link Id 2466 AB_Capacity WB
East/West Street:     S. Stadium Road
North/South Street:   River Rd

Intersection Orientation: NS                 Study period (hrs):  0.25

______________________Vehicle Volumes and Adjustments__________________________
Major Street:  Approach       Northbound              Southbound
               Movement     1      2      3     |  4      5      6
                            L      T      R     |  L      T      R
_______________________________________________________________________________
Volume                             96     44       56     560
Peak-Hour Factor, PHF              1.00   1.00     1.00   1.00
Hourly Flow Rate, HFR              96     44       56     560
Percent Heavy Vehicles             --     --       0      --     --
Median Type          Undivided
RT Channelized?
Lanes                              1    0             0   1
Configuration                          TR              LT
Upstream Signal?                   No                     No
```

Figure 4-2. AB Capacity Calculation Using HCS 2000

Figure 4-2 contd.

Minor Street: Approach	Westbound			Eastbound		
Movement	7	8	9	10	11	12
	L	T	R	L	T	R
Volume	132		60			
Peak Hour Factor, PHF	1.00		1.00			
Hourly Flow Rate, HFR	132		60			
Percent Heavy Vehicles	0		0			
Percent Grade (%)		0			0	
Median Storage						
Flared Approach: Exists?						
Storage						
RT Channelized?			No			
Lanes	1		1			
Configuration	L		R			

Delay, Queue Length, and Level of Service

Approach	NB	SB	Westbound			Eastbound		
Movement	1	4	7	8	9	10	11	12
Lane Config		LT	L		R			
v (vph)		56	132		60			
C(m) (vph)		1456	348		939			
v/c		0.04	0.38		0.06			
95% queue length		0.12	1.72		0.20			
Control Delay		7.6	21.5		9.1			
LOS		A	C		A			
Approach Delay				17.6				
Approach LOS				C				

4.4.1 Summary of Capacity Calculations

Five sets of capacity values were calculated. These sets were designated as Set A, B, C, D and E. Set A was the set of average values, which were used prior to the study. Set C was obtained by averaging the capacity values of Set B for each facility type. The capacity values are summarized in Table 4-2.

Large differences were noticed between Set A and C. This was due to the fact that Set A averages were generalized values whereas Set C averages were specific to the subregion. In Set C, averages of two-lane undivided links were increased by links representing River Road, which had very high capacity due to the absence of signals and stop signs. The average capacity of two-lane links with left-turn lanes was high because most links represented Higland Road, which was an arterial, characterized by high g/C ratios. Most four-lane roads in the subregion were arterials intersected mostly by minor streets. Therefore, they had high g/C ratios and subsequently high capacities.

Table 4-2. Capacity Sets A and C

Facility Type	Set A (vph)	Set C (vph)
2-lane undivided	550	997
2-lane with left-turn lane	750	1538
4 lane undivided	1150	1603
4 lane divided	1350	2303
6 lane undivided	1600	1704
3 Lane Freeways	5100	6469

Capacity sets B, D, E and F were link-by-link capacity values calculated separately for each direction (AB and BA). Set B was calculated by applying all adjustment factors of the HCM to the arterial links. Set D was calculated by ignoring the effects of all adjustment factors. This was done by making all adjustment factors equal to 1 in Equation 2-10. This simplified Equation 2-10 and 2-11 to Equation 2-16, which was used in the Parsons Brinkerhoff methodology. Set E was calculated by ignoring the effects of left-turn and right-turn adjustment factors. This was done by making f_{LT} and f_{RT} equal to 1 in Equation 2-10. Also whenever there was an exclusive left-turn lane present with only permitted left-turn phasing, f_{LT} was assigned the value 0. Set F was calculated by using Equation 2-17 for arterial links. This is the equation used by the Parsons Brinkerhoff methodology after incorporating the effects of area types. The summary of AB and BA capacity values for sets B, D, E and F are summarized in Table 4-3. All the values are in vehicles per hour (vph). Some entries are blank because some links represented one way facilities.

Table 4-3 Capacity Sets B, D, E and F

Link Id	Set B (vph)		Set D (vph)		Set E (vph)		Set F (vph)	
	AB	BA	AB	BA	AB	BA	AB	BA
926	1692	-	2054	-	1809	-	2085	-
975	477	164	514	171	503	174	506	168
1250	578	544	578	544	578	544	578	544
1251	1356	1222	1688	1222	1555	1222	1688	1222
1254	544	578	544	578	544	578	544	578
1255	747	1404	814	1508	774	1401	838	1553
1256	2277	1096	2818	1688	2482	1390	2818	1688
1257	526	817	526	857	526	838	526	857
1260	1732	3581	1475	3800	1424	1390	1519	3914
1265	1058	1152	1186	897	1083	837	1186	897
1266	1639	1479	2389	1478	2194	1405	2461	1522
1292	578	1540	683	1689	578	1540	683	1677
1294	1064	1217	1064	1266	1064	1217	1057	1250
1295	1072	999	990	1208	944	1122	963	1175
1296	999	1072	1208	990	1122	944	1175	963
1297	2109	1873	1761	1300	1656	1204	1761	1283
1298	416	762	416	813	416	759	416	802
1299	2463	1359	2640	1362	2572	1243	2640	1344
1300	451	305	451	289	451	290	445	285
1301	1152	1058	897	1186	837	1083	897	1186
1303	2625	3392	2850	3724	2625	3395	2907	3836
1304	1923	795	2389	1099	2194	957	2461	1132
1305	456	496	456	580	456	496	456	580
1306	2468	1543	2818	1584	2492	1380	2818	1584
1307	496	456	580	456	496	456	580	456
1308	1698	1510	1900	1510	1773	1510	1900	1510
1309	1609	1764	1609	1900	1609	1773	1609	1900
1311	1762	1398	1900	1398	1773	1398	1900	1398
1312	245	616	260	616	275	616	257	616
1313	1456	1752	1456	1900	1456	1773	1456	1900
1314	1773	1412	1900	1412	1773	1412	1881	1412
1315	245	616	260	616	275	616	257	616
1316	1835	3056	2054	2981	1851	2651	2085	3041
1317	245	225	329	260	314	295	322	257
1318	1676	3280	1843	2981	1682	2845	1885	3041
1319	1835	3056	2054	2981	1851	2651	2085	3041
1320	1835	3056	2054	2981	1851	2651	2085	3041
1321	2073	1798	1423	1456	1463	1341	1395	1427
1322	1798	2073	1456	1423	1341	1463	1427	1395

Table 4-3 contd.

Link Id	Cap B (vph)		Cap D (vph)		Cap E (vph)		CapF (vph)	
	AB	BA	AB	BA	AB	BA	AB	BA
1323	467	571	467	654	467	579	454	649
1324	2577	3486	2905	3894	2574	3486	2963	3972
1325	1376	2014	1043	1423	998	1419	1015	1395
1326	894	514	894	412	894	388	872	404
1327	753	1671	823	1900	818	1900	802	1862
1328	753	1671	823	1900	818	1900	807	1853
1331	1360	897	1407	743	1360	706	1379	723
1950	1096	2277	1688	2818	1390	2482	1688	2818
1987	6723	-	6723	-	6723	-	6723	-
1989	6638	-	6638	-	6638	-	6638	-
2039	6299	-	6299	-	6299	-	6299	-
2379	467	579	467	654	467	579	454	649
2381	1923	795	2389	1099	2194	957	2461	1132
2455	1150	977	1393	687	1213	626	1383	668
2456	977	1150	687	1393	626	1213	668	1383
2457	1676	3280	1843	2981	1682	2845	1880	3041
2458	2577	3486	2905	3894	2574	3486	2963	3972
2463	1479	1639	1478	2389	1405	2194	1522	2461
2465	1031	1359	1208	1362	1140	1243	1175	1344
2466	1287	714	1287	633	1287	623	1326	629
2467	1287	714	1287	633	1287	623	1326	629
2470	6215	-	6215	-	6215	-	6215	-
2633	1704	-	1878	-	1724	-	1938	-
2635	1692	1704	2054	1878	1809	1724	2085	1938
2636	1692	1704	2054	1878	1809	1724	2120	1906
2637	3056	1835	2981	2054	2651	1851	3041	2085
2799	526	817	526	857	526	838	526	857
2800	1152	1058	897	1186	837	1083	897	1186
2982	1124	1852	756	1900	811	1900	746	1849
3066	526	817	526	857	526	838	526	857
3172	2577	3486	2905	3894	2574	3486	2963	3972
3218	1096	2277	1688	2818	1390	2482	1688	2818
3314	1072	999	990	1208	944	1122	963	1175
3500	526	817	526	857	526	838	526	857

CHAPTER 5. DATA ANALYSIS

This chapter describes the significance of the HCM adjustment factors used to calculate the capacities of arterial links. It also summarizes the results of statistical comparisons of the different sets of capacity values, travel times, travel speeds and volume to capacity ratios that resulted from travel demand modeling. Comparisons were made using root mean square error calculations and t-tests, using Set B as benchmark.

5.1 Significance of Adjustment Factors

The HCM methodology calculates the adjustment factors separately for through lanes, exclusive left-turn lanes during protected phasing, exclusive left-turn lanes during permitted phasing and exclusive right-turn lanes. The distribution of the adjustment factor values in the subregion, for the above four cases has been shown in Appendix B.

From the distribution plots it was observed that the variation was the highest for g/C ratios. Therefore the g/C ratio is the most import factor for determining capacity in this case. This suggested that the common practice of not accounting for the effect of g/C ratios on a link-by-link basis, was not accurate. The lane widths in the subregion ranged between 10 feet to 13 feet, number of bus stops between 0 and 15 and percentage of heavy vehicles ranged between 0 and 9. These variations are comparable to that of other networks. Also significant variations were observed for adjustment factors for left-turns, right-turns and lane-utilization.

To determine if the adjustment factors had a significant effect on capacity calculations, t-tests were performed to test if the adjustment factors were significantly different from 1. The results of the tests are summarized in Table 5-1. For almost all cases f_g and f_A took the value 1. This is because all links lie outside the CBD and have mostly flat grades.

For through lanes, factors f_W, f_{HV}, f_{bb}, f_{LU}, f_{RT} and f_{LT} were significantly different from 1 and therefore affected capacity calculations. This suggested that lane widths, percentage heavy vehicles, bus stops per hour, lane utilization factor, right-turns and left-turns had a significant effect on capacity calculations for through lanes of network links. However, there was not enough representation for grades, area types and parking. Therefore no general conclusions can be made on the effect of these factors, for this case.

Table 5-1 Significance of Adjustment Factors

Factor	Through Lanes		Left-Turn Lanes Protected Phase		Left-Turn Lanes Permitted Phase		Right-Turn Lanes	
	Mean	**t**	**Mean**	**t**	**Mean**	**t**	**Mean**	**t**
f_W	.9879	-3.66	.9749	-4.60	.9572	-8.31	.9657	-2.69
f_{HV}	.9867	-7.23	.9961	-1.56	.9943	-2.13	.9952	-1.453
f_g	.9999	-1	1	∞	1	∞	1	∞
f_p	.997	-1.75	.9968	-1	.9978	-1	1	-1
f_{bb}	.9937	-5.06	.996	-1.85	.9965	-2.117	.9968	-1.453
f_A	1	∞	1	∞	1	∞	1	∞
f_{LU}	.978	-8.16	.999	-1	1	∞	1	∞
f_{RT}	.9836	-8.22	1	∞	1	∞	.85	∞
f_{LT}	.9513	-4.45	.95	∞	.35	-22.07	1	∞

For left-turn lanes during protected phasing, it was observed that f_W and f_{bb} were significantly different from 1. This suggested that lane widths and bus stops per hour significantly affected capacity for this case. Factors f_{RT} and f_{LT} always took fixed values of 1 and 0.95 respectively. Therefore, f_{RT} can be ignored and the effect of f_{LT} can easily be incorporated for any large-scale capacity calculations. Factors f_{HV}, f_P and f_{LU} were not significantly different from one. This suggested that heavy vehicles, parking and lane utilization factors did not affect capacity for this case.

For left-turn lanes during permitted phasing f_W, f_{HV}, f_{bb} and f_{LT} had a significant effect on capacity calculations. This suggested that lane widths, heavy vehicles, bus stops per hour and left-turns affected capacity for this case. Factors f_{LU} and f_{RT} took a fixed value of 1. Also f_P was not significant for capacity calculations. This suggested that lane utilization, right-turning vehicles and parking did not affect capacity for this case.

For right-turn lanes f_W was significantly different from 1. This suggested that lane widths significantly affected capacity. Factors f_{HV}, f_p and f_{bb} were not significantly different from one. Also factors f_{LU} and f_{LT} always took the value 1. This suggested that heavy vehicles, parking, bus stops per hour, lane utilization and left-turns did not affect capacity for this case. Factor f_{RT} took the fixed value 0.85 and can therefore be easily incorporated for large-scale capacity calculations.

5.2 Description of the Comparison Tests

The results of travel demand modeling were analyzed to determine if there were significant differences when link-by-link capacity values were used. This was accomplished by making statistical comparisons by pairing the measures of each set with the measures of the same link in the benchmark Set B. Comparisons were made using Root Mean Square Errors (RMSE), Root Mean Square Error percentages (RMSE(%)) and t-tests. RMSE is generally used to measure how close a forecast $\hat{y}_t$ is to an actual value y_t (Mendenhall, 1993). The RMSE(%) measures the percentage variation of a forecast to the actual value. The advantage of a RMSE(%) is that it has no units. The formulae for calculating the above two measures is shown in Equation (5-1) and (5-2).

$$RMSE = \sqrt{\frac{1}{n}\sum_{t=1}^{n}(y_t - \hat{y}_t)^2} \qquad (5-1)$$

$$RMSE(\%) = \sqrt{\frac{1}{n}\sum_{t=1}^{n}\left(\frac{(y_t - \hat{y}_t)100}{y_t}\right)^2} \qquad (5-2)$$

A paired sample t-test could not be used for comparisons because the paired differences had several positive and negative values. Therefore, t-tests were conducted on the absolute differences between pairs of measures such as capacity, where pairs were made by pairing the measure of each link with that of the same link in the benchmark Set B. The t statistic for the test was calculated using Equation (5-3)

$$t = \frac{\overline{D}}{\frac{S_D}{\sqrt{N}}} \qquad (5-3)$$

$\overline{D}$ = The observed mean of absolute differences of paired observations

S_D= The standard deviation of the differences of paired observations

N= The number of pairs

The resulting distribution of t was a Student's t with N-1 degrees of freedom. From the test statistic, the one-tailed probability P was obtained. The null hypothesis stated that the mean of the absolute differences was 0. A 95% level of significance was assumed for all tests. The null hypothesis was rejected if the P value was less than 0.05.

5.3 Comparison of Capacity Values

The capacities in the AB and BA directions for all links in the subregion were pooled for analysis. The square of deviations of capacity values in Sets A, C, D, E and F from the corresponding value Set B were calculated for each link in the subregion. The RMSE was calculated from this total using Equation 5-1. Similarly the RMSE(%) was calculated using Equation 5-2 and the results are summarized in Table 5-2.

Table 5-2. RMSE of Capacities

Paired Sets	RMSE (vph)	RMSE%
BA	908	54.27
BC	617	91.36
BD	260	22
BE	208	19.11
BF	273	17.88

From the table it can be seen that pairs B-A and B-C had high RMSE(%) values. This suggested that average capacity values differed greatly from link-by-link capacity values. The RMSE % values reduced considerably for pairs B-D, B-E and B-F. This suggested that Sets D, E and F are better estimates than A and C.

Absolute differences were also obtained by pairing link capacities in Sets A, C, D E and F with the corresponding link capacity in Set B. A t-test was performed on the absolute differences in capacity values to test if they are significantly different from 0. The summary of the test is shown in Table 5-3.

Table 5-3. T-Test for Absolute Differences in Capacities

Pair	t	df	Sig. (1-tailed)	Mean Difference (vph)	95% Confidence Interval of the Difference (vph)	
					Lower	Upper
BA	14.019	139	.000	695	597	793
BC	15.933	139	.000	496	435	558
BD	11.654	139	.000	183	152	214
BE	8.703	139	.000	123	95	151
BF	11.131	139	.000	187	154	220

From the table it was seen that the P value was less than 0.05 for all pairs. Therefore, all sets including D, E and F were significantly different from Set B. This suggested that the compromises made in Sets D, E and F by ignoring the effects of adjustment factors, also affected capacity calculations.

5.4 Comparison of Travel Demand Modeling Results

Travel demand modeling was performed by assigning each of the capacity values in Sets A, B, C, D, E and F to the links in the subregion. Differences were observed in the total vehicle miles traveled and total vehicle time traveled as shown in Table 5-4. These differences indicated that paths of trips change when links-by-link capacity values were used.

Table 5-4. Total Vehicle Time and Distance Traveled

Capacity Set Used	Total Vehicle Time Traveled (Minutes)	Total Vehicle Distance Traveled (Miles)
A	13076177.7	6682303.63
B	13058980.5	6681121.23
C	13054012.6	6680449.54
D	13049933.1	6680614.97
E	13052949.4	6680795.62
F	13050108.9	6680580.60

The travel volumes, travel times, travel speeds and v/c ratios that resulted from modeling were analyzed for differences.

5.4.1 Comparison of Flow Volumes

The flow volumes in both the AB and BA directions were obtained for each link in the region and were pooled together for analysis. Six sets of assignment volumes (A to F) were obtained using each set of capacity values. Set B represented the benchmark for comparison of volumes because it was obtained using the capacity values in the benchmark Set B. The RMSE and RMSE (%) were calculated for each of the paired sets and are summarized in Table 5-5. From the table it can be seen that the assignment volumes produced by using the capacity values in Sets A and C varied considerably from the benchmark. This suggested that use of average capacity values affected the directional travel volume estimates that resulted from modeling. Sets D, E and F resulted in much lower RMSE % values suggesting in this instance that Sets D, E and F are better volume estimates than Sets A and C.

Table 5-5. RMSE for Flow Volumes

Paired sets	RMSE (Veh/day)	RMSE %
BA	703	77.39
BC	377	15.6
BD	137	4.84
BE	148	4.90
BF	151	4.87

T-tests were also performed to analyze the absolute differences in flow volumes between each set and Set B. The results are summarized in Table 5-6. Significant differences were observed for all pairs at a 95% level of confidence.

Table 5-6. T-Test for Absolute Differences in Flow Volumes

Pair	T	df	Sig. (1-tailed)	Mean Difference (Veh/day)	95% Confidence Interval of the Difference	
					Lower(Veh/day)	Upper (Veh/day)
BA	9.247	139	.000	431	339	523
BC	6.746	139	.000	186	132	241
BD	8.685	139	.000	80	62	99
BE	7.475	139	.000	78	58	99
BF	8.745	139	.000	90	69	110

This suggested that compromises in Sets D, E and F also affected the travel volume estimates resulting from travel demand modeling.

5.4.2 Comparison of Travel Times

Six sets of travel time A, B, C, D, E and F were obtained for links in the subregion using the corresponding six sets of capacity values. The travel time Set B, was the benchmark for comparisons. The results of the RMSE and RMSE(%) calculations are summarized in Table 5-7.

Table 5-7. RMSE for Travel Times

Paired sets	RMSE (Minutes)	RMSE%
BA	0.054705	14.44
BC	0.012868	3.72
BD	0.005629	1.52
BE	0.005487	1.32
BF	0.005905	1.50

From the table it was apparent that Set A travel times were not reliable. However the travel time estimates of Sets C, D, E and F all had low RMSE% values. This suggested that use of accurate averages may be sufficient to produce reliable travel time estimates. The summary of t tests for travel times is summarized in Table 5-8.

Table 5-8. T-Test for Absolute Differences in Travel Time

Pair	t	df	Sig. (1-tailed)	Mean Difference (Minutes)	95% Confidence Interval of the Difference	
					Lower (Minutes)	Upper (Minutes)
BA	4.382	139	.000	1.90579E-02	1.04584E-02	2.76573E-02
BC	4.239	139	.000	4.35357E-03	2.32293E-03	6.38422E-03
BD	4.782	139	.000	2.11571E-03	1.24089E-03	2.99053E-03
BE	4.316	139	.000	1.88643E-03	1.02228E-03	2.75058E-03
BF	4.805	139	.000	2.22900 E-03	1.31 E-03	3.15 E-03

Significant differences were observed in all cases. This suggested that both average capacity values and link-by-link values calculated by ignoring adjustment factors, affected travel time estimates resulting from travel demand modeling.

5.4.3 Comparison of Travel Speeds

Estimates of travel speeds were obtained from the link distances and travel times. The results of RMSE and RMSE % calculations are summarized in Table 5-9.

Table 5-9. RMSE for Travel Speed

Paired Sets	RMSE (mph)	RMSE%
BA	3.09	8.85
BC	1.15	5.13
BD	.50	1.61
BE	.41	1.33
BF	.51	1.57

All RMSE % values were low. However it was observed that travel times D, E and F had lower RMSE% values than A and C. This suggested that link-by-link capacity values estimated travel speeds better than average capacity values. The t-test results for travel speeds are shown in Table 5-10.

Table 5-10 T-Test for Absolute Differences in Travel Speed

Pair	t	df	Sig. (1-tailed)	Mean Difference (mph)	95% Confidence Interval of the Difference	
					Lower (mph)	Upper (mph)
BA	5.151	139	.000	1.236018	.761626	1.710411
BC	3.782	139	.000	.352123	.168056	.536191
BD	4.594	139	.000	.182904	.104192	.261617
BE	4.620	139	.000	.152632	.087312	.217952
BF	4.729	139	.000	.188857	.109897	.267817

Significant differences were observed in all cases. This suggested that both average capacity values and link-by-link values calculated by ignoring adjustment factors, affected travel speed estimates.

5.4.4 Comparison of v/c Ratios

Set B represented the benchmark because it was obtained using Set B capacity values. All other sets of v/c ratios were compared to Set B. The results of RMSE and RMSE (%) calculations are summarized below.

Table 5-11. RMSE for v/c Ratios

Paired sets	RMSE	RMSE%
BA	.273	157.03
BC	.161	46.41
BD	.067	15.73
BE	.059	21.4
BF	.069	16.12

It can be seen from the above table that capacity Sets A and C resulted in high RMSE % values. This suggested that they did not estimate v/c ratios accurately. Sets D, E and F appear to estimate v/c ratios better than A and C.

The summary of one-sample t-tests is shown in Table 5-12.

Table 5-12. T-Test for Absolute differences in v/c Ratios

Pair	T	df	Sig. (1-tailed)	Mean Difference	95% Confidence Interval of the Difference	
					Lower	Upper
BA	13.314	139	.000	.202758	.172648	.232868
BC	9.007	139	.000	.097192	7.58564E-02	.118529
BD	9.033	139	.000	.040552	3.16768E-02	4.94289E-02
BE	8.380	139	.000	.033879	2.58855E-02	4.18730E-02
BF	9.030	139	.000	.041690	3.26 E-02	5.08E-02

All differences were significant. This suggested that average capacity values and link-by-link capacity values, calculated by ignoring the effect of adjustment factors, affected v/c ratio estimates.

CHAPTER 6. CONCLUSIONS AND FUTURE WORK

6.1 Conclusions

The objective of the research was to analyze the current practice of assigning capacity values to links in the Baton Rouge street network and to determine how capacity values could be assigned more accurately without greatly increasing time, effort and costs.

The current practice of assigning average capacity values depending on just the facility type and number of lanes, was compared to the practice of assigning capacities on a link-by-link basis using the HCM methodology. The measures that were compared were capacity and the results of travel demand modeling such as travel volumes, travel speeds, travel times and v/c ratios. The comparisons were made using Root Mean Square Error (RMSE), RMSE percentage and t-tests of absolute differences in measures obtained for both practices. It was found that for the Baton Rouge street network, assigning capacities on a link-by-link basis produced significant differences in results of modeling when compared to the practice of assigning average capacities. This suggested that the current practice of assigning capacity to links of a network, depending on a broad classification system was not accurate.

The variability of g/C ratios and HCM adjustment factors for calculating capacities of signalized arterial links was studied. It was found that the g/C ratio had the highest variation in the study sites selected and was therefore the most important factor for capacity calculations. This suggested that the current practice of using generalized averages, for g/C ratios was not accurate. For through lanes, which contribute most of the capacity of an arterial link it was found that all adjustment factors, except factors for area type and grade, had a significant effect on capacity calculations. This suggested that for the Baton Rouge network the adjustment factors for lane widths, heavy vehicles, parking, bus stops, lane utilization, right-turns and left-turns should be considered for estimating the through-lanes capacity of links. For left-turn lanes it was found that adjustment factors for lane width, bus stops and left-turns significantly affected capacity and therefore should be considered for estimating capacity of links. Similarly for right turn lanes it was found that adjustment factors for lane widths and right-turns should be included for capacity estimation. Grades and area type did not have an effect on capacity because all the study sites had flat grades and were located outside the central business district. However the insignificance of these factors cannot be generalized for the entire network.

An attempt was made to determine how capacities could be assigned to reduce data collection effort and cost, without significantly affecting modeling results. To achieve this objective, sets of link capacities were calculated making various compromises, by ignoring the effects of adjustment factors. Results of travel demand modeling, using these sets of capacities were compared to a benchmark. The benchmark contained results of modeling, using capacities calculated by including all the HCM adjustment factors. Measures of capacity, travel volume, travel time, travel speed and v/c ratios were compared using RMSE, RMSE percentage and t-tests. The RMSE calculations for travel volumes, travel speeds and travel times resulted in low values. This initially suggested that the effects of adjustment factors could be ignored to reduce data collection effort while assigning capacities. However, t-tests of absolutes differences in measures showed significant differences for all comparisons. This suggested that compromises made in the thesis for estimating the various sets of capacities, also affected the results of modeling. Therefore, the thesis failed to make any conclusions on whether the effect of some adjustment factors could be ignored to reduce data collection effort without significantly affecting the results of modeling. It was further believed that the size of subregion selected for the study was not sufficient for this purpose. Similar studies should be conducted on larger subregions to make any conclusions on whether the effect of some factors could be ignored.

Assigning capacity based on a broad classification system is a common practice used in networks of other cities. The study region selected for this thesis had ranges of lane widths, heavy vehicles and bus stops resembling other networks. Also the study region had a sufficient range of values for g/C ratios and adjustment factors for left-turns, right-turns and lane utilization. However, the study region did not have any variation for grades and area type. Therefore, the results of this study can be applied to other networks with similar characteristics.

6.2 Future Work

The HCS software currently cannot be used for large-scale capacity calculations. Therefore studies could be carried out on the development of algorithms and software for large-scale capacity calculations.

Estimating capacities on a large scale would require traffic, geometric and signalization data for several links in a network. Researchers have worked on using advanced technologies like Global Positioning Systems (GPS) (Quiroga, 1997) for collecting data like travel times. Further studies could be carried out on cost effective data collection methods for networks.

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APPENDIX A. LIST OF STUDY SITES

Link ID	AB Direction	BA Direction
926	Nicholson Dr @ Terrace St	N/A
975	Terrace St @ Nicholson Dr	Terrace St @ Highland Rd
1250	Benhur Rd @ Burbank Dr	Benhur Rd @ Nicholson Dr
1251	Nicholson Dr @ W Lee Drive	Nicholson Dr @ Benhur Rd
1254	Benhur Rd @ Nicholson Dr	Benhur Rd @ Burbank Dr
1255	W Lee Dr @ Burbank Dr	W Lee Dr @ Nicholson Dr
1256	Nicholson Dr @ Jennifer Jean Dr	Nicholson Dr @ W Lee Dr
1257	Bright Side Dr @ River Rd	Bright Side Dr @ Nicholson Dr
1260	Burbank Dr @ W Lee Dr	Burbank Dr @ Benhur Rd
1265	Highland Rd @ LSU Ave	Highland Rd @ Lee Dr
1266	Burbank Dr @ E. Boyd Dr	Burbank Dr @ W Lee Dr
1292	LSU Ave @ Highland Rd	Stanford Ave @ W. Lakeshore Dr
1294	W Lakeshore Dr @ Stanford Ave	W Lakeshore Dr @ E Parker Blvd
1295	Highland Rd @ Dalrymple	Highland Rd @ Stadium Dr
1296	Highland Rd @ Stadium Dr	Highland Rd @ Dalrymple
1297	Highland Rd @ LSU Ave	Highland Rd @ W Parker Blvd
1298	W Parker Blvd @ Burbank Dr	W Parker Blvd @ Highland Rd
1299	Highland Rd @ Nicholson Dr Ext	Highland Rd @ W Parker Blvd
1300	E Parker Blvd @ W Lakeshore Dr	E Parker Blvd @ Highland Rd
1301	Highland Rd @ Lee Dr	Highland Rd @ LSU Ave
1303	Nicholson Dr @ Nicholson Dr Ext	Nicholson Dr @ Burbank Dr
1304	Burbank Dr @ E Boyd Dr	Burbank Dr @ Nicholson Dr
1305	Gourrier Ave @ River Rd	Gourrier Ave @ Nicholson Dr
1306	Nicholson Dr @ Jennifer Jean Dr	Nicholson Dr @ Burbank Dr
1307	Gourrier Ave @ Nicholson Dr	Gourrier Ave @ River Rd
1308	River Rd @ Stadium Dr	River Rd @ Gourrier Ave
1309	River Rd @ Bright Side Dr	River Rd @ Gourrier Ave
1311	River Rd @ W Kinley St	River Rd @ W Roosevelt St
1312	W Roosevelt St @ Nicholson Dr	W Roosevelt St @ River Rd
1313	River Rd @ Stadium Dr	River Rd @ W Roosevelt St
1314	River Rd @ Oklahama St	River Rd @ W Mckinley St
1315	W Roosevelt St @ Nicholson Dr	W Roosevelt St @ River Rd
1316	Nicholson Dr @ Terrace St	Nicholson Dr @ W Roosevelt St
1317	W Roosevelt St @ Highland Rd	W Roosevelt St @ Nicholson Dr
1318	Nicholson Dr @ Stadium Dr	Nicholson Dr @ W Roosevelt St
1319	Nicholson Dr @ Terrace St	Nicholson Dr @ W Roosevelt St
1320	Nicholson Dr @ Terrace St	Nicholson Dr @ W Roosevelt St

Appendix A contd.

Link ID	AB Direction	BA Direction
1321	Highland Rd @ W Roosevelt St	Highland Rd @ E Washington St
1322	Highland Rd @ E Washington St	Highland Rd @ W Roosevelt St
1323	Nicholson Dr Ext @ Highland Rd	Nicholson Dr Ext @ Nicholson Dr
1324	Nicholson Dr @ Stadium Dr	Nicholson Dr @ Nicholson Dr Ext
1325	Highland Rd @ Dalrymple Dr	Highland Rd @ W Roosevelt St
1326	E Roosevelt St @ Thomas Delpit Rd	E Roosevelt St @ Highland Rd
1327	Thomas Delpit Rd @ E Roosevelt St	Thomas Delpit Rd @ E Washington St
1328	Thomas Delpit Rd @ E Washington St	Thomas Delpit Rd @ E Roosevelt St
1331	Dalrymple Dr @ Morning Glory	Dalrymple Dr @ Highland Rd
1950	Nicholson Dr @ Burbank Dr	Nicholson Dr @ Jean Jennifer Dr
1987	I-10 W (Near Dalrymple Dr Entrance)	N/A
1989	I-10 E (Near Dalrymple Dr Exit)	N/A
2039	I-10 W (Near Nicholson Dr Entrance)	N/A
2379	Nicholson Dr Ext @ Highland Rd	Nicholson Dr Ext @ Nicholson Dr
2381	Burbank Dr @ E Boyd Dr	Burbank Dr @ Nicholson Dr
2455	Stadium Dr @ Nicholson Dr	Stadium Dr @ Highland Rd
2456	Stadium Dr @ Highland Rd	Stadium Dr @ Nicholson Dr
2457	Nicholson Dr @ Stadium Dr	Nicholson Dr @ W Roosevelt St
2458	Nicholson Dr @ Stadium Dr	Nicholson Dr @ Nicholson Dr Ext
2463	Burbank Dr @ W Lee Dr	Burbank Dr @ E Boyd Dr
2465	Highland Rd @ Stadium Dr	Highland Rd @ W Parker Blvd
2466	Stadium Dr @ River Rd	Stadium Dr @ Nicholson Dr
2467	Stadium Dr @ River Rd	Stadium Dr @ Nicholson Dr
2470	I-10 E (Near Nicholson Dr Ext)	N/A
2633	N/A	Nicholson Dr @ South Blvd
2635	Nicholson Dr @ Terrace St	Nicholson Dr @ South Blvd
2636	Nicholson Dr @ South Blvd	Nicholson Dr @ Terrace St
2637	Nicholson Dr @ W Roosevelt St	Nicholson Dr @ Terrace St
2799	Bright Side Dr @ River Rd	Bright Side Dr @ Nicholson Dr
2800	Highland Road @ Lee Dr	Highland Road @ LSU Ave
2982	Stadium Dr @ W Parker Blvd	Stadium Dr @ Highland Rd
3066	Bright Side Dr @ River Rd	Bright Side Dr @ Nicholson Dr
3172	Nicholson Dr @ Stadium Dr	Nicholson Dr @ Nicholson Dr Ext
3218	Nicholson Dr @ W Lee Dr	Nicholson Dr @ Jennifer Jean Dr
3314	Highland Rd @ Dalrymple Dr	Highland Rd @ Stadium Dr
3500	Brightside Dr @ River Rd	Bright Side Dr @ Nicholson Dr

APPENDIX B. DISTRIBUTION OF ADJUSTMENT FACTOR VALUES

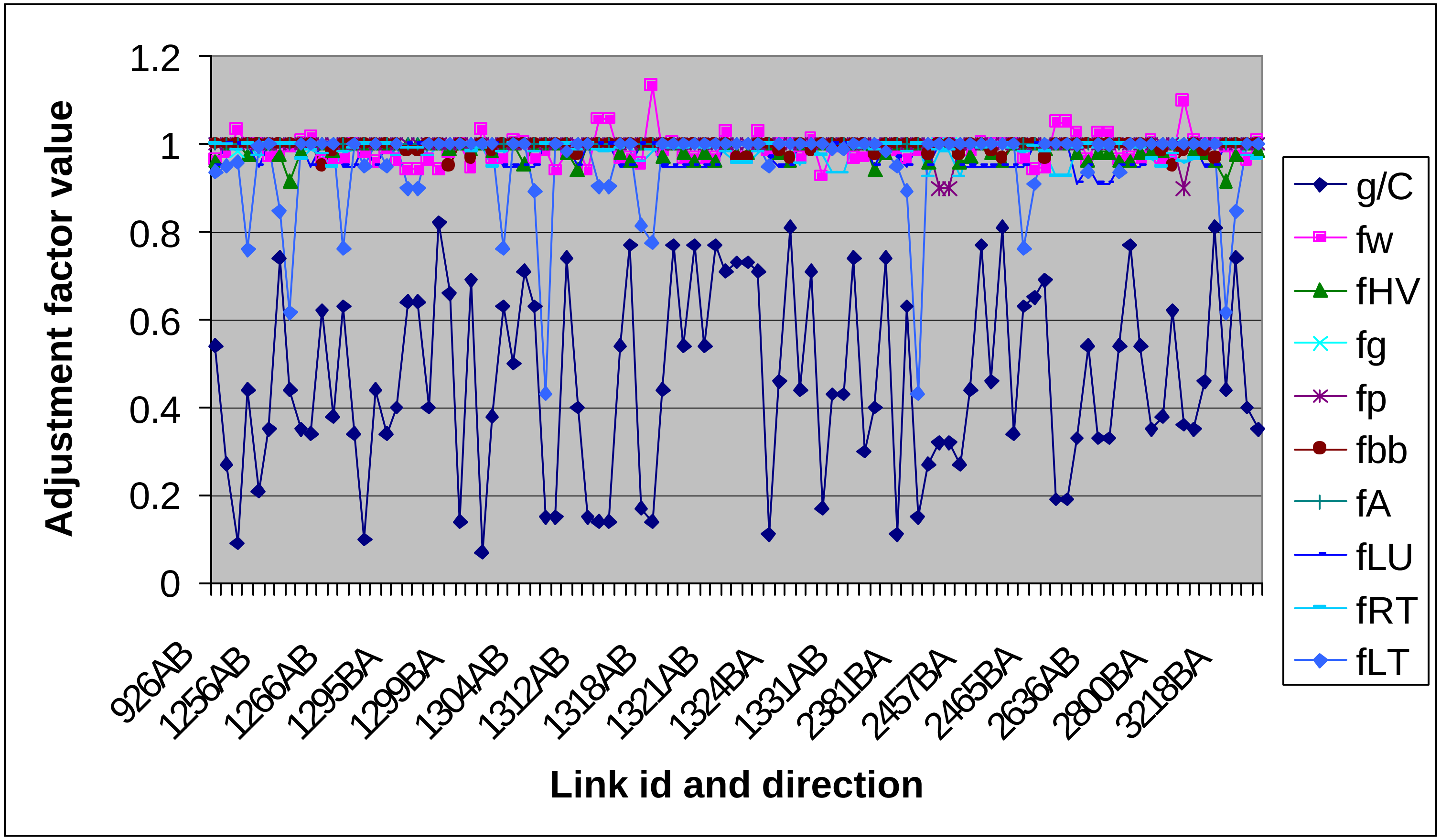

Figure B-1 Distribution of Adjustment Factors for Through Lanes

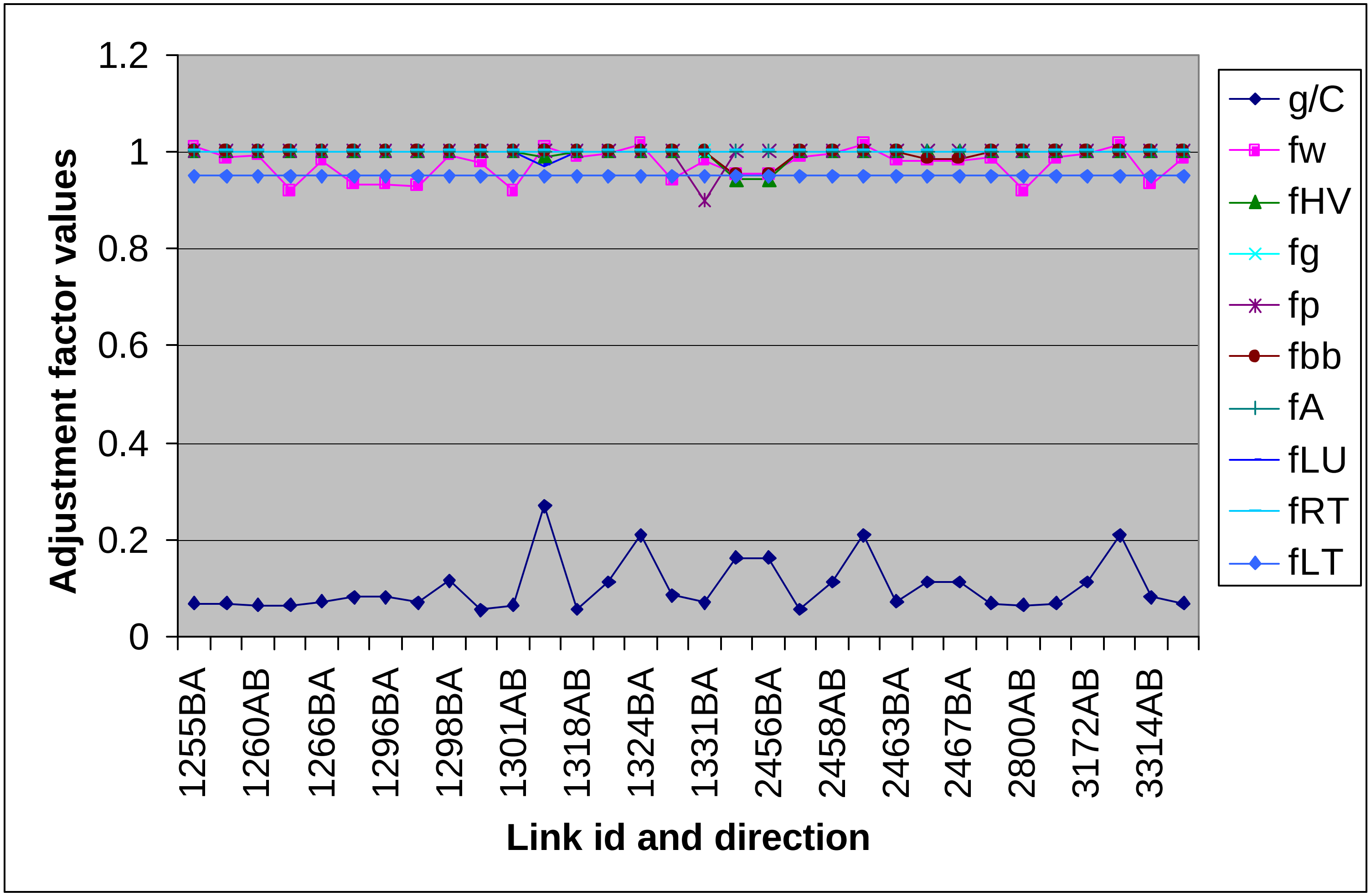

Figure B-2 Distribution of Adjustment Factors for Left-Turn Lanes -Protected Phasing

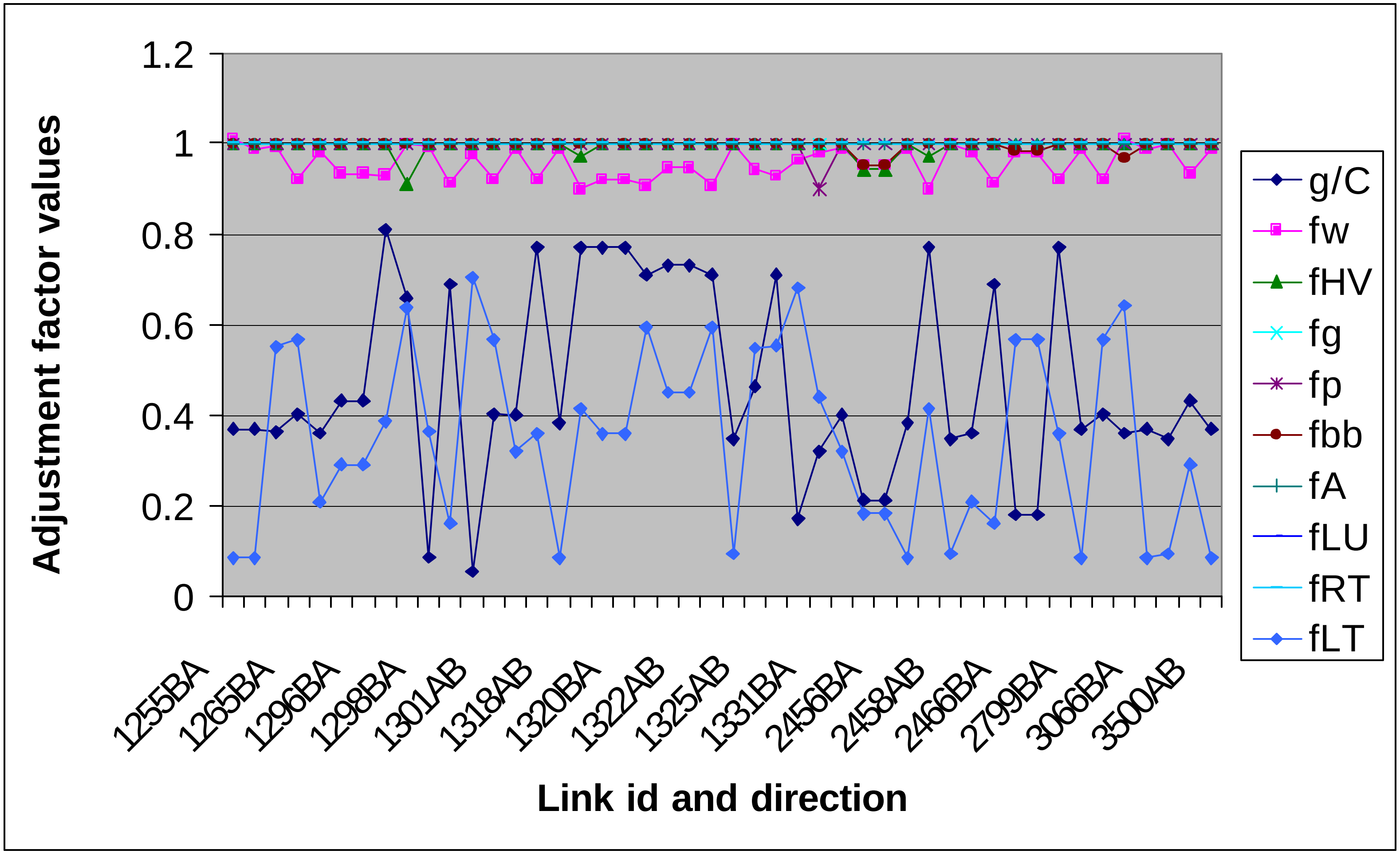

Figure B-3 Distribution of Adjustment Factors for Left-Turn Lanes- Permitted Phasing

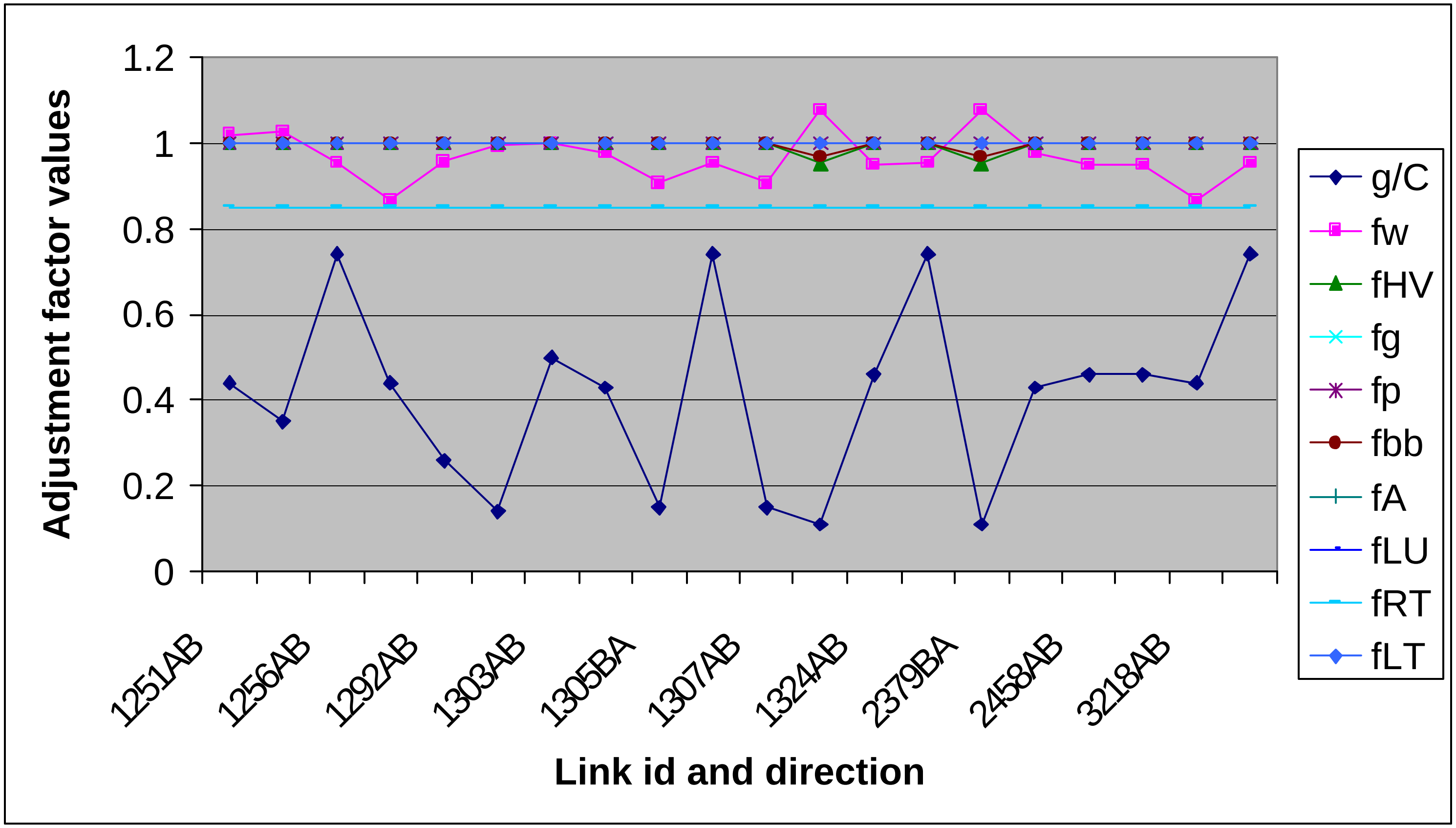

Figure B-4 Distribution of Adjustment Factors for Right-Turn Lanes

APPENDIX C. DIRECTIONAL FLOW VOLUMES (VEHICLES PER DAY)

Link ID	Set A		Set B		Set C		Set D		Set E		Set F	
	AB	BA	AB	BA	AB	BA	AB	BA	AB	BA	AB	BA
926	91	-	32	-	32	-	32	-	32	-	32	-
975	6718	1633	6771	1658	7702	1667	6876	1663	6845	1660	6843	1660
1250	2572	229	2080	229	1664	229	1652	229	1643	229	1652	229
1251	3259	582	3908	582	3889	583	3889	582	3902	583	3889	582
1254	2567	217	2075	217	1658	217	1647	217	1638	217	1647	217
1255	5912	2905	5626	2905	5790	2905	5600	2906	5619	2905	5599	2906
1256	4213	3780	6354	4186	6335	4346	6336	4154	6348	4179	6336	4154
1257	2003	2766	511	2075	511	2079	511	2080	511	2075	511	2080
1260	6387	1537	6069	1495	6136	1502	6135	1491	6126	1509	6134	1500
1265	5770	2988	6433	3107	7079	3115	6264	3105	6526	3103	6261	3109
1266	7448	1083	6306	1066	6023	1060	6622	1064	6677	1059	6621	1067
1292	1303	6454	966	6319	948	6597	977	6382	971	6661	977	6371
1294	4370	3975	4415	3559	4399	3559	4355	3558	4322	3608	4368	3559
1295	8768	9831	10742	10529	10699	10526	10512	10509	10494	10487	10443	10490
1296	2342	4241	2600	5128	2602	5179	2602	5025	2594	4996	2596	4937
1297	1720	4910	1850	5382	1853	5727	1851	5164	1845	5137	1846	5161
1298	2001	2341	1171	2379	2172	1756	1273	2333	747	2373	1274	2333
1299	6982	4501	8563	4159	8654	4332	8124	4325	8613	4187	8102	4320
1300	3576	2528	3041	2706	3179	4043	3175	2601	3082	2592	3176	2583
1301	2725	11065	2790	11675	2801	12324	2801	11519	2791	11772	2796	11506
1303	7223	1703	7220	1601	7169	1599	7389	1603	7343	1606	7387	1606
1304	2079	6718	2534	5396	2488	6490	2485	5610	2528	5144	2489	5609
1305	5213	506	4326	506	5335	505	4433	505	3961	505	4434	505
1306	2048	7635	2048	8625	2049	8446	2049	8638	2049	8625	2049	8638
1307	0	0	0	0	0	0	0	0	0	0	0	0
1308	3638	345	3583	345	3578	345	3578	345	3583	345	3578	345
1309	345	3638	345	3583	345	3578	345	3578	345	3583	345	3578
1311	3060	1798	2260	1886	2255	1505	2254	1783	2260	1804	2254	1783
1312	288	104	284	104	284	104	284	104	284	104	284	104
1313	1902	3348	1990	2543	1609	2539	1887	2538	1908	2543	1887	2538
1314	3071	1912	2307	1997	2302	1618	2301	1895	2306	1917	2301	1895
1315	288	104	284	104	284	104	284	104	284	104	284	104
1316	9472	5362	9335	4966	9204	5304	9601	5069	9535	5044	9666	5073
1317	934	942	896	940	895	940	894	941	895	940	894	941
1318	5263	9180	4865	9010	5203	8878	4969	9274	4943	9209	4972	9339
1319	11768	5169	11595	4774	11465	5111	11861	4877	11795	4850	11927	4881
1320	11394	4609	11258	4223	11116	4559	11513	4325	11446	4298	11578	4329
1321	6071	5909	6853	8121	6853	8066	6831	7872	6812	7795	6812	7803

Appendix C contd.

Link ID	Set A		Set B		Set C		Set D		Set E		Set F	
	AB	BA	AB	BA	AB	BA	AB	BA	AB	BA	AB	BA
1322	9276	6656	11425	7405	11384	7408	11190	7385	11113	7366	11121	7367
1323	129	876	47	1533	47	424	47	1424	47	1908	47	1509
1324	8099	1832	8753	1648	7593	1646	8813	1650	9252	1653	8897	1653
1325	7273	6732	8007	8909	8007	8855	7985	8663	7965	8581	7967	8594
1326	1551	1939	1479	1889	1479	1889	1480	1890	1475	1889	1479	1890
1327	1939	1551	1889	1479	1889	1479	1890	1480	1889	1475	1890	1479
1328	5345	337	5434	285	5447	284	5443	286	5445	284	5442	286
1331	196	107	49	96	48	95	50	99	48	95	50	99
1950	7635	2048	8625	2048	8446	2049	8638	2049	8625	2049	8638	2049
1987	29942	-	29820	-	29891	-	29839	-	29894	-	29844	-
1989	24850	-	24990	-	25072	-	25058	-	25058	-	25060	-
2039	12391	-	12395	-	12393	-	12391	-	12393	-	12391	-
2379	3098	3393	2480	4094	2651	4134	2647	3759	2514	4276	2647	3825
2381	1330	9435	1260	7372	1224	8684	1228	7807	1262	7335	1232	7806
2455	540	303	540	303	540	303	540	303	540	303	540	303
2456	303	2033	439	1893	303	540	303	1936	448	1915	303	1968
2457	5263	9180	4865	9010	5203	8878	4969	9274	4943	9209	4972	9339
2458	10141	3049	10109	2739	9007	2736	10265	2740	10681	2743	10330	2743
2463	802	9247	756	8076	753	7797	757	8395	760	8458	760	8394
2465	3589	1403	4469	1679	4520	1681	4365	1678	4337	1673	4277	1673
2466	3454	876	3367	1625	3708	1625	3469	1625	3440	1625	3469	1625
2467	867	2715	118	2802	118	2422	118	2700	118	2721	118	2700
2470	17407	-	17412	-	17416	-	17416	-	17414	-	17416	-
2633	-	11272	-	11741	-	12125	-	11993	-	11914	-	12020
2635	91	11272	32	11741	32	12125	32	11993	32	11914	32	12020
2636	91	11272	32	11741	32	12125	32	11993	32	11914	32	12020
2637	4521	11214	4137	11328	4473	11128	4239	11583	4212	11505	4243	11645
2799	594	2310	594	2366	594	2370	594	2371	594	2366	594	2371
2800	1412	4389	1559	4972	1563	5625	1559	4814	1554	5070	1554	4810
2982	399	1842	518	1709	381	356	383	1753	526	1731	383	1785
3066	2003	2766	511	2075	511	2079	511	2080	511	2075	511	2080
3172	9059	2801	8141	2491	8008	2488	8404	2492	8339	2496	8469	2496
3218	4447	3941	6588	4347	6568	4507	6569	4315	6582	4340	6569	4315
3314	6787	7240	8956	8102	8901	8100	8712	8083	8627	8059	8642	8064
3500	3638	345	3583	345	3578	345	3578	345	3583	345	3578	345

APPENDIX D. DIRECTIONAL TRAVEL TIMES (MINUTES)

Link ID	Set A		Set B		Set C		Set D		Set E		Set F	
	AB	BA	AB	BA	AB	BA	AB	BA	AB	BA	AB	BA
926	0.280	-	0.280	-	0.280	-	0.280	-	0.280	-	0.280	-
975	0.080	0.060	0.097	0.070	0.064	0.060	0.089	0.068	0.091	0.068	0.091	0.069
1250	0.656	0.651	0.653	0.651	0.652	0.651	0.652	0.651	0.652	0.651	0.652	0.651
1251	0.448	0.440	0.441	0.440	0.442	0.440	0.440	0.440	0.440	0.440	0.440	0.440
1254	0.483	0.480	0.482	0.480	0.480	0.480	0.481	0.480	0.481	0.480	0.481	0.480
1255	0.835	0.827	0.867	0.827	0.829	0.827	0.854	0.827	0.861	0.827	0.851	0.827
1256	0.594	0.584	0.565	0.567	0.578	0.568	0.565	0.565	0.565	0.565	0.565	0.565
1257	0.564	0.567	0.562	0.562	0.562	0.562	0.562	0.562	0.562	0.562	0.562	0.562
1260	0.132	0.130	0.131	0.130	0.131	0.130	0.131	0.130	0.131	0.130	0.131	0.130
1265	0.505	0.482	0.490	0.480	0.483	0.480	0.486	0.481	0.490	0.481	0.486	0.481
1266	0.838	0.816	0.819	0.816	0.818	0.816	0.817	0.816	0.817	0.816	0.817	0.816
1292	1.248	1.351	1.248	1.253	1.248	1.254	1.248	1.252	1.248	1.255	1.248	1.252
1294	0.933	0.916	0.884	0.881	0.885	0.882	0.884	0.881	0.884	0.881	0.884	0.881
1295	0.103	0.132	0.060	0.062	0.062	0.062	0.062	0.057	0.064	0.058	0.063	0.057
1296	0.754	0.790	0.751	0.756	0.751	0.758	0.750	0.758	0.750	0.759	0.750	0.758
1297	0.450	0.462	0.449	0.450	0.449	0.451	0.449	0.451	0.449	0.452	0.449	0.451
1298	0.514	0.515	0.513	0.513	0.512	0.512	0.513	0.513	0.512	0.513	0.513	0.513
1299	0.191	0.175	0.172	0.172	0.174	0.172	0.172	0.172	0.172	0.172	0.172	0.172
1300	0.780	0.765	0.784	0.831	0.761	0.763	0.788	0.835	0.785	0.833	0.790	0.837
1301	0.290	0.495	0.290	0.354	0.290	0.307	0.290	0.328	0.290	0.350	0.290	0.328
1303	0.590	0.583	0.583	0.583	0.584	0.583	0.583	0.583	0.583	0.583	0.583	0.583
1304	0.360	0.366	0.360	0.372	0.360	0.362	0.360	0.364	0.360	0.365	0.360	0.363
1305	0.832	0.743	0.833	0.743	0.752	0.743	0.842	0.743	0.806	0.743	0.842	0.743
1306	0.762	1.183	0.760	0.771	0.760	0.819	0.760	0.770	0.760	0.777	0.760	0.770
1307	1.120	1.120	1.120	1.120	1.120	1.120	1.120	1.120	1.120	1.120	1.120	1.120
1308	0.519	0.504	0.505	0.504	0.506	0.504	0.505	0.504	0.505	0.504	0.505	0.504
1309	1.026	1.055	1.026	1.026	1.026	1.028	1.026	1.026	1.026	1.026	1.026	1.026
1311	0.365	0.361	0.360	0.360	0.360	0.360	0.360	0.360	0.360	0.360	0.360	0.360
1312	0.401	0.401	0.401	0.401	0.401	0.401	0.401	0.401	0.401	0.401	0.401	0.401
1313	1.049	1.068	1.047	1.047	1.047	1.047	1.046	1.047	1.047	1.047	1.046	1.047
1314	1.393	1.376	1.373	1.373	1.373	1.373	1.373	1.373	1.373	1.373	1.373	1.373
1315	0.360	0.360	0.360	0.360	0.360	0.360	0.360	0.360	0.360	0.360	0.360	0.360
1316	0.220	0.213	0.214	0.212	0.213	0.212	0.213	0.212	0.214	0.212	0.213	0.212
1317	1.105	1.105	1.108	1.110	1.105	1.105	1.106	1.108	1.106	1.107	1.106	1.108
1318	0.791	0.814	0.789	0.789	0.789	0.791	0.789	0.789	0.789	0.790	0.789	0.789
1319	0.339	0.313	0.320	0.312	0.315	0.312	0.317	0.312	0.320	0.312	0.317	0.312
1320	1.072	0.998	1.017	0.996	1.004	0.996	1.011	0.996	1.018	0.996	1.010	0.996

Appendix D contd.

Link ID	Set A		Set B		Set C		Set D		Set E		Set F	
	AB	BA	AB	BA	AB	BA	AB	BA	AB	BA	AB	BA
1321	0.543	0.540	0.511	0.513	0.513	0.516	0.514	0.517	0.514	0.519	0.514	0.517
1322	0.807	0.653	0.612	0.599	0.624	0.602	0.629	0.604	0.640	0.603	0.630	0.604
1323	0.831	0.831	0.831	0.832	0.831	0.831	0.831	0.832	0.831	0.833	0.831	0.832
1324	0.154	0.151	0.151	0.151	0.151	0.151	0.151	0.151	0.151	0.151	0.151	0.151
1325	0.720	0.697	0.646	0.639	0.642	0.646	0.668	0.648	0.674	0.648	0.671	0.649
1326	0.210	0.210	0.209	0.210	0.209	0.209	0.209	0.211	0.209	0.211	0.209	0.211
1327	0.765	0.764	0.764	0.764	0.764	0.764	0.764	0.764	0.764	0.764	0.764	0.764
1328	1.093	0.964	1.004	0.964	0.977	0.964	0.992	0.964	0.993	0.964	0.994	0.964
1331	0.990	0.990	0.990	0.990	0.990	0.990	0.990	0.990	0.990	0.990	0.990	0.990
1950	0.893	0.575	0.606	0.573	0.618	0.574	0.579	0.573	0.586	0.573	0.579	0.573
1987	0.427	-	0.422	-	0.422	-	0.422	-	0.422	-	0.422	-
1989	0.322	-	0.320	-	0.320	-	0.320	-	0.320	-	0.320	-
2039	1.245	-	1.244	-	1.244	-	1.244	-	1.244	-	1.244	-
2379	0.569	0.572	0.567	0.581	0.565	0.587	0.569	0.569	0.567	0.585	0.570	0.570
2381	0.433	0.462	0.433	0.481	0.433	0.438	0.433	0.449	0.433	0.455	0.433	0.447
2455	1.204	1.203	1.203	1.203	1.203	1.203	1.203	1.203	1.203	1.203	1.203	1.203
2456	0.694	0.696	0.694	0.694	0.694	0.694	0.694	0.694	0.694	0.694	0.694	0.694
2457	0.438	0.450	0.437	0.437	0.436	0.438	0.436	0.437	0.437	0.437	0.436	0.437
2458	0.024	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023
2463	0.632	0.672	0.632	0.638	0.632	0.637	0.632	0.634	0.632	0.634	0.632	0.633
2465	0.770	0.751	0.754	0.750	0.755	0.750	0.752	0.750	0.752	0.750	0.752	0.750
2466	0.465	0.465	0.465	0.465	0.465	0.465	0.465	0.465	0.465	0.465	0.465	0.465
2467	0.405	0.405	0.405	0.406	0.405	0.405	0.405	0.407	0.405	0.407	0.405	0.407
2470	0.254	-	0.253	-	0.253	-	0.253	-	0.253	-	0.253	-
2633	-	0.190	-	0.189	-	0.190	-	0.189	-	0.189	-	0.189
2635	0.120	0.129	0.120	0.124	0.120	0.121	0.120	0.123	0.120	0.124	0.120	0.123
2636	0.120	0.129	0.120	0.124	0.120	0.121	0.120	0.123	0.120	0.124	0.120	0.123
2637	0.328	0.351	0.327	0.335	0.328	0.330	0.327	0.332	0.328	0.335	0.327	0.332
2799	1.239	1.245	1.239	1.240	1.239	1.239	1.239	1.240	1.239	1.240	1.239	1.240
2800	0.400	0.407	0.400	0.403	0.400	0.401	0.400	0.402	0.400	0.403	0.400	0.402
2982	0.840	0.842	0.840	0.840	0.840	0.840	0.840	0.840	0.840	0.840	0.840	0.840
3066	0.078	0.079	0.078	0.078	0.078	0.078	0.078	0.078	0.078	0.078	0.078	0.078
3172	0.123	0.119	0.120	0.119	0.120	0.119	0.120	0.119	0.120	0.119	0.120	0.119
3218	0.031	0.031	0.030	0.030	0.030	0.030	0.030	0.030	0.030	0.030	0.030	0.030
3314	0.637	0.686	0.508	0.504	0.518	0.504	0.516	0.487	0.522	0.492	0.519	0.489
3500	0.997	0.969	1.001	0.969	0.972	0.969	1.000	0.969	1.001	0.969	1.000	0.969

APPENDIX E. DIRECTIONAL TRAVEL SPEEDS (MPH)

Link ID	Set A		Set B		Set C		Set D		Set E		Set F	
	AB	BA	AB	BA	AB	BA	AB	BA	AB	BA	AB	BA
926	30.00	-	30.00	-	30.00	-	30.00	-	30.00	-	30.00	-
975	22.39	29.80	18.56	25.82	28.35	29.85	20.16	26.32	19.72	26.55	19.89	26.12
1250	34.75	35.00	34.91	35.00	35.00	35.00	34.96	35.00	34.96	35.00	34.96	35.00
1251	44.19	45.00	44.95	45.00	44.85	45.00	44.98	45.00	44.97	45.00	44.98	45.00
1254	34.75	35.00	34.89	35.00	34.99	35.00	34.96	35.00	34.96	35.00	34.96	35.00
1255	44.53	44.97	42.93	44.99	44.88	44.99	43.54	44.99	43.20	44.99	43.69	44.99
1256	42.44	43.19	44.59	44.48	43.57	44.39	44.61	44.60	44.60	44.58	44.61	44.60
1257	44.72	44.41	44.84	44.82	44.84	44.82	44.84	44.82	44.84	44.82	44.84	44.82
1260	45.35	46.01	45.91	46.01	45.84	46.01	45.80	46.01	45.77	46.01	45.80	46.01
1265	42.76	44.83	44.10	44.96	44.70	44.99	44.48	44.91	44.13	44.87	44.48	44.91
1266	48.72	50.00	49.84	50.00	49.85	50.00	49.96	50.00	49.94	50.00	49.96	50.00
1292	25.00	23.10	25.00	24.89	25.00	24.87	25.00	24.92	25.00	24.87	25.00	24.92
1294	28.31	28.82	29.87	29.97	29.83	29.93	29.87	29.97	29.88	29.97	29.87	29.97
1295	17.56	13.67	30.05	29.17	28.85	29.17	29.03	31.86	28.13	31.03	28.66	31.58
1296	19.90	18.99	19.99	19.84	19.99	19.78	19.99	19.80	19.99	19.77	19.99	19.79
1297	34.70	33.78	34.71	34.67	34.71	34.61	34.71	34.58	34.71	34.54	34.71	34.57
1298	30.38	30.31	30.43	30.42	30.45	30.46	30.42	30.43	30.46	30.42	30.42	30.43
1299	31.46	34.32	34.92	34.94	34.48	34.97	34.94	34.94	34.92	34.92	34.94	34.94
1300	29.22	29.80	29.10	27.45	29.95	29.88	28.93	27.31	29.05	27.38	28.88	27.24
1301	43.42	25.44	43.51	35.60	43.52	40.99	43.46	38.40	43.45	35.99	43.46	38.41
1303	34.58	35.00	34.97	35.00	34.95	35.00	34.97	35.00	34.97	35.00	34.98	35.00
1304	34.99	34.40	35.00	33.92	35.00	34.85	35.00	34.64	35.00	34.57	35.00	34.68
1305	26.67	29.89	26.65	29.89	29.53	29.89	26.36	29.89	27.54	29.89	26.36	29.89
1306	44.87	28.90	45.00	44.35	44.99	41.78	45.00	44.41	45.00	43.99	45.00	44.41
1307	30.00	30.00	30.00	30.00	30.00	30.00	30.00	30.00	30.00	30.00	30.00	30.00
1308	53.19	54.72	54.71	54.72	54.58	54.72	54.71	54.72	54.71	54.72	54.71	54.72
1309	55.00	53.46	55.00	54.99	55.00	54.86	55.00	54.99	55.00	54.99	55.00	54.99
1311	34.50	34.94	35.00	35.00	34.99	35.00	35.00	35.00	35.00	35.00	35.00	35.00
1312	29.90	29.90	29.90	29.90	29.90	29.90	29.90	29.90	29.90	29.90	29.90	29.90
1313	34.90	34.27	34.97	34.97	34.97	34.95	34.98	34.97	34.97	34.97	34.98	34.97
1314	34.47	34.89	34.97	34.97	34.95	34.97	34.97	34.97	34.97	34.97	34.97	34.97
1315	30.00	30.00	30.00	30.00	30.00	30.00	30.00	30.00	30.00	30.00	30.00	30.00
1316	32.80	33.87	33.66	33.99	33.87	33.98	33.76	33.99	33.64	33.99	33.77	33.99
1317	29.86	29.86	29.78	29.72	29.86	29.86	29.84	29.79	29.83	29.82	29.83	29.78
1318	34.89	33.92	34.98	34.99	35.00	34.90	34.99	34.96	34.97	34.95	34.99	34.97
1319	31.84	34.49	33.79	34.59	34.29	34.59	34.04	34.59	33.76	34.59	34.06	34.59
1320	32.46	34.86	34.20	34.93	34.65	34.93	34.42	34.93	34.18	34.93	34.44	34.93

Appendix E contd.

Link ID	Set A		Set B		Set C		Set D		Set E		Set F	
	AB	BA	AB	BA	AB	BA	AB	BA	AB	BA	AB	BA
1321	37.58	37.81	39.93	39.75	39.77	39.55	39.68	39.50	39.72	39.33	39.66	39.47
1322	29.74	36.75	39.22	40.08	38.44	39.85	38.18	39.74	37.52	39.79	38.07	39.72
1323	30.31	30.31	30.31	30.29	30.31	30.31	30.31	30.31	30.31	30.26	30.31	30.30
1324	35.13	35.83	35.76	35.83	35.76	35.83	35.79	35.83	35.74	35.83	35.79	35.83
1325	35.02	36.15	39.00	39.44	39.23	39.02	37.72	38.86	37.39	38.89	37.53	38.83
1326	22.91	22.88	22.93	22.87	22.93	22.93	22.93	22.78	22.93	22.74	22.93	22.77
1327	21.95	21.98	21.99	22.00	22.00	22.00	21.99	22.00	21.99	22.00	21.99	22.00
1328	20.30	23.02	22.12	23.02	22.72	23.02	22.38	23.02	22.36	23.02	22.33	23.02
1331	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00
1950	28.90	44.87	42.55	45.00	41.77	44.99	44.54	45.00	44.02	45.00	44.54	45.00
1987	53.43	-	54.07	-	54.02	-	54.07	-	54.07	-	54.07	-
1989	55.90	-	56.20	-	56.18	-	56.20	-	56.20	-	56.20	-
2039	50.13	-	50.14	-	50.14	-	50.14	-	50.14	-	50.14	-
2379	29.55	29.36	29.65	28.92	29.76	28.63	29.54	29.52	29.62	28.72	29.49	29.47
2381	34.68	32.47	34.68	31.22	34.68	34.24	34.68	33.41	34.68	32.97	34.68	33.54
2455	19.94	19.94	19.94	19.94	19.94	19.94	19.94	19.94	19.94	19.94	19.94	19.94
2456	19.89	19.84	19.89	19.89	19.89	19.89	19.89	19.89	19.89	19.89	19.89	19.89
2457	34.28	33.33	34.36	34.36	34.38	34.29	34.37	34.35	34.36	34.34	34.37	34.35
2458	25.32	26.43	26.43	26.43	26.43	26.43	26.43	26.43	26.32	26.43	26.43	26.43
2463	44.62	41.99	44.62	44.23	44.62	44.25	44.62	44.51	44.62	44.47	44.62	44.53
2465	19.47	19.99	19.89	20.00	19.88	20.00	19.95	20.00	19.94	20.00	19.95	20.00
2466	39.97	40.00	39.97	39.98	40.00	40.00	39.97	39.97	39.97	39.97	39.97	39.97
2467	40.00	39.99	40.00	39.86	40.00	40.00	40.00	39.80	40.00	39.78	40.00	39.79
2470	49.68	-	49.74	-	49.74	-	49.74	-	49.74	-	49.74	-
2633	-	34.74	-	34.99	-	34.74	-	34.99	-	34.99	-	34.99
2635	35.00	32.63	35.00	33.84	35.00	34.60	35.00	34.15	35.00	33.84	35.00	34.23
2636	35.00	32.63	35.00	33.84	35.00	34.60	35.00	34.15	35.00	33.84	35.00	34.20
2637	34.76	32.50	34.82	34.07	34.81	34.53	34.82	34.30	34.81	34.05	34.82	34.32
2799	46.50	46.28	46.50	46.45	46.50	46.48	46.50	46.46	46.50	46.46	46.50	46.46
2800	44.99	44.23	45.00	44.68	45.00	44.88	44.99	44.82	44.99	44.68	44.99	44.82
2982	30.00	29.94	30.00	30.00	30.00	30.00	30.00	30.00	30.00	30.00	30.00	30.00
3066	53.71	53.30	53.85	53.78	53.85	53.85	53.85	53.85	53.85	53.85	53.85	53.85
3172	34.15	35.18	35.15	35.21	35.12	35.18	35.15	35.21	35.15	35.21	35.15	35.21
3218	38.22	39.09	39.87	40.68	39.60	40.40	40.54	40.68	40.40	40.68	40.54	40.68
3314	30.12	27.99	37.83	38.13	37.07	38.11	37.25	39.41	36.75	39.04	36.99	39.29
3500	43.93	45.19	43.78	45.19	45.08	45.19	43.79	45.19	43.78	45.19	43.79	45.19

VITA

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