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An integrated systems methodology for pedestrian traffic flow analysis

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AN INTEGRATED SYSTEMS METHODOLOGY FOR PEDESTRIAN TRAFFIC FLOW ANALYSIS

By

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ABSTRACT

The passage of the Intermodal Surface Transportation Efficiency Act of 1991 advanced the concept of intermodalism and renewed vigor into the accommodation of pedestrians as part of the nation's transportation system. In comparison to most of the rest of the world, pedestrian travel demand in the United States is relatively low. However, when pedestrian demand is concentrated at urban intersections, conflicts, safety, comfort, and capacity management are significant concerns.

The typical urban pedestrian transportation system involves three basic elements: sidewalks or walkways; midblock or intersection corner, holding, or queueing areas; and pedestrian crossings of roads, rail lines, or other physical features. The pedestrians on sidewalks or walkways have operating characteristics analogous to motorized vehicles on roadways. The level of service and capacity analyses of sidewalks have been documented in the literature. In a similar manner the concept of capacity and level of service have been individually applied to the street corner area and the crosswalk. Each critical pedestrian element has been considered individually, but not as a balanced system, especially at the most critical link--the signalized urban intersection.

In this research, a methodology and guidelines have been developed to analyze existing pedestrian elements at a signalized intersection, i.e., the sidewalk, intersection corner, and crosswalk; with a systems approach that identifies key interrelationships of the individual elements. This systems approach can guide the design of a balanced at-grade pedestrian transportation system; used to evaluate existing signalized at-grade intersection pedestrian elements; and develop decision support tools to evaluate the potential need for a grade-separated pedestrian facility.

A case study of the signalized at-grade intersection of Flamingo Road and Las Vegas Boulevard South in the Las Vegas valley area of Clark County, Nevada is presented to demonstrate the application of the methodology. Comments and recommendations regarding potential utilization of the research product presented in this thesis for pedestrian planning and design are offered.

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Travel by pedestrians is the most common mode of transportation throughout the world. In the United States the safe and efficient movement of motorized vehicles has been emphasized with the accommodation of pedestrians a lesser priority. For example, the planning and construction of the largest national highway project in the history of the United States, the federal interstate or national defense freeway system, banned the pedestrian from its right-of-way. Although the lowliness of pedestrian in comparative status to other modes of American transportation seems a modern problem, the following passage provides a historical continuum. (21)

Pedestrians Should Be Loved
From Ilf and Petrov, The Golden Calf
Moscow, 1931

> Pedestrians comprise the greater part of humanity. Moreover--its better part. Pedestrians created the world. It is they who built cities, erected multi-story buildings, laid sewerage and water mains, paved streets, and illuminated them with electric lights. It is they who spread civilization throughout the world, invented book printing, gunpowder, deciphered Egyptian hieroglyphics, introduced safety razors, abolished slave trade and discovered that 114 nourishing meals can be prepared from soybeans.
>
> When everything was finished, when our beloved planet assumed a fairly habitable look, motorists appeared on the scene.

> One should note that the automobile itself was invented by pedestrians, but somehow the motorists forgot that very quickly. Meek and intelligent pedestrians began to get squashed. Streets, created by pedestrians, were usurped by motorists. Roadways were widened to double their former size, sidewalks shrank to tape width and pedestrians began to cower in fear against the walls of buildings.
>
> In a large city, pedestrians lead a life of martyrdom. A kind of transportation ghetto was set up for them. They are allowed to cross streets only at intersections, that is precisely in those places where traffic is heaviest and where the hair by which a pedestrian's life usually hangs is most easily broken. In our large country, the automobile, intended by pedestrians for peaceful transportation of people and goods, assumed, the proportions of a lethal weapon. It puts out of commission row upon row of union members and their family and if, on occasion, a pedestrian succeeds in escaping from under the silver nose of an automobile, he is promptly fined for violating the traffic law.
>
> In general, the authority of pedestrians has been shaken considerably. They, who gave the world such outstanding figures as Horatio, Boyle, Labachavsky, and Anatole France, are now forced to clown in the tritest manner just to remind the world of their existence. God, oh God, Thou who in reality are dead, where did Thou, who dost not exist, leave the pedestrian!

The relegation of the pedestrian to a lower priority has forced the interaction of the pedestrian on a level with its most pervasive threat--the motorized vehicle. The pedestrians with their inferior operating characteristics are forced to enter the roadway, the domain of the vehicle, and compete.

In 1992, pedestrian accidents accounted for 6,809 of the 39,235 motor vehicle deaths nationwide (70). It is estimated that "109,000 pedestrians were injured or killed in motor vehicle collisions" (70) "costing American society about $1 billion annually."(38) "Approximately 83 percent of all pedestrian accidents and 74 percent of all pedestrian fatalities in the United States in 1985" (72) occurred in urban areas.

Pedestrian traffic is a major component of traffic flow, especially in urban areas. It is also the most unpredictable component of the roadway environment due to the generally unrestricted mobility, travel paths, and actions that a pedestrian can perform. The effects of the behavior of pedestrians become most notable at the most critical part of the urban surface arterial network--the signalized intersection.

Pedestrian behavior and interactions with other pedestrians and vehicular traffic have significant effects on traffic operations and traffic safety at signalized intersections. At many signalized intersections traffic control devices are used to direct, control, and guide pedestrian movements. For example, pedestrian traffic signals, push-buttons, and pedestrian interval phasing are considered in the design and construction of traffic signals.

Safety is the primary foundation for traffic laws. Along with these laws is the evolution of various traffic control devices at signalized intersections to enhance the safety and mobility of pedestrians. Despite these measures, undesirable pedestrian behavior at signalized intersections degrades traffic flow and exposes the pedestrian to potential accidents. Pedestrian traffic signals and traffic control devices also rely on visual cues. The visual information overload can create problems for the pedestrian to process information and react in a timely manner.

Despite measures to direct, control and guide pedestrian movements, the correct utilization and compliance with traffic control devices, such as pedestrian signals, by pedestrians falls short of desired behavior. More specifically, a significant percentage of pedestrians do not comply with pedestrian signal indications, such as the WALK, flashing DON'T WALK, and solid DON'T WALK or corresponding symbolic HAND-MAN messages in accordance with the Manual on Uniform Traffic Control Devices (58).

The utilization of the pedestrian push-button with traffic actuated signals (fixed time signals do not have pedestrian push-buttons) and the understanding of the pedestrian phases as part of the overall signal operation is low. Activation of push-buttons and pedestrian reaction to signal indications do not necessarily result in pedestrian movements that follow the pavement markings, such as crosswalks, provided to guide the pedestrian's path, especially in high pedestrian volume conditions. Because pedestrians are not as confined in their pathway as a vehicle is in a roadway, their actions are much more unpredictable and uncontrollable. Non-compliant pedestrian actions cause major disruptions of right and left turn movements at signalized intersections. Pedestrians cause obstructions that adversely affect the level of service and capacity of these vehicle movements.

1.2 NEEDS IN CURRENT PEDESTRIAN TRAFFIC SYSTEM METHODOLOGY AT SIGNALIZED INTERSECTIONS

Sidewalks are similar to roadways in that the width of the sidewalk determines how many pedestrians can walk at various levels of service--from free flow to congestion. Sidewalks in densely populated areas, central business districts, and attractive resort areas are very heavily used. It is important to ensure that adequate sidewalk width is available to provide adequate levels of service. Physical or moveable objects on the sidewalk can severely restrict the effective width of sidewalk and force pedestrians into streets or out of crosswalk areas into the paths of vehicular traffic. Pedestrian-vehicle conflicts cause adverse impacts on both vehicle and pedestrian flow. Pedestrian safety is also very important economically to resort areas.

The methodology developed in the Highway Capacity Manual: Special Report 209 (52) (HCM) by the Transportation Research Board of the National Research Council describes analytical procedures that can be utilized in analyses to determine deficient sidewalk locations. Levels of service and capacities can be calculated based on pedestrian flow rates, pedestrian densities, and the effective width of sidewalks. The effective sidewalk width takes into account the reduction in available physical sidewalk width due to fixed or moveable obstructions. The effective sidewalk width is one of the three basic elements of pedestrian traffic flow at signalized intersections.

The second major element of the pedestrian traffic system at signalized intersections is the street corner. The corner area provides available space for use by pedestrians, while waiting for the appropriate vehicular or pedestrian signal or to traverse by walking from one roadway to another without entering the intersection area. The HCM provides "level of service descriptions for standing spaces based on average pedestrian space, personal comfort, and degrees of internal mobility" (52). As density increases, the ability to circulate or move is restricted. The street corner is more complex than a queueing or waiting area, such as a transit platform, because it involves "intersecting sidewalk flows, pedestrians crossing the street, and others queued waiting for the signal to change" (52). In the pedestrian sidewalk network "the corner is often the critical link" (52).

Within the signalized intersection, the crosswalk is the third major element of the pedestrian traffic system. The crosswalk traverses the domain of the vehicle, so its pedestrian traffic flow is interrupted. Otherwise, the characteristics of uninterrupted flow on crosswalks are similar to sidewalks. The major differences of pedestrian flow analysis between sidewalks and crosswalks are attributable to signal timing and turning vehicles that interfere with the pedestrian green or "WALK" and "FLASHING DON'T WALK" (pedestrian clearance time) phases.

1.3 NEED FOR A SYSTEMS LEVEL OF SERVICE METHODOLOGY

The urban street network provides for a range of functions from access to property at the local street classification to through traffic at the major arterial classification. A critical element throughout the street network is the intersection. Planning and operations techniques have been developed to analyze the elements of the street network--freeways, two lane and multi-lane highways, signalized intersections, and unsignalized intersections. Arterial or corridor analysis techniques provide a "systems" tool that includes uninterrupted (two-lane or multi-lane segments) and interrupted flow (signalized intersections).

Current analytical tools to evaluate pedestrian flow concentrate on walkways, queueing areas, street corners, and crosswalks. The walkway, street corner, and crosswalk comprise the pedestrian traffic system at a signalized intersection. Each element can be analyzed individually, but not as a system. The interrelationships of the three elements have not been investigated. An integrative systems methodology is needed that can evaluate the pedestrian traffic system at a signalized intersection.

1.4 RESEARCH PURPOSE AND APPROACH

This research will focus on the interrelationships of the three elements of the pedestrian traffic system at a signalized intersection--the walkway, the street corner, and the crosswalk. Key factors that affect each element will be identified. The methodology used to evaluate the level of service and capacity will be discussed.

After identification of the factors and methodologies associated with each pedestrian element, interrelationships will be explored to develop an integrated pedestrian traffic analysis methodology at signalized intersections. The development of this systems methodology will provide a decision support tool and guidelines to plan and design pedestrian elements at a signalized intersection.

1.5 A CASE STUDY

The application of the pedestrian traffic systems methodology is demonstrated using pedestrian data collected at a local major signalized intersection located on the "Strip," a major resort corridor in the Las Vegas valley area of Clark County, Nevada. Pedestrian counts conducted as part of the Flamingo Road (I-15 to Koval Lane) Capacity Improvements Feasibility Study (16) are utilized to demonstrate the actual application of the proposed systems methodology. The peak hour pedestrian count is used so that the evaluation is conducted at the most critical period of the pedestrian traffic system at the signalized intersection of Las Vegas Boulevard South and Flamingo Road.

The results of the systems evaluation are compared to proposed guidelines to determine what pedestrian elements; i.e., the walkway, street corner, or crosswalk, need to be adjusted. With positive adjustments a balanced pedestrian traffic system can be designed to provide an acceptable level of service.

1.6 ORGANIZATION OF THE THESIS

Chapter 1 provides a perspective of the pedestrian mode as part of the global transportation system. The problem and associated individual elements are identified and the need for an integrated systems methodology discussed.

A review of the literature is presented in Chapter 2. Pedestrian research has been conducted in the areas of human factors, safety, planning, design and operations. Chapter 13 of the HCM provides the most relevant research on individual pedestrian traffic system elements. However, no research has been found that discussed the pedestrian traffic network at a signalized intersection as an integrated system.

Chapter 3 provides a discussion of the pedestrian at signalized intersections. The conflicts of vehicles and pedestrians at signalized intersections are discussed. A discussion of traffic control devices at signalized intersections describes the intended purpose of said devices. Unfortunately, pedestrian compliance is often rather low.

Chapter 4 elaborates on methodologies that have been developed to evaluate the level of service and capacity of the individual elements of the pedestrian traffic network at a signalized intersection. The chapter focuses on the individual elements, i.e., the walkway, the street corner, and the crosswalk.

A proposed systems methodology is developed in Chapter 5. The integrated systems methodology addresses the interrelationships of the elements of the pedestrian network at a signalized intersection. Guidelines are developed that allows assessments on a systems basis.

The proposed systems methodology is applied in Chapter 6. A case study of the signalized intersection of Las Vegas Boulevard South and Flamingo Road in Clark County, Nevada, is conducted.

Chapter 7 provides conclusions from the research. Recommendations and guidelines are offered regarding the potential use of this research for pedestrian planning and design at signalized intersections. The utilization of the methodology as a decision support tool in the evaluation of the potential need for pedestrian grade separations is also discussed.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

A literature review was conducted to evaluate pedestrian related issues and considerations in the context of the urban transportation system. These include aspects pertaining to pedestrian accident experience, pedestrians at signalized intersections, human factors, and elements of the intersection pedestrian system. The effort concentrated on the pedestrian at or near the signalized urban intersection.

It was found that past research has been conducted by academic institutions, by professional societies or foundations with specific interests in transportation engineering, by advisory organizations established to promote research efforts, by federal government sponsored research or by specific studies conducted for state and local governments. Professional societies, such as the Institute of Transportation Engineers (ITE), the Eno Transportation Foundation, and the American Association of State Highway Transportation Officials (AASHTO), continually promote research and use their activities as a forum to improve the state-of-the-art.

The Highway Capacity Manual: Special Report 209 of the TRB was found to provide the most relevant research, especially Chapter 13. Other transportation research records, studies, or reports published by the TRB were also used.

Studies either conducted or sponsored by the Federal Highway Administration, United States Department of Transportation, provided information relevant to pedestrians as part of the transportation system. This information relates to pedestrian safety, design, planning, and operations. In research conducted for the National Cooperative Highway Research Program Project 20-19, "Pedestrian Convenience and Safety on Suburban and Rural Highways", Smith states:

> "Although pedestrian issues may not have received adequate attention from the traffic engineering community in the past, the needs to reduce traffic congestion and improve pedestrian safety demand that every mode of transportation, including pedestrian travel, be examined." (45)

Specific areas or categories of research relevant to pedestrians are used in this chapter to organize the literature found and available. There was a common void throughout the literature review. There was very little discussion about the planning and design of a balanced pedestrian system in terms of level of service at signalized intersections.

2.2 PEDESTRIAN ACCIDENTS

In these modern times with higher density land uses, major roadway facilities, and urban multi-lane arterials, "it is often extremely difficult to make adequate provisions for pedestrians" (2). Smith (1993) states that "the transportation engineer is continually faced with the dilemma of how to allow for (3) convenient and safe pedestrian crossings and maintain traffic capacity"(45).

According to the Nevada Office of Traffic Safety in 1993 in the State of Nevada, there were 45 pedestrian fatalities with eight (8) at intersections, as noted in Table 1. In the State of Nevada from 1988 to 1993, there were a total of 258 fatal pedestrian

PEDESTRIAN ACCIDENTS BY LOCATION CATEGORY IN THE STATE OF NEVADA IN 1993

GENERAL LOCATION	FREQUENCY (NO. %)
Intersection - In Crosswalk	3 (37.5%)
Intersection - On Roadway, Not in Crosswalk	3 (37.5%)
Intersection - on Roadway, Crosswalk Availability Unknown	1 (12.5%)
Intersection - Not on Roadway	1 (12.5%)
	8

Source: Nevada Office of Traffic Safety

Table 1

accidents, as shown in Table 2 (29). In 1992 six fatal pedestrian accidents occurred. For 1992 and 1993 fatal intersection pedestrian accidents comprised approximately 18.4 percent of the total fatal pedestrian accidents. A study of a segment of Las Vegas Boulevard South from Sahara Avenue to Tropicana Avenue revealed that most of the pedestrian accidents occur during the busiest or peak vehicular time periods of the day, which starts at approximately 10 a.m. and continues to midnight, as shown in Figure 1.

In the City of Phoenix it was stated by Sparks (1988) (46) that "pedestrian accidents occur at signalized intersections a disproportionate number of times" (46) and "in general, citywide accident statistics indicate that locations that have a higher number of pedestrian accidents are at signalized intersections (46). Spark (1988) also states that "Phoenix has less than 3% signalized intersections, yet every year, nearly 40% of the citywide pedestrian accidents occur at signals" (46).

The "intersection dash" type accident is a common intersection accident. The vehicle turn/pedestrian conflict is very common at signalized intersections. The conflicts occur when pedestrians and vehicle are crossing with the same signal phase and conflicts are created with vehicles turning right or left across the crosswalks in use by pedestrians (10). A study by Robertson and Carter (1984) (37) revealed that left turns have a higher accident potential than right turns at signalized intersections, as shown in Table 3. The through movement was less than either. Todd (1992) in his research has added that the current system of pedestrian regulations "is incompatible with pedestrian safety" (50). Studies by Herms (1972) in the City of San Diego revealed a 6 to 1 ratio of accidents in marked versus unmarked crosswalks and a 3 to 1 ratio of accidents when using volume in the comparison (18). The U.S.D.O.T. (63) has documented pedestrian crash occurrence

Table 2

PEDESTRIAN FATAL ACCIDENTS AND FATALS BY YEAR AND COUNTY

	1988		1989		1990		1991		1992		1993		TOTAL	
	ACCIDENTS	FATALS	ACCIDENTS	FATALS	ACCIDENTS	FATALS	ACCIDENTS	FATALS	ACCIDENTS	FATALS	ACCIDENTS	FATALS	ACCIDENTS	FATALS
CARSON CITY	1	2	1	1	2	2	0	0	0	0	1	1	5	6
CHURCHILL	2	2	0	0	0	0	0	0	1	1	2	2	5	5
CLARK	32	34	25	28	45	45	27	27	23	23	31	33	183	188
DOUGLAS	1	1	0	0	0	0	3	3	1	1	0	0	5	5
ELKO	0	0	1	1	0	0	0	0	0	0	1	1	2	2
ESMERALDA	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EUREKA	0	0	0	0	0	0	0	0	0	0	0	0	0	0
HUMBOLDT	0	0	0	0	0	0	1	1	0	0	0	0	1	1
LANDER	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LINCOLN	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LYON	0	0	0	0	0	0	0	0	0	0	5	5	5	5
MINERAL	0	0	0	0	1	1	2	2	0	0	0	0	3	3
NYE	0	0	3	3	0	0	0	0	1	1	0	0	4	4
PERSHING	0	0	0	0	0	0	1	1	0	0	0	0	1	1
STOREY	0	0	0	0	0	0	0	0	0	0	0	0	0	0
WASHOE	10	10	5	5	9	9	6	6	5	5	3	3	38	38
WHITE PINE	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TOTAL	48	49	35	38	57	57	40	40	31	31	43	45	252	258

Source: State of Nevada Safety Engineering Section

L V BLVD STUDY INTERSECTIONS SUMMARY
PEDESTRIAN ACCIDENTS BY HOUR

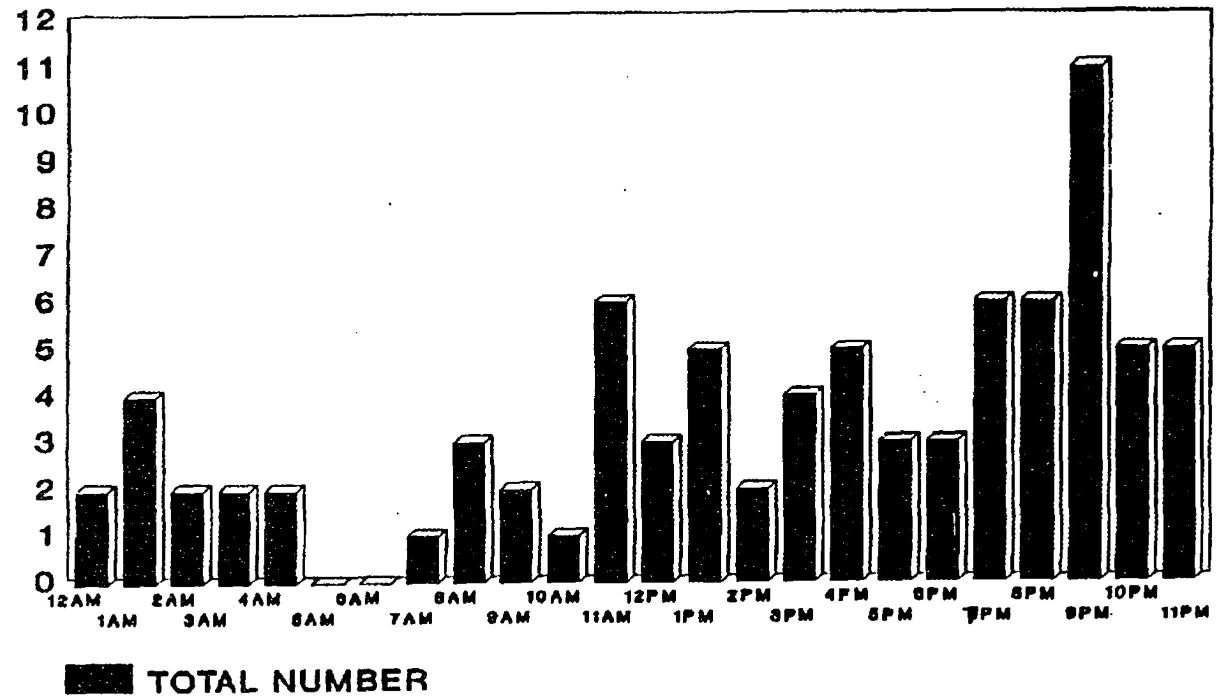


Figure 1

1987 THRU 1991

Source: State of Nevada Safety Engineering Section

Pedestrian Accident Rates by Type of Control

	Type of Control			
Type of Rate [a, b]	No Signal	Signal Only	Pedestrian Signal	All
Left turn	([c])	5.99	3.69	4.33
Right turn	2.24	1.85	2.59	2.34
Total turn	1.22	3.78	3.06	3.22
Through	5.95	1.54	1.17	1.51
Total vehicle	5.52	1.95	1.60	1.90
Pedestrian volume	3.16	1.41	0.81	1.10

[a] Accident rates based on vehicles = number of pedestrian accidents divided by total 10-hr vehicle volumes times 10,000.
[b] Accident rates based on pedestrians = number of pedestrian accidents divided by total 10-hr pedestrian volume times 1,000.
[c] No left turn accidents occurred at unsignalized intersections. Left turns made up 45 percent of the total turns.

Source: Robertson and Carter, 1984(37)

Table 3

and concluded that "in urban areas, peak pedestrian accident experience occurs between 3:00 and 6:00 p.m., which is typically the afternoon rush period" (63). Garber and Lineau (1994) also concluded that "the zone just outside the intersection (stop line to 150 feet from stop line) has the highest accident involvement rate for pedestrians" (15).

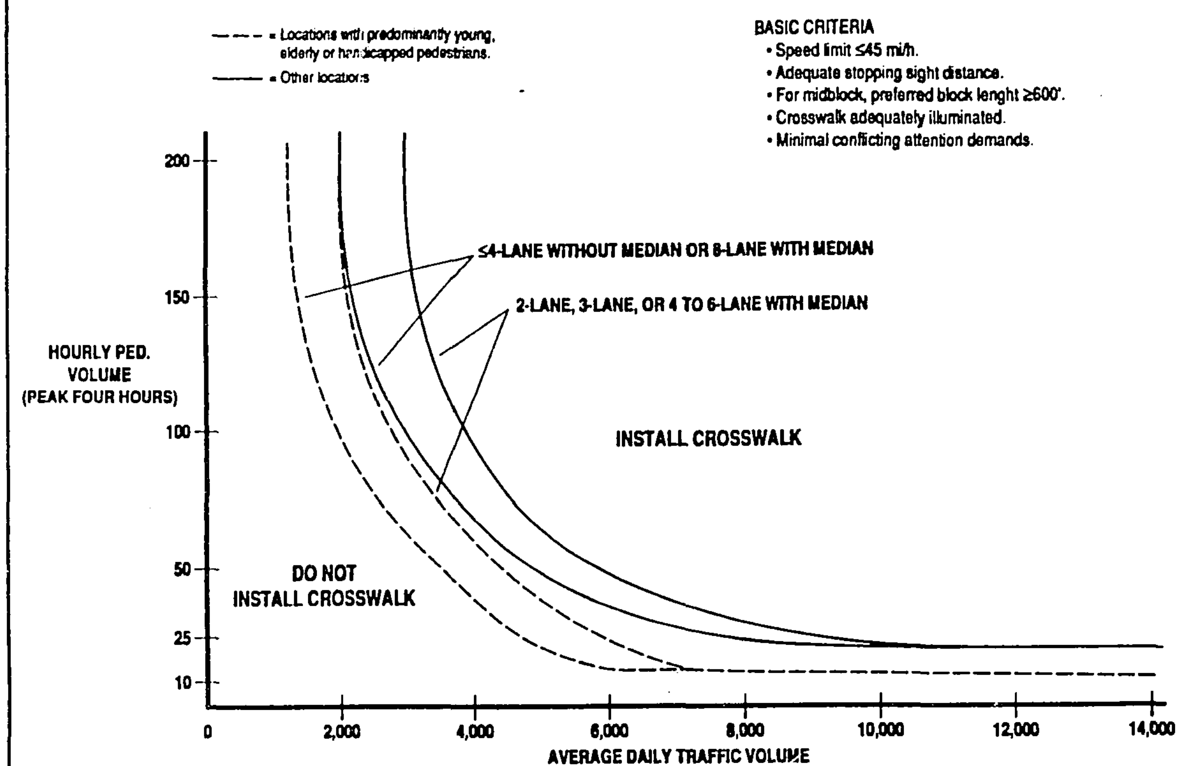
2.3 PEDESTRIANS AT SIGNALIZED INTERSECTIONS

The crossing opportunities for pedestrians are at signalized intersections determined by the phasing of the traffic signal, placement of marked crosswalks or the allowance of pedestrian crossings, the availability of corner holding areas, the existence of medians, and the development of sidewalks or walking areas. At traffic signals interrupted flow conditions are created for both the vehicle and pedestrians. The addition of pedestrian signals has had limited benefit according to the U.S. Department of Transportation:

> The use of "WALK/DON'T WALK" signals is often assumed to reduce pedestrian accidents. However research studies have found no difference in pedestrian accidents for sites with no pedestrian signals versus those with standard-timed pedestrian signal phasing (that is, timed so pedestrians have a "WALK" interval while vehicles travel parallel pedestrians and may turn right or left across pedestrian's paths). The use of exclusively-timed pedestrian intervals (that is, intervals of the signal cycle where all vehicle movements are given a red signal while pedestrians may cross in any direction) show fewer pedestrian accidents, but greatly increase vehicular delay. (60)

In this report, as with many others, minimum pedestrian volume and vehicular volume thresholds have been established, as shown in Figure 2, to establish a warrant to determine the need for a marked crosswalk. What is missing from almost all literature, although touched on in the Highway Capacity Manual, and by Khisty (1994) (25), Sarkar (1995) (41), Fruin (1971) (12), Navin and Wheeler (1969) (28), and O'Flaherty and

Figure 2



1. If using only the peak hour, threshold must be increased by 1.5
2. For streets with median, use one-way (directional) ADT volume.

Other notes: Minimum striping is 6" parallel lines. Consider bolder markings and/or supplementary advance markings or signing at uncontrolled locations where speed limits exceed 35 mi/h.

Guidelines for crosswalk installation at uncontrolled intersections and mid-block crossings.

Source: Steven A. Smith and Richard L. Knoblauch
"Guidelines for the Installation of CrosswalkMarking"
in Transportation Research Record 1141: Pedestrian and Bicycle Planning with Safety Considerations
TRB (Wash. D.C.) 1987

Parkinson (1972) (32), is the design and planning of the pedestrian related elements, i.e., sidewalk, corner area, and width of crosswalk to ensure the provision of an adequate level of service and capacity for the signalized urban intersection pedestrian system.

2.4 HUMAN FACTORS

The operating characteristics of pedestrians are relevant to the development and application of traffic control devices and the establishment of guidelines. For example, it has been determined from observations that walking speeds for pedestrians crossing an intersection "range from approximately 2.5 to 6 feet per second" (2).

In research conducted by the ITE Technical Council Committee 5P-3 and reported by Nizlek (1992)(31), an average elderly crossing speed of 3.86 feet per second was found. The average speed of an elderly person with a cane or a walker was 3.13 feet per second and 2.88 feet per second, respectively (31). A compilation of statistics based on the research of this committee is shown in Table 4 (31). Wigan (1995) (69), from a sample of 18,000 Australians, determined that 4.7 km/hr or 4.26 feet per second was the median value for pedestrian movement in uncongested areas. Virkler, et al, (1995) (67) concluded that walking speeds decrease with higher congestion and lower levels of service and also concluded that "existing procedures for determining pedestrian crosswalk-time requirements are inadequate because they ignore the number of people crossing" (68). More congested conditions affect walking rates with lower rates by pedestrians in crowded conditions (54) (71). The Manual on Uniform Traffic Control Devices recommends the assumption of a normal walking rate of 4.0 feet per second (58). Kell (1982) recommends consideration of 3.5 feet per second for the elderly (24).

AVERAGE SPEEDS OF SPECIAL PEDESTRIANS

Attribute of Pedestrian	Average Speed	# Observed
Using a Cane	3.13 ft/sec	108
Pushing/Pulling Grocery Cart	3.48 ft/sec	25
Using a Walker	2.88 ft/sec	9
Blind	3.59 ft/sec	6

Source: ITE Technical Council Committee 5P-3

Table 4

The unpredictability of pedestrian actions is recognized by the American Association of State Highway and Transportation Officials (2). The young and elderly are disproportionately represented in accidents (2). Pedestrians consider that traffic laws do not generally apply to them and resist changes in elevation or direct paths (2). A conclusion of the Nevada Department of Transportation (1992) was that "the majority of these pedestrian accidents may be traced to risk-taking behavior by the pedestrian" (30). Smith (1993) states that "it has been well documented that the majority of pedestrian accidents are caused by errors in pedestrian judgment" (45). Bailey, et al (1992) (3) stated in a study of elderly pedestrians that "more than half avoid crossing the street during peak traffic hours" partially due to "concerns for safety and feelings of anxiety." Bailey, et al (1992) (3) also discussed the physiological factors of vision, audition, cognition, and gait.

The non-compliance with official traffic signals and right turn on red (RTOR) was researched in behavioral studies conducted by Pietrucha, et al (1990) (34). After about 440 hours of field work, it was determined that "about 61 percent of the RTOR vehicles failed to make a full stop" (34) but "only 1.4 percent of all right-turning motorists and 3.1 percent of those turning right on red caused a conflict" (34).

2.5 ELEMENTS OF THE URBAN INTERSECTION PEDESTRIAN SYSTEM

The main elements of urban pedestrian transportation systems are the sidewalk, the intersection corner or holding area, and the crosswalk (52). The sidewalk is to the pedestrian what the roadway is to the vehicle. AASHTO (2) recognizes and recommends the speed and density relationships stated in the Highway Capacity Manual (HCM 1985 edition) (52) and re-emphasizes that at "the optimum speed and density, the walkway will carry the largest volume." A width of four feet to eight feet is recommended, generally. AASHTO also indicates that at an intersection "the sidewalk should provide sufficient storage area for those waiting to cross plus area for cross traffic to pass." More detailed analytical techniques are provided in the HCM (52).

The AASHTO A Policy on Geometric Design of Highways and Street (2) (commonly called the "Green Book"), describes seven functions of medians, but also does not make reference to uses by pedestrians. Medians can improve the safety of the crossing task at signalized intersections and improve flexibility in signal timing, if the median is adequate in width and provides an adequate pedestrian storage area. Unfortunately, at many heavily traveled intersections, the medians are inadequate to handle the storage of heavy volumes of pedestrian traffic.

Zegeer (1994) (71) recognized that "the safe and efficient movement of pedestrians on sidewalks requires the proper placement of street furniture (e.g., newspaper racks, telephone booths, benches)". This problem with sidewalk restrictions was previously discussed in research conducted by the U.S. Department of Transportation in that "the potential pedestrian capacity of CBD sidewalks is reduced further by the intrusion of refuse cans, fire hydrants, fire alarm boxes, parking meters, traffic signals and poles, newsstands, telephone booths, mailboxes, planters, sewer and ventilation gratings and other devices" (61). In addition to the adverse affect on sidewalk capacity, this research recognized that "space is needed at intersections for the accumulation of pedestrians waiting for traffic signals and the weaving of pedestrian flows" (61) and that "the pedestrian is further harassed by vehicles stopped in the crosswalk or turning into the path of crossing pedestrians" (61). Handbill distributors and sidewalk vendors adversely affect sidewalk capacity and level of service, also.

2.6 MEASURES OF EFFECTIVENESS

The pedestrian traffic system is similar to that of the motorized vehicles with analogous linkages between the traffic flow on roadways-sidewalks, queue or storage lane requirements - intersection corners, and the interrupted flow effects of vehicular traffic - crosswalks. In the National Cooperative Highway Research Program Report 279 (53), the "amount of pedestrian activity" (53) has a direct influence on vehicle flow rates and are an important consideration for right turning vehicles (53). Research on the evaluation of walkway capacities and levels of service have been conducted by Fruin (1971) (12), Navin and Wheeler (1969) (28), and O'Flaherty and Parkinson (1972) (32). Fruin and Benz (1984) (13) provided the preliminary version of the 1985 and current, 1994 HCM by developing procedures for determining levels of service at street corners and in crosswalks. This was seen as an improvement over previous TRB Circular 212 procedures. The procedures in 1994 HCM still use the work of Fruin and Benz (1984) as the basis for its evaluative procedures and level of service analysis. Tanaboriboon and Guyano (1989) (47) developed six levels of service for pedestrian facilities similar to the United States, but the pedestrian area occupancies are lower and the flows accommodated in each level of service (LOS) are higher. Khisty (1994) (25) discusses the level of service guidelines established in the 1984 HCM; but proposes to take the LOS concept further by including a practical method of assessing pedestrian facilities by taking into account qualitative environmental factors, such as attractiveness, comfort, convenience, safety, security, system coherence, and system continuity. Sarkar (1995) (41) proposes a LOS evaluation for a macro design scale from A-D and F and quality of service (QOS) from A-D based on qualitative conditions assigned to each QOS for micro design. The U.S.D.O.T. (1994) (63) recommended that a LOS analysis be conducted in a central business district, but did not discuss the pedestrian system at an urban signalized intersection. Seneviratne and Morrall (1985) (42) conducted pedestrian studies of sidewalks, malls, crosswalks, stairs, and ramps in Calgary, Alberta and discussed levels of service and the alternative quality of service concept, also based on environmental factors.

2.7 SUMMARY

The signalized intersection causes interrupted flow conditions for both the vehicle and pedestrians. This creates unique challenges in attempting to balance the level of service of the uninterrupted segments (sidewalks) with the interrupted flow part of the system (corners and crosswalks at signalized intersections). Studies have shown that a disproportionate number of pedestrian accidents occur at signalized intersections with a high number during peak periods, especially from 3:00 p.m. to 6:00 p.m. Pedestrians have the highest involvement rate in the zone from the stop line to 150 feet from the stop line, suggesting inadequate crosswalk widths as a possible factor. The accident problem is complicated by low compliance with pedestrian signals (WALK-DON'T WALK or HAND-MAN) and the unpredictability of pedestrian behavior. The factors strongly suggest a relationship between critical pedestrian location and time periods and the ability to provide an adequate balanced pedestrian facility. Techniques are available to evaluate the level of service and capacity of the individual elements, but not as a system as a whole.

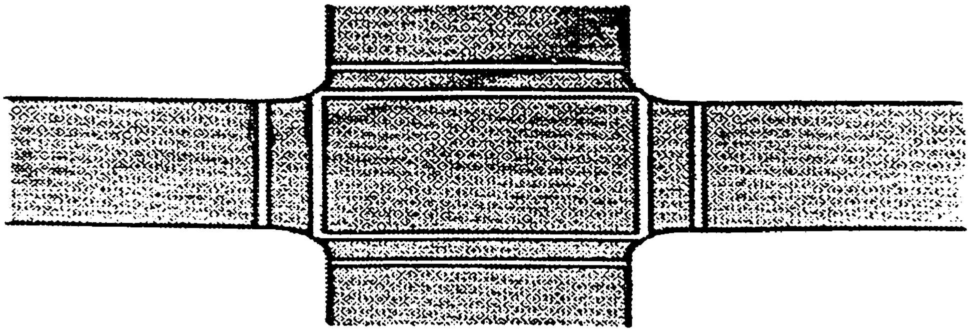
CHAPTER 3

PEDESTRIANS AT SIGNALIZED INTERSECTIONS

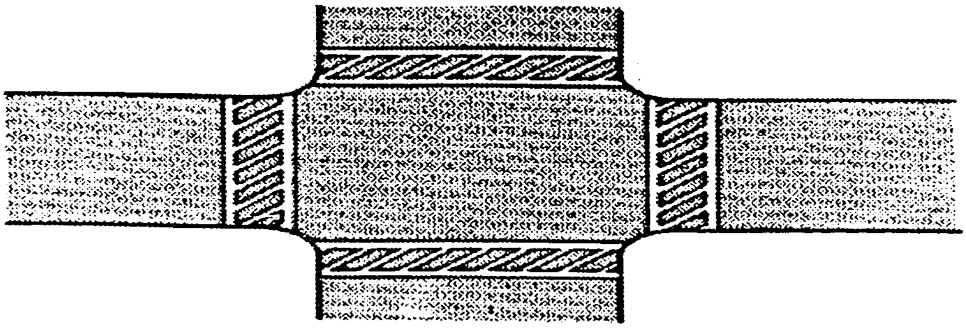
3.1 INTRODUCTION

The signalized intersection is the focal point of the urbanized surface roadway network. It creates interrupted traffic flow conditions for both vehicles and pedestrians. In addition to the various traffic signal phases, typically from two to eight, pedestrian phases are included at locations where conditions warrant supplemental pedestrian traffic control. The concurrent pedestrian phase is the most commonly used. This allows both pedestrians and vehicles to cross the same legs of the signalized intersection. Other pedestrian phases used are the early release, late release, exclusive, and the scramble.

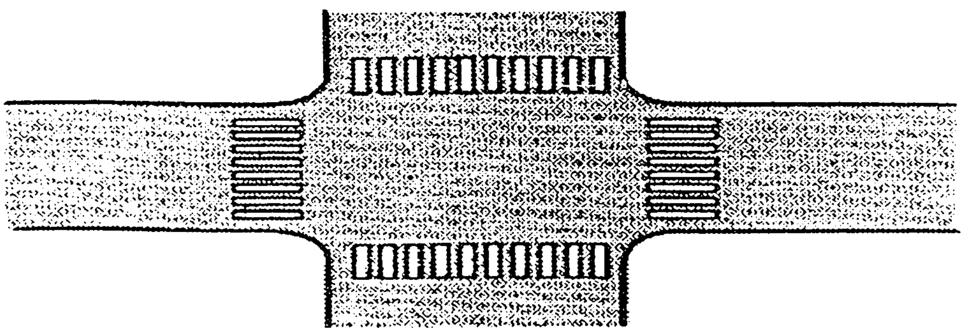
Traffic control devices are used to provide positive guidance for the pedestrian in any crossing of a signalized intersection. Typically, the WALK-DON'T WALK or symbolic HAND-MAN pedestrian signals are used to supplement the standard vehicular traffic signal indications. Pedestrian push-buttons allow pedestrian actuation at traffic actuated signals and allow the implementation of special pedestrian timing. Marked crosswalks are provided to guide pedestrians across the intersection. Several crosswalk designs can be used. Figure 3 from the Manual on Uniform Traffic Control Devices commonly serves as a rule of thumb. Although the MUTCD is used widely as a guide, there are no criteria provided in that document to guide the proper design of the width of a -- Standard crosswalk marking.



b -- Crosswalk marking with diagonal lines for added visibility.



c -- Crosswalk marking with longitudinal lines for added visibility.



TYPICAL CROSSWALK MARKINGS

Source: Manual on Uniform Traffic Control Devices 1988 edition

Figure 3

crosswalks at signalized intersections to account for pedestrian volumes, especially at peak periods.

3.2 COMPLIANCE WITH PEDESTRIAN TRAFFIC SIGNAL SYSTEMS

Research relative to pedestrian behavior and compliance with traffic control devices at signalized intersections was reviewed. A recent study conducted by Tidwell (1993) (49) for the AAA Foundation revealed the following in response to this scenario (True-False):

> "Assume you have just started crossing a street on a WALK signal, but the signal quickly begins flashing DON'T WALK. This means there isn't enough time to cross and you should return to the curb (49)."

The correct response is "False," but the results indicated below that almost half of the respondents did not understand the meaning of the flashing DON'T WALK message (49).

Responses	Driver License Exam. Station (%)	American Assoc. of Retired Persons (%)
True	42	46
False	51	48
Don't Know	7	6

Still another scenario was proposed in the same study:

> "Assume you are at an intersection with a pedestrian signal that has a button labeled 'Push-Button for Walk Signal'. The signal will immediately change to WALK when you push the button (49)."

The correct response is "False." The results below indicate a higher level of understanding on the operation of a pedestrian push-button (49).

Responses	Driver License Exam. Station (%)	American Assoc. of Retired Persons (%)
True	10	10
False	84	80
Don't Know	6	10

It is still rather surprising that 16% to 20% do not understand the simple operation of a pedestrian push-button.

Another scenario was proposed to drivers regarding the "right turn on red:"

"Assume you are at an intersection that lets you turn right on red after you stop. The pedestrian has begun to cross at the crosswalk. He must wait and let you turn before he finishes crossing (49)."

Responses	Driver License Exam. Station (%)	American Assoc. of Retired Persons (%)
True	16	13
False	79	82
Don't Know	5	5

The responses to the following questions were very disturbing:

"A WALK signal at an intersection means that you may cross the road safely because no cars will be driving through or turning into the crosswalk."

The correct response is "False," but an amazing 49% replied incorrectly or didn't know, as shown below:

Responses	Driver License Exam. Station (%)	American Assoc. of Retired Persons (%)
True	47	47
False	51	51
Don't Know	2	2

Another survey indicated that from 92% to 95% of drivers understood that drivers must yield to pedestrians in the crosswalk when turning left on a green signal indication.

A recent study by the U.S.D.O.T. (1991) (61) indicated possible reasons for the lack of effectiveness of pedestrian signals:

1. Lack of understanding of pedestrian signal messages.
2. False sense of security regarding the WALK signal.
3. Poor compliance and respect for pedestrian signal, i.e. 65.9% began crossing during the flashing or steady DON'T WALK indication.
4. Reluctance to activate the push-button (only 51.3% compliance).

The City of San Buenaventura, California has implemented a program to attempt to reduce public confusion about the messages through the use of more detailed pedestrian signs at push-buttons on traffic signal poles and through public education.

A study by the Federal Highway Administration (1982) (11) indicates, as many other studies do, that younger and elderly pedestrians are more susceptible to being involved in an accident. It is also stated that past behavioral analysis studies in Washington, D.C., San Francisco, and Oakland, California, at six intersections revealed that "a very large portion of the users pay little, if any, attention to the pedestrian signal (11)."

The same study revealed that "few pedestrians understand the meaning of flashing WALK and DON'T WALK signals, whereas symbolic pedestrian signals such as the walking pedestrian and upheld hand offers an improved understanding over word messages (11)." A study by Robertson (1977) (36) also concluded that the symbol display showed a significant improvement.

As stated previously, research by Bruce Herms (1972) (18) of 400 intersections in San Diego revealed that "more accidents occur in marked crosswalks than in unmarked crosswalks by a ratio of six to one." The accident rate based on crosswalk use volume (marked versus unmarked) was three to one revealing that "approximately twice as many pedestrian accidents occur in marked crosswalks as in unmarked crosswalks."

In a study by Biotechnology, Inc. (1977) (5), it was indicated that seven seconds of WALK was normally needed to allow a discharge of 24 persons from a corner. Less than seven seconds down to four to five seconds was applicable for low pedestrian volume conditions, i.e., less than ten pedestrians per cycle. The MUTCD (58) recommends four to seven seconds of WALK time. U.S.D.O.T. (1987) (57) indicated in its behavioral analyses the following:

1. Marked crosswalks create an "illusion" of safety.
2. Despite limited travel, 35 to 42 percent of pedestrian accidents occur at night and improved lighting can reduce accidents by 50%.
3. The average pedestrian estimates their nighttime visibility to be twice what it actually is. Retroreflective clothing can increase nighttime visibility manyfold.
4. Running at intersections to make it across late is a common cause of accidents.
5. Safety islands can provide a refuge.
6. Traffic signals provide safer crossing areas for pedestrians by indicating to pedestrians when it is safe to cross.
7. Many pedestrians, especially the elderly or children, do not understand the meaning of the WALK-DON'T WALK (flashing) indications.

8. Pedestrians tend to react to what they see on or beside the road rather than to what they read on a sign.

Cox (1983) (7) states:

> "Studies have shown that interaction between humans and their surroundings is a two-way imposition: that is, while humans affect their environment by imposing themselves, it (the environment) in turn affects and to a certain degree imposes upon them... Since we are assuming, here, that the environment influences behavior and that planners and developers influence the environment, we can conclude that planners and developers influence human behavior."

It was also indicated that a basic semi-physiological need is harm avoidance, i.e., the need to avoid injury, escape dangerous situations, and take precautionary measures. This was previously mentioned as a special concern of the elderly. Philosophically, this supports an integrated pedestrian systems planning approach.

TRB (56) stated that many older pedestrians walk at a rate slower than the four feet per second rate espoused in the MUTCD. A walking rate of three to three and one-half feet per second, was recommended for consideration, where applicable, without causing significant disbenefits by increased vehicular delay.

The Traffic Control Devices Handbook (62) states that "pedestrian volume affects walking speed". Past studies have shown that groups of pedestrians walk at a slower rate than individual pedestrians. It also confirms that the elderly and younger pedestrians walk at a slower rate than the "normal" pedestrian. Bowman and Vecellio (1994) (6) also concluded that pedestrians aged over 60 years have a walking rate less than the 18 to 60 age group.

Most states throughout the United States of America have adopted the Manual on Uniform Traffic Control Devices (MUTCD) as the legal guideline that states and local agencies must follow in the design, placement, and maintenance of traffic control devices, such as pedestrian signals (see Figure 4) and crosswalks. In Section 4D-2 of the MUTCD the following meaning is assigned the pedestrian indications:

1. The DON'T WALK indication, steadily illuminated, means that a pedestrian shall not enter the roadway in the direction of the indication.
2. The DON'T WALK indication, while flashing, means that a pedestrian shall not start to cross the roadway in the direction of the indication, but that any pedestrian who has partly completed his crossing during the steady WALK indication shall proceed to a sidewalk, or to a safety island.
3. The WALK indication means that a pedestrian facing the signal indication may proceed across the roadway in the direction of the indication. The WALK indication means that there may or may not be possible conflicts of pedestrians with turning vehicles.
4. A WALK indication shall not be flashed.

With a fixed or pre-timed signal pedestrian push-buttons are not needed to activate the signal, which is the case with a traffic actuated signal. Typical pedestrian signal indications from the MUTCD are shown in Figure 4.

TYPICAL PEDESTRIAN SIGNAL INDICATIONS

Source: Manual on Uniform Traffic Control Devices (1988 edition)

Figure 4

The MUTCD established minimum design criteria that have evolved from past research. Some of the basic criteria are listed below:

1. Pedestrian signal indications shall be visible from 10 feet to full width of area to be crossed.
2. All pedestrian indications must be rectangular, internally illuminated, with lettered or symbolized WALK and DON'T WALK messages.
3. The WALK shall be white and the DON'T WALK shall be portland orange.
4. For crossing from the near curb to the pedestrian signal, 60 feet or less, the letters shall be at least three inches high and the symbols at least six inches high; greater than 60 feet the letters should be at least 4.5 inches high and symbols at least nine inches high.
5. The bottom of the pedestrian signal housing shall be at least seven feet nor more than ten feet above sidewalk level.

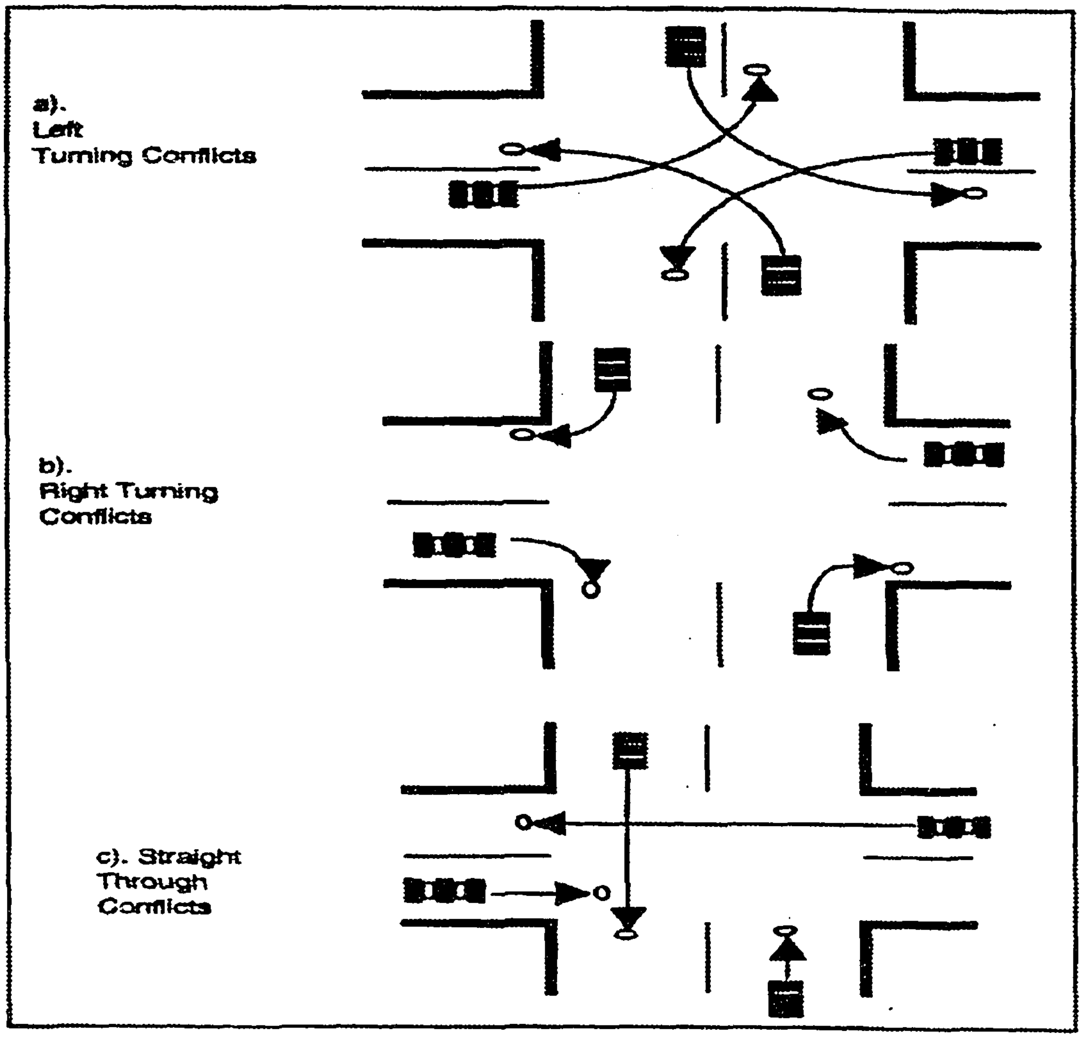
Pedestrian interval timing is also based on past research. A normal pedestrian walking speed of four feet per second is recommended for calculating pedestrian clearance interval time with 3.5 feet per second walking speed recommended for the elderly and younger pedestrians.

The WALK interval is recommended to be from four to seven seconds to allow enough time for the pedestrian to leave the curb before the clearance interval begins. The clearance interval, flashing DON'T WALK, should be long enough to allow a pedestrian to leave the curb and travel to the center of the farthest traveled lane before conflicting vehicles receive a green signal indication. The solid DON'T WALK interval is displayed when pedestrians must not enter the roadway due to vehicle conflicts. The pedestrian push-button and signals provide pedestrians the ability to initiate and then, following the messages of the pedestrian signal, cross an intersection leg. Crosswalks, as shown in Figure 3, serve to guide pedestrians along correct travel paths. Typically, crosswalks are marked at signalized intersections where there is substantial conflict between vehicles and pedestrians. To improve visibility to approaching drivers supplemental white diagonal or longitudinal lines can be used.

3.3 VEHICLE PEDESTRIAN CONFLICTS AT SIGNALIZED INTERSECTIONS

As mentioned earlier, concurrent vehicle-pedestrian phasing is most commonly and almost exclusively used, except in occasional unique applications, such as in the downtown Las Vegas where exclusive or scramble phasing is used. A discussion of the typical vehicle-pedestrian conflicts at signalized intersections that utilize concurrent pedestrian phasing follows. The three basic types of conflicts are shown in Figure 5.

At a two phase intersection the vehicle and pedestrian movements occur concurrently. The pedestrians cross with the "green vehicle interval" with or without the aid of pedestrian specials. Conflicts occur during both crossing phases because both allow permissive turn movements. Vehicles turning right or left will traverse the crosswalks when the crosswalk is in use by pedestrians. With a five phase intersection no pedestrian movements are allowed during the protected left turn phases on the major street. Left turn vehicle pedestrian conflicts are eliminated with the protected left turn phases. With the eight phase operation no pedestrian movements are allowed during the protected left turn movements, so the vehicle-pedestrian pedestrian conflict is eliminated. The right turn on red conflict exists with all, unless right turns are prohibited.



TYPES OF CONFLICT

Source: Seneviratne and Javid, "Applying Conflict Technique to Pedestrian Safety Evaluation" in the ITE Journal - Institute of Transportation Engineers (Wash. D.C. Mar. 1991) 22.

Figure 5

3.4 SUMMARY

From the discussion various conclusions have been made. A substantial proportion of the pedestrians do not understand the meanings of the WALK or DON'T WALK messages. Generally, compliance with the HAND-MAN symbolic message is higher. Almost half of the pedestrians believe a WALK sign indicates that there is no potential conflict.

A smaller percentage of pedestrians still believe that activation of a pedestrian push-button should result in an immediate WALK signal indication, which is not the case. Only about half the pedestrians utilize the push-button according to other research, but locally, compliance seems higher. Marked crosswalks provide the pedestrian with a "false sense of security." The "environment" of an intersection does have an affect on pedestrian behavior. Busy intersections (heavy pedestrian and heavy traffic volumes) create a visual overload of information that exceeds the ability for a pedestrian to perform walk and cross optimally. Many crosswalks and corner queue or holding areas are inadequate at intersections, especially signalized intersections. A small percentage of drivers do not understand that they must yield the right-of-way to a pedestrian in a crosswalk on a right turn on red movement.

CHAPTER 4

METHODOLOGIES TO EVALUATE ELEMENTS OF A PEDESTRIAN TRAFFIC SYSTEM AT SIGNALIZED INTERSECTIONS

4.1 INTRODUCTION

Typically, the signalized urban intersection is the critical point in the urban surface transportation network, especially during peak periods. Heavy volumes of vehicular traffic vie for right-of-way at these points. Heavy concentrations of pedestrian flows from nearby traffic generators further exacerbate the ability of traffic to flow smoothly by forcing the utilization of pedestrian phasing and timing and creating conflicts with right and left turning traffic.

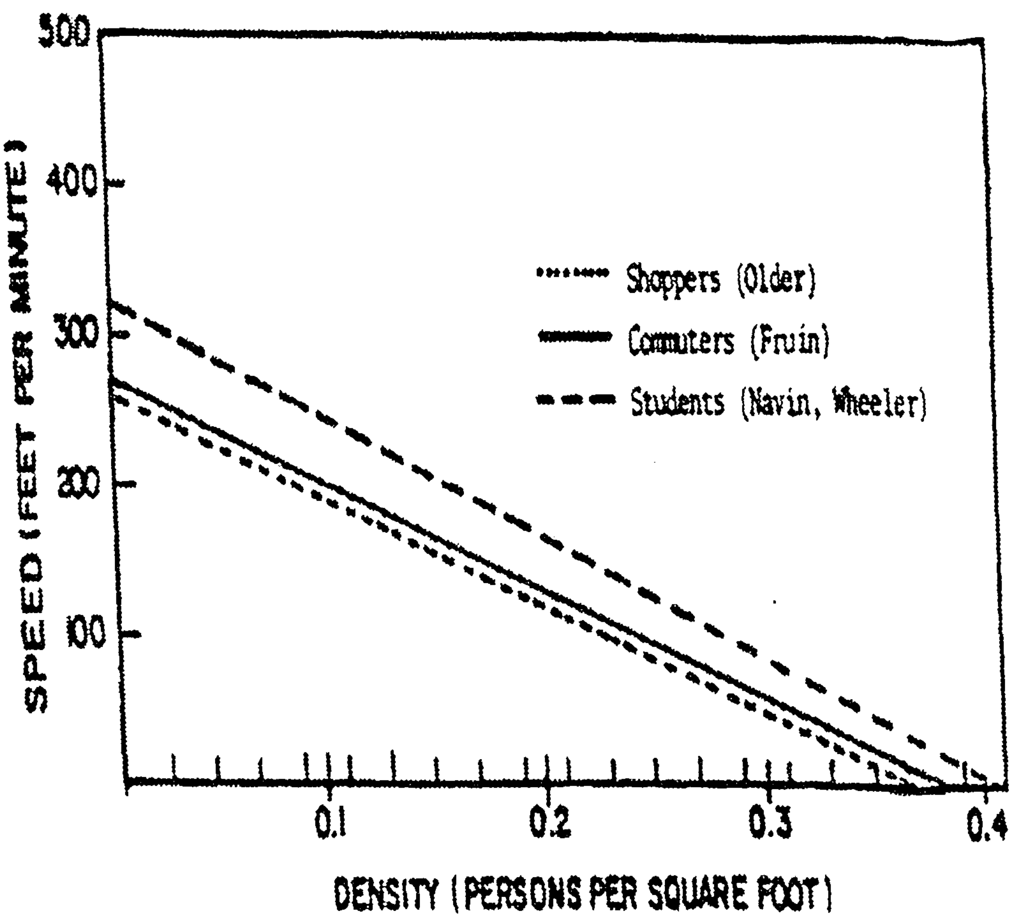
For the pedestrian transportation system at urban signalized intersections there are three elements -- the sidewalk, the street corner, and the crosswalk. Analysis techniques for these have been discussed by many researchers, but after evaluation of the research techniques developed, Chapter 13 of the Highway Capacity Manual has found the most widespread use and acceptance, so its methodologies are used in this research.

The three elements must be in balance in terms of level of service and capacity for a pedestrian network to operate properly. The pedestrian flow on the sidewalk is essentially uninterrupted, but affected by the pulsing of pedestrian groups from nearby signalized intersections. The pedestrian flow of the street corner involves both interrupted flow to and from the crosswalks and uninterrupted flow of pass-through pedestrian traffic that does not cross the intersection, but uses the corner area to traverse from sidewalk to sidewalk. The crosswalk involves interrupted flow.

4.2 LEVEL OF SERVICE CONCEPT AND PEDESTRIAN SPEED-FLOW-DENSITY RELATIONSHIPS

The density-speed-flow relationships for pedestrians are basically the same as for vehicular traffic streams (12). These relationships are shown in Figures 6, 7, and 8. As volume and density increase pedestrian speed declines (52). The relationships show an optimum relationship of speed and flow rate to space at which maximum capacity occurs. After this the flow rate falls rapidly. With few pedestrians the higher walking speeds can be attained, but as density increases both flow speed and flow decrease.

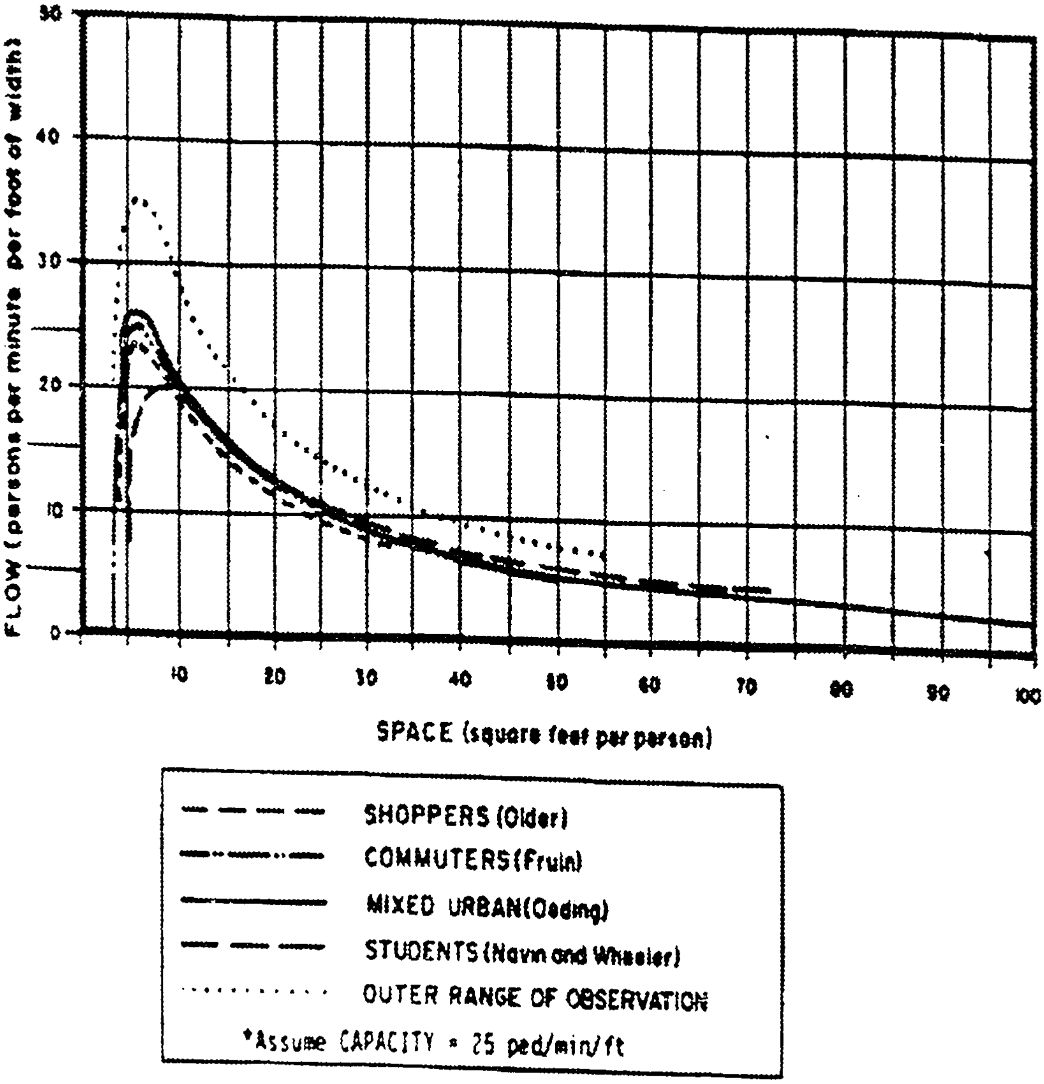
The level of service (LOS) concept has been discussed by Khisty (1994)(25), Sarkar (1995) (41), Fruin (1971) (12), Navin and Wheeler (1969) (28) and O'Flaherty and Parkinson (1972) (32). Fruin and Benz (1984)(13) developed the preliminary version of the methodologies for the 1985 HCM and now, the 1994 HCM. The level of service concept, when applied to pedestrian traffic flow considers walking speeds, ability to bypass slower pedestrians, and ability to avoid conflicts with other pedestrians in terms of pedestrian density and volume. The concept is applicable to sidewalks, street corners, and crosswalks.



Relationships between pedestrian speed and density.

Source: Highway Capacity Manual: Special Report No. 209 (1994 edition)

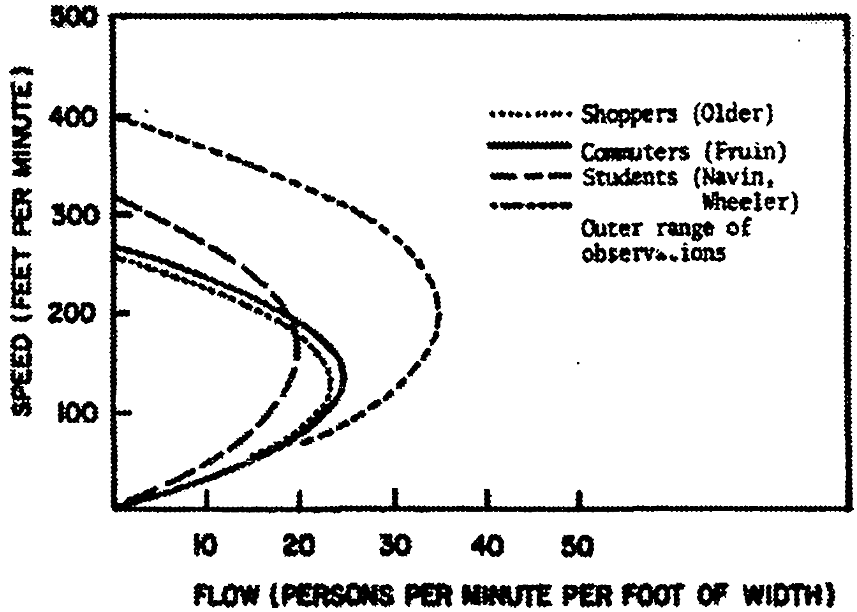
Figure 6



Relationships between pedestrian flow and space.

Source: Highway Capacity Manual: Special Report No. 209 (1994 edition)

Figure 7



Relationships between pedestrian speed and flow

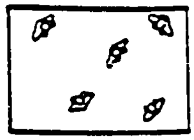
Source: Highway Capacity Manual: Special Report No. 209 (1994 edition)

Figure 8

The LOS of a pedestrian element defines a range of flow rates, speeds, and space per pedestrian. LOS levels range from A (best) to F (worst). A graphic depiction is shown in Figure 9 and in Table 5. The space and average speed decline from LOS "A" to "F", whereas the flow rate and volume to capacity ratio increase. The average speed declines from 4.33 feet per second or more at LOS "A" to 2.5 feet per second at LOS "E". Congestion causes a decrease in speed. At LOS "C", the design standard to be used for the case study presented in this thesis, the average walking speed is 4 to 4.17 feet per second, the space is 24 to 39+ square feet per pedestrian, and the flow rate is 10 pedestrians per minute per foot of width to 7 (+) pedestrians per minute per foot of width.

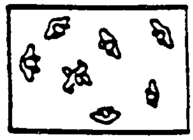
LEVEL OF SERVICE A

Average Pedestrian Area Occupancy: 13 sq ft/person or more
Average Inter-Person Spacing: 4 ft. or more
Description: Standing and free circulation through the queuing area is possible without disturbing others within the queue.



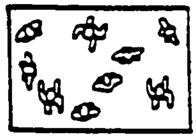
LEVEL OF SERVICE B

Average Pedestrian Area Occupancy: 10 to 13 sq ft/person
Average Inter-Person Spacing: 3.5 to 4.0 ft
Description: Standing and partially restricted circulation to avoid disturbing others within the queue is possible.



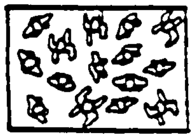
LEVEL OF SERVICE C

Average Pedestrian Area Occupancy: 7 to 10 sq ft/person
Average Inter-Person Spacing: 3.0 to 3.5 ft
Description: Standing and restricted circulation through the queuing area by disturbing others within the queue is possible; this density is within the range of personal comfort.



LEVEL OF SERVICE D

Average Pedestrian Area Occupancy: 3 to 7 sq ft/person
Average Inter-Person Spacing: 2 to 3 ft
Description: Standing without touching is possible; circulation is severely restricted within the queue and forward movement is only possible as a group; long term waiting at this density is discomforting.

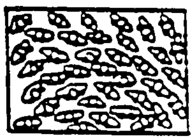


LEVEL OF SERVICE E

Average Pedestrian Area Occupancy: 2 to 3 sq ft/person
Average Inter-Person Spacing: 2 ft or less
Description: Standing in physical contact with others is unavoidable; circulation within the queue is not possible; queuing at this density can only be sustained for a short period without serious discomfort.

LEVEL OF SERVICE F

Average Pedestrian Area Occupancy: 2 sq ft/person or less
Average Inter-Person Spacing: Close contact with persons
Description: Virtually all persons within the queue are standing in direct physical contact with those surrounding them; this density is extremely discomforting; no movement is possible within the queue; the potential for panic exists in large crowds at this density.



SOURCE: Highway Capacity Manual: Special Report No. 209 (1994 edition)

ILLUSTRATION OF WALKWAY LEVELS OF SERVICE

Figure 9

PEDESTRIAN LEVEL OF SERVICE ON WALKWAYS*

LEVEL OF SERVICE	SPACE (SQ FT/PED)	EXPECTED FLOWS AND SPEEDS		
		AVE. SPEED. S (FT/MIN)	FLOW RATE, v (PED/MIN/FT)	VOL/CAP RATIO, v/c
A	≥ 130	≥ 260	≤ 2	≤ 0.08
B	≥ 40	≥ 250	≤ 7	≤ 0.28
C	≥ 24	≥ 240	≤ 10	≤ 0.40
D	≥ 15	≥ 225	≤ 15	≤ 0.60
E	≥ 6	≥ 150	≤ 25	≤ 1.00
F	< 6	< 150	----Variable----	

*Average conditions for 15 min.

PEDESTRIAN LEVEL OF SERVICE ON WALKWAYS

SOURCE: Highway Capacity Manual: Special Report No. 209 (1994 edition)

Table 5

4.3 SIDEWALKS

The sidewalk is one of the major elements of the pedestrian traffic system at a signalized intersection. The effective or clear width of the sidewalk is the major determinant of the level of service and capacity of the sidewalk. The clear or "effective" walkway width relates "to the portion of a walkway that can be effectively used for pedestrian movements" (52). Obstructions, such as poles, signs, planters, fire hydrants, newsracks, etc. are subtracted or "preempted" from the overall sidewalk width to provide a clear or "effective" width. The effects or reductions caused by preemptions are shown in Table 6. A graphical depiction is shown in Figure 10. It is assumed that there is approximately equal flow of pedestrians in each direction for the LOS analysis. The effect of pedestrian platoons, such as those created by traffic signals, cause short term random fluctuations in pedestrian flow. From field research the following mathematical relationship has been developed for this (52):

$$\text{Platoon Flow} = \text{Average Flow} + 4$$

$$v_p = v + 4$$

Where: v_p = Platoon Flow (ped/min/ft)

v = Average Flow (ped/min/ft)

The methodology for the calculation and analysis of the level of service or capacity of a sidewalk is shown with the following procedures (52):

STEP 1: Field or projected data collected.

a. Peak 15 minute count v_{p15} in peds/15 minute

b. Total walkway width, W_T in feet

c Obstacle identification

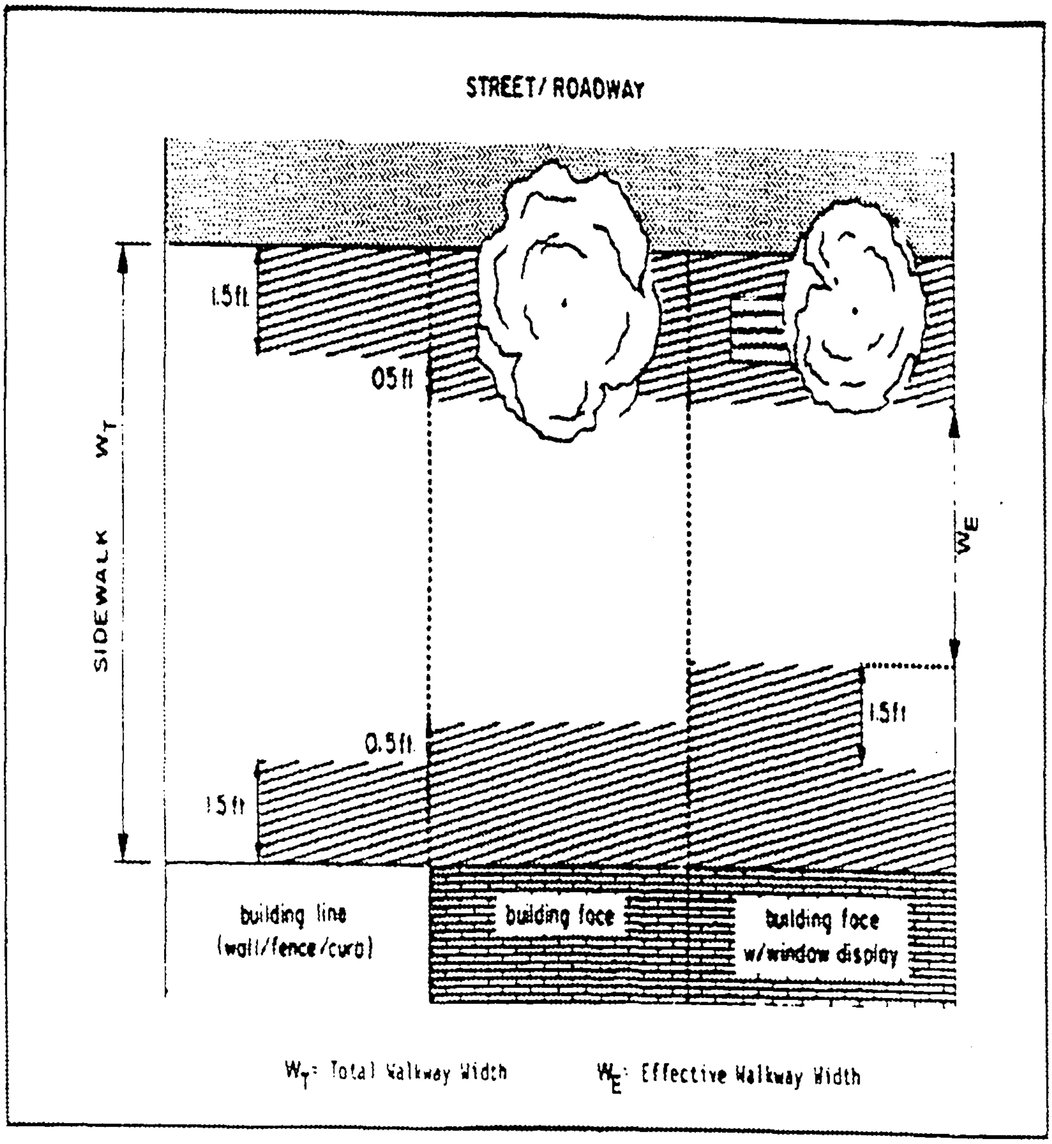
FIXED OBSTACLE WIDTH ADJUSTMENT FACTORS FOR WALKWAYS*

OBSTACLE	APPROX. WIDTH PREEMPTED (FT)*
STREET FURNITURE	
Light Poles	2.5-3.5
Traffic Signal Poles and Boxes	3.0-4.0
Fire Alarm Boxes	2.5-3.5
Fire Hydrants	2.5-3.0
Traffic Signs	2.0-2.5
Parking Meters	2.0
Mail Boxes (1.7 ft. By 1.7 ft.)	3.2-3.7
Telephone Booths (2.7 ft. By 2.7 ft.)	4.0
Waste Baskets	3.0
Benches	5.0
PUBLIC UNDERGROUND ACCESS	
Subway Stairs	5.5-7.0
Subway Ventilation Gratings (raised)	6.0+
Transformer Vault Ventilation Gratings (raised)	5.0+
LANDSCAPING	
Trees	2.0-4.0
Planting Boxes	5.0
COMMERCIAL USES	
Newsstands	4.0-13.0
Vending Stands	variable
Advertising Displays	variable
Store Displays	variable
Sidewalk Cafes (two rows of tables)	variable, try 7.0
BUILDING PROTRUSIONS	
Columns	2.5-3.0
Stoops	2.0-6.0
Cellar Doors	5.0-7.0
Standpipe Connections	1.0
Awning Poles	2.5
Truck Docks (trucks protruding)	variable
Garage Entrance/Exit	variable
Driveways	variable

*To account for the avoidance distance normally occurring between pedestrians and obstacles, an additional 1.0 to 1.5 ft. must be added to the preemption width for individual obstacles.
**Curb to edge of object, or building face to edge of object.

Source: Highway Capacity Manual: Special Report No. 209 (1994 edition)

Table 6



Preemption of walkway width.

Source: Highway Capacity Manual: Special Report No. 209 (1994 edition)

Figure 10

STEP 2: Calculate "effective" or clear width of walkway (W_E) by subtracting from the total width (W_T) any preemptions (W_B).

$$W_E = W_T - W_B$$

STEP 3: Calculate the pedestrian unit flow rate (ped/min/ft)

$$v = v_p/15\ W_E$$

STEP 4: The flow rate within platoons is estimated.

$$v_p = v + 4$$

STEP 5: The LOS is found by comparison to flow rates in Table 5.

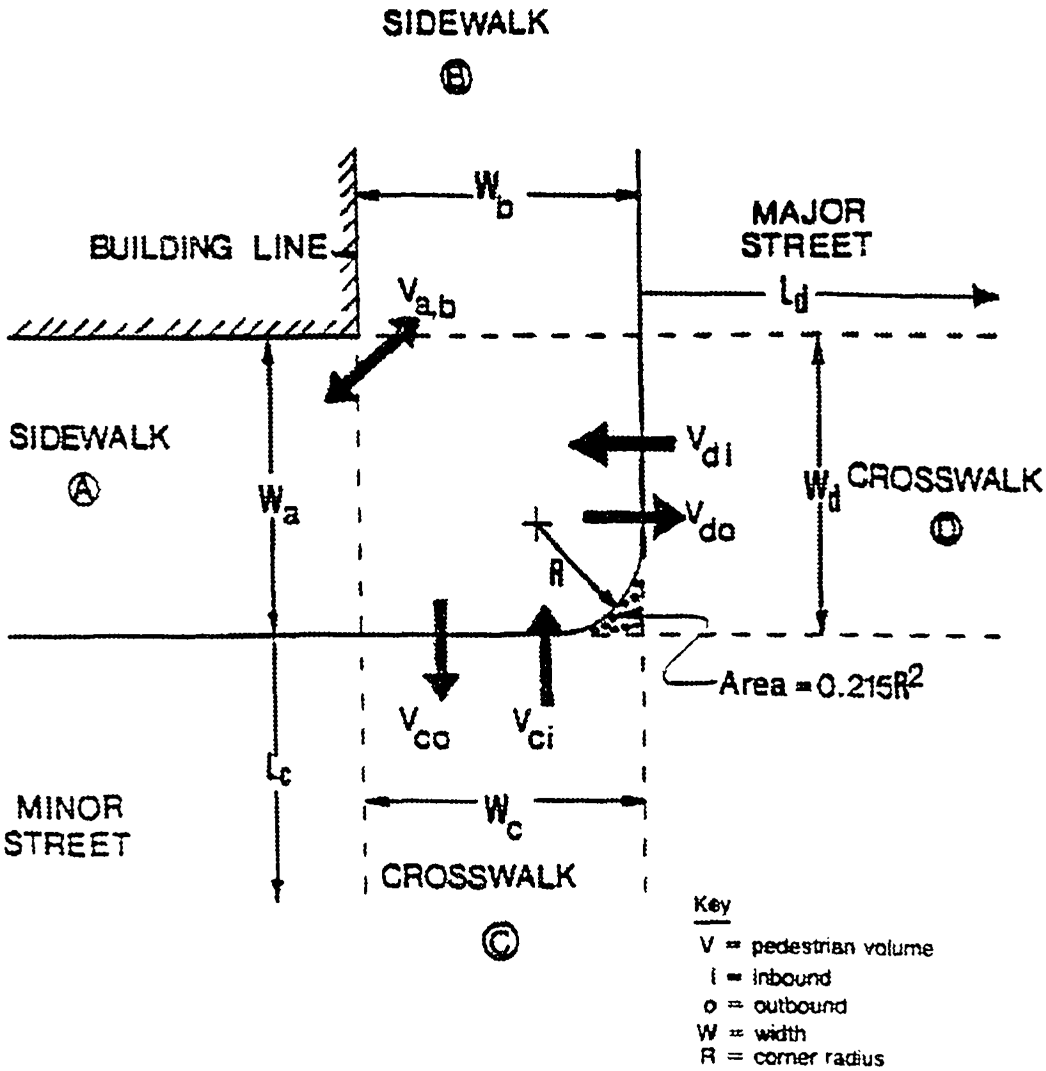
A typical worksheet used in this analysis is shown in Appendix "A".

4.4 INTERSECTION CORNER AREAS

The corner area involves uninterrupted (sidewalk) flow, interrupted flow (crosswalks), and pass-through traffic. The "sidewalk flows, pedestrians crossing the street, and others queued waiting for the signal to change" mix in the corner area, creating a critical link between the sidewalk and the crosswalk. There are two area needs (52):

1. Holding area for pedestrians waiting for the signal to change.
2. Circulation area for pedestrians crossing with the green interval, coming off the street in the crosswalk, coming from the sidewalk into the corner, and pedestrians not crossing the street, but moving between adjoining sidewalks.

These combinations create rather complex movements, as shown in Figure 11. The methodology uses a "time-space concept" (52). The methodology assumes that pedestrians waiting for the signal to change occupy about 5 square feet per pedestrian in



Intersection corner geometrics and pedestrian movements.

Source: <u>Highway Capacity Manual: Special Report No. 209 (1994 edition)</u>

Figure 11

the "holding area." The average time that pedestrians occupy the corner area is assumed to be in the range of 3 to 5 seconds in the Highway Capacity Manual (1994) (52). The analysis considers the circulation area and holding area. Two conditions (minor street crossing phase and major street crossing phase) can be analyzed. The time just before the signal phase change that allows pedestrians to cross is used.

The methodology requires sidewalk widths, the corner radius, the roadway width, signal cycle length with splits, and green-amber times for the major and minor streets, and 15 minute peak pedestrian counts. The methodology involves the following procedures (52):

STEP 1: The net corner area is the product of intersecting sidewalk widths (W_a and W_b) minus the lost corner area due to the radius (R) and obstructions. Comments on this formula are provided in Chapters 5 and 6.

The total available time-space (TS) per cycle is calculated by the product of net corner area (A) and time (t). "T" is equal one signal cycle length in seconds (C).

$$A = W_a W_b - 0.215\ R^2$$

$$TS = A \times C/60$$

Where:

A = Corner area, square feet

W_a =sidewalk A width in feet

W_b = sidewalk B width in feet

R = radius in feet

C = cycle length, in seconds

TS = total time-space available in square feet-minute

STEP 2: The holding area waiting times are computed. Uniform arrival times are assumed at crossing queues. The average pedestrian holding times, (Q_{tco} and Q_{tdo}) for crosswalks C and D are one-half the product of the outbound flows during a signal cycle (v_{co} and v_{do} in pedestrians/cycle), the proportion of the cycle that the flows are held up, and the red signal phase holding time.

For the minor street crossing (major street WALK or green phase):

$$Q_{tco} = [v_{co} \times (R_{mj}/C) \times (R_{mj}/2]/60$$

For the major street crossing (minor street WALK or green phase):

$$Q_{tdo} = [v_{do} \times (R_{mi}/C) \times (R_{mi}/2)]/60$$

Where:

Q_{tdo} = total ped. time waiting to cross major street per signal cycle (ped-min)

Q_{tco} = total ped. time waiting to cross minor street per signal cycle (ped-min)

v_{co} = number of pedestrians per cycle crossing minor street (ped/cycle)

v_{do} = number of pedestrians per cycle crossing major street

R_{mi} = red phase of minor street, i.e., DON'T WALK phase (in sec.)

R_{mj} = red phase of major street, i.e., DON'T WALK phase (sec.)

C = signal cycle length (sec.)

The R/C term helps describe the number of pedestrians per cycle that must wait for the green indication, which is v x R/C. The average wait per pedestrian is assumed to be R/2 seconds.

STEP 3: The holding area time-space requirements are determined by the product of the total waiting times and average area used by a waiting pedestrian (5 sq. ft/ped.).

$TS_h = 5\ (Q_{tdo} + Q_{tco})$

Where:

TS_h = total time-space holding area requirements (sq.ft-min)

STEP 4: The net corner time space available for circulation is determined. This is the total intersection time-space minus the holding waiting pedestrian time-space.

$TS_c = TS - TS_h$

Where:

TS_c = total time-space available for circulating pedestrians (sq.ft-min.)

STEP 5: The total number of circulating pedestrians per cycle is determined. This is the sum of all pedestrian flows (ped/cycle):

$v_c = v_{ci} + v_{co} + v_{di} + v_{do} + v_{ab}$

Where:

v_c = total number of circulating pedestrians (ped/cycle)

STEP 6: The total circulation time utilized by circulating pedestrians is the product of all the total circulation volume and an assumed average circulation time, which I call C_{av} in this thesis is assumed in the Highway Capacity Manual (1994) (5) to be four (4) seconds.

$t_c = v_c \times C_{av}/60$

Where:

t_c = total circulation time (ped-min.)

STEP 7: The circulation area per pedestrian or the "pedestrian area module" (M) is calculated as the net time-space available for circulation (TS_c) divided by the total circulation time (t_c).

$M = TS_c/t_c$

STEP 8: The corner LOS is now determined by comparison of the "pedestrian area module (M)" to the criteria in Table 5.

A typical worksheet used in this analysis is shown in Appendix "B".

4.5 CROSSWALKS

Pedestrians on crosswalks are subject to the interrupted flow conditions caused by traffic signals. Otherwise, the speed, density, and flow relationships are similar to those of the sidewalk. The effects of turning vehicles during the pedestrian phase also must be considered, if significant.

The time-space concept is applicable in the analysis of the crosswalk. This time space is the "WALK" phase time less the platoon start up time (assumed 3 seconds in the Highway Capacity Manual (1994 ed.) and the crosswalk area. The “demand” for the space is the product of the pedestrian crossing flow and the average crossing time. The available time space divided by the "demand" provides the space per moving pedestrian available during the green phase. This value can be compared to the LOS criteria table. The negative affect of turning vehicles can be estimated by assuming a "vehicle swept path area" (52) and time per turning vehicle in the crosswalk. This methodology involves the following procedures (52):

STEP 1: The time-space available is determined for one signal cycle by multiplying the crosswalk area and "WALK" interval.

$A_w = W \times L$

$TS_w = A_w \times G_w/60$

Where:

A_w = crosswalk area (sq. ft.)

W = crosswalk width (ft.)

L = crosswalk length (ft.)

TS_w = total time-space available in the crosswalk for one signal cycle (sq. ft.-min.)

G_w = WALK interval (sec.)

STEP 2: The average crossing time is determined by dividing the length of the crosswalk (roadway width) by the walking speed. This is typically assumed to be 4.5 feet per second.

$t_w = L/4.5$

Where:

t_w = average time spent by pedestrian in crosswalk (sec.)

L = crosswalk length (ft.)

STEP 3: The total crosswalk occupancy time is calculated by multiplying the average crossing time by the number of pedestrians using the crosswalk per signal cycle.

$T_w = (v_i + v_o)\ t_w/60$

Where:

T_w = total crosswalk occupancy time (ped.min.)

v_i = incoming ped. volume (ped/cycle)

v_o = outgoing ped. volume (ped/cycle)

STEP 4: The average circulation space per pedestrian and the average LOS is determined. The average circulation space is calculated by dividing the time space available for crossing by the total occupancy time. The result is the average area module (M).

$M = TS_w/T_w$

STEP 5: The LOS is determined for the maximum surge condition, which analyzes when the two opposing platoons of pedestrians meet. The area module (M) for the surge condition is the area of the crosswalk divided by the maximum number of pedestrians in the crosswalk. The crosswalk flows (peds/min.) are multiplied by the "DON'T WALK" interval plus the crossing time, t_w.

$V_m = (v_i + v_o)(R_w + t_w)/60$

$M = A_w/V_m$

Where:

V_m = max-number of pedestrians in crosswalk

v_i = incoming pedestrian volume (ped/min.)

v_o = outgoing pedestrian volume (ped/min.)

R_w = DON'T WALK interval (sec.)

The surge LOS is typically worse than the average LOS. The value is compared to Table 5 for determination of LOS.

4.6 RIGHT TURNING VEHICLES

Research by Luh and Lu (1990), Virkler and Maddela (1995), Perez (1995) and TRB (1985) confirm that the allowance of right turn movement during the concurrent pedestrian phasing detrimentally impacts the level of service and capacity of the crosswalk affected. This impact is determined quantitatively by "assuming an average area occupancy of a vehicle in the crosswalk, based on the product of vehicle swept-path and crosswalk widths, and an estimate of the time that the vehicle preempts this space (52)." The HCM proposes a swept-path of 8 feet and a vehicle occupancy of the crosswalk of 5 seconds. The number of vehicles turning right is multiplied by the time-space preemption for each vehicle. This total time space preemption due to right turn is vehicles deducted from the total available time-space calculated for the crosswalk (TS).

CHAPTER 5

PROPOSED SYSTEMS METHODOLOGY TO EVALUATE A PEDESTRIAN TRAFFIC NETWORK AT SIGNALIZED INTERSECTIONS

5.1 INTRODUCTION

The level of service (LOS) of the pedestrian elements at a signalized intersection -- sidewalk, corner area, and crosswalk -- must be balanced to provide an acceptable pedestrian traffic system at urban signalized intersections. As discussed in Chapter 4, methodologies exist to evaluate the individual elements (sidewalk, corner area, and crosswalk). From previous discussions it is critical that this balanced system operate at an acceptable LOS during the peak periods of vehicular and pedestrian traffic.

Pedestrian accidents occur disproportionately at signalized intersections during peak periods within the zone from the stop line to within 150 feet of the stop line. Compliance, understanding and utilization of supplemental pedestrian traffic signal indications and messages is low, exacerbating the pedestrian-vehicle conflict problem that exists with right and left turning vehicles. Current practice sizes sidewalks, crosswalks, and corner areas in accordance with minimum standards established in the AASHTO, A Policy on Geometric Design of Highways and Streets (2) and the Manual on Uniform Traffic Control Devices (58), which provide the basis for standards in most state and local jurisdictions.

5.2 CONSIDERATIONS FOR DEVELOPMENT OF A SYSTEMS METHODOLOGY

In order to develop a systems methodology, the key variables that relate to each of the three elements need to be identified and their interrelationships considered. As a system, these groups of variables affect the level of service (LOS) of each element and the ability to "balance" the pedestrian system at a signalized intersection. There are key geometric, traffic signal operation, and traffic groups of variables that affect the system, as shown in Table 7.

There are key geometric variables of the system that affect the LOS of one or more elements. The effective width of the sidewalk, the crosswalk width and the holding area directly affect the LOS of three elements. The width of the crosswalk directly affects the LOS of the crosswalk. The narrower the crosswalk, the worse the LOS. The effective width of the sidewalk directly affects the LOS of the sidewalk, i.e., for the same pedestrian flow a narrower sidewalk will degrade the level of service. The holding area of the corner directly affects the level of service of the corner. An inadequate or smaller holding area on the corner degrades the LOS of the corner.

The traffic signal operation introduces several key variables that affect the LOS of the crosswalk and corner area. The signal cycle length has an affect on the corner area and crosswalk width. Generally, the longer the cycle length the larger the holding area and the wider the crosswalk must be to provide the same LOS. More specifically, the longer red time of each cycle forces pedestrians to wait longer at each corner, thereby creating the need for a larger holding area. In addition, the longer red time creates a larger platoon that must be accommodated by a wider crosswalk, especially when

GROUPS OF KEY VARIABLES

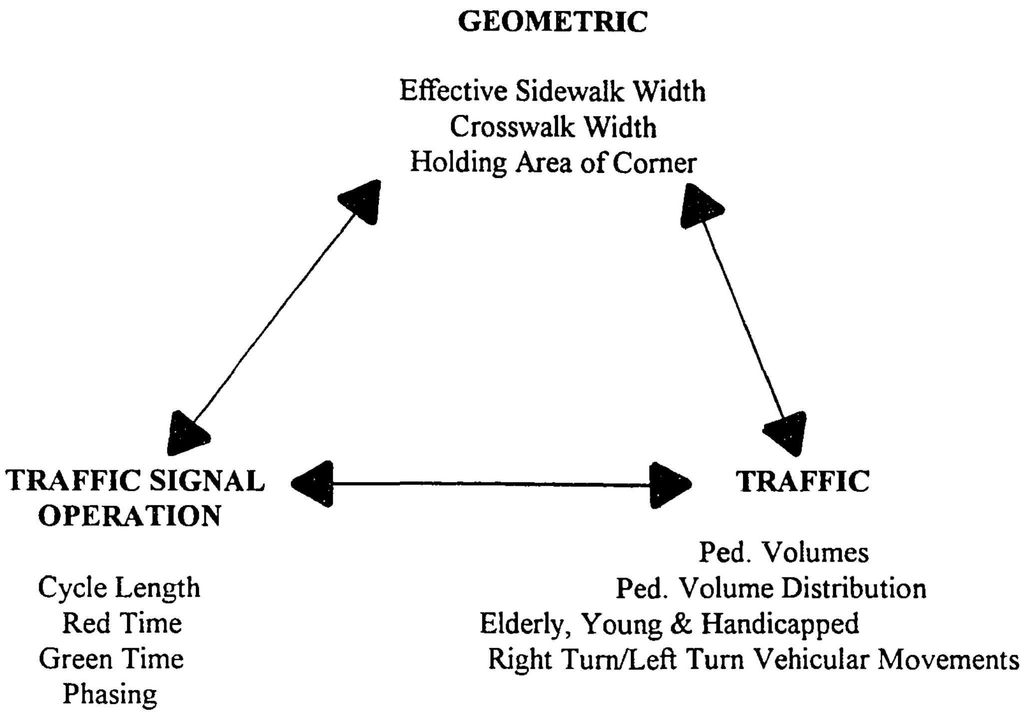
GEOMETRIC	TRAFFIC SIGNAL OPERATION	TRAFFIC
Effective sidewalk width	Cycle length	Volume of pedestrians
Crosswalk width	Red time for pedestrian movement	Inbound, outbound and pass through pedestrian volume distribution
Holding area of corner	Green time for pedestrian movement	Right and left turn vehicular movements
	Phasing	Elderly, young and handicapped

Table 7

considering the surge condition. An increase in green time has the opposite affect. Indirectly, the traffic signal phasing also has an affect in that the higher the number of vehicle phases, the less green time or more red time proportionately there is per cycle for pedestrian movements.

The third group of variables relate to the pedestrian and vehicular traffic. Obviously, the volume of pedestrian traffic directly affects the LOS of the sidewalk, corner area and crosswalk. With a given sidewalk width, corner area, and crosswalk width, the higher the pedestrian volume the lower the LOS of each element. The values of inbound, outbound, and pass-through pedestrian traffic affect the holding areas and circulating areas needed to provide an acceptable LOS. The composition of pedestrian traffic is considered in this methodology as related to walking speed. Higher percentage of handicapped, elderly or young pedestrians can affect the LOS by decreasing the walking speed and the LOS. Unfortunately, the HCM methodology assumes a walking speed of 4.5 feet per second. In the systems methodology developed later in this chapter, the term S_p has been used to represent the "variable" term of walking speed. Vehicular traffic can affect the LOS of a crosswalk due to adverse affects caused by turning vehicles traversing the crosswalk during concurrent right turn or left turn movements. Theoretically, with exclusive or protected left turn phasing, the left turn interference is eliminated. A heavy right turn movement can directly affect the LOS of a crosswalk by reducing the crossing time and crosswalk space available for pedestrians.

The interrelationships of the three groups of variables are shown in Figure 12. These relationships to the key elements (sidewalk, corner area, and crosswalk) show that a



INTERRELATIONSHIPS OF GROUPS OF VARIABLES

Figure 12

balanced increase in the width of the sidewalk and crosswalk, and an increase in the holding area of the corner will improve the LOS of the "system."

Other fundamental interrelationships exist between the variables of the three groups--geometric, traffic signal operation, and traffic--that are not apparent from Figure 12. An increase or decrease in one variable will directly or indirectly cause concurrent changes in the values of other variables to ensure that the desired LOS is maintained. Interrelationships exist between the following variables as follows:

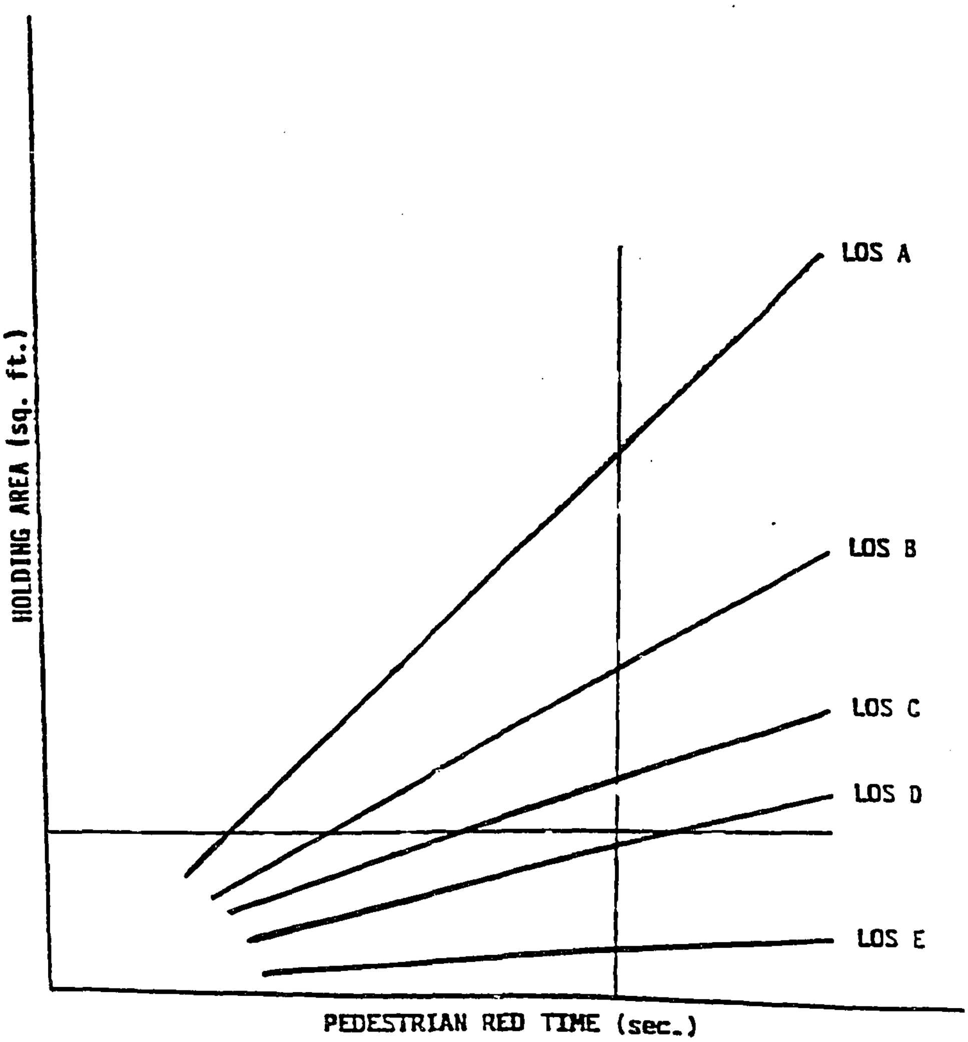
1. Pedestrian Red Time and Holding Area:

   As the red time to a pedestrian movement increases, the holding area size must increase to accommodate a larger platoon of pedestrians. The opposite effect is true with more pedestrian green time rather than red time. If the pedestrian red time is held constant, the holding area size must increase to improve the level of service. If the holding area is held constant, then the pedestrian red time must decrease to improve the level of service.

   These relationships are shown schematically in Figure 13 by vertical and horizontal lines. Linear relationships are assumed for discussion purposes.

2. Pedestrian Red Time and Crosswalk Width:

   With larger platoons the surge condition in the crosswalk increases thereby causing the need for a wider crosswalk. The opposite effect is true with more pedestrian green time. If the pedestrian red time is held constant, then the crosswalk width must increase to improve the level of service. If the crosswalk width is held constant, then the pedestrian red time must decrease to improve the level of



INTERRELATIONSHIP BETWEEN HOLDING AREA AND
PEDESTRIAN RED TIME

Figure 13

service. These relationships are shown schematically in Figure 14. Linear relationships are assumed for discussion purposes.

3. Crosswalk Width and Vehicular Right Turns:

   An increase in the vehicular right turn movement traversing a crosswalk during a concurrent phase will cause an increase in crosswalk width to offset the loss of time-space due to the right turn movement, if additional green time is not available.

4. Pedestrian Green and Vehicular Right Turns:

   An increase in the vehicular right turn movement traversing a crosswalk during a concurrent phase will cause an increase in pedestrian green time to offset the loss of time-space due to the right turn movement, if additional crosswalk width is not available.

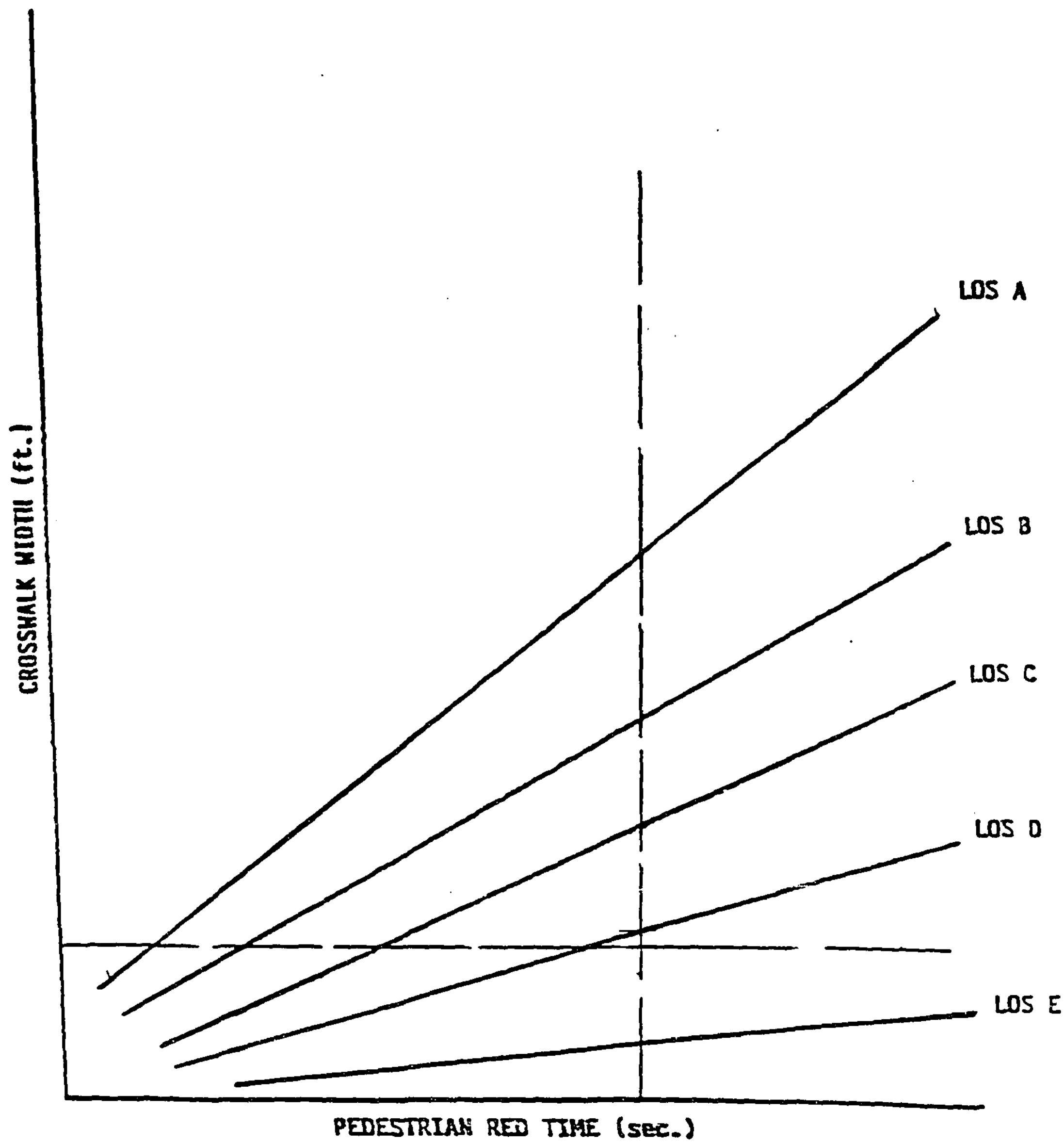
5. Pedestrian Green Time and Elderly, Young and Handicapped:

   A higher composition of the elderly, young and handicapped will cause a slower walking speed, thus increasing the time needed to cross a street. This increase creates a higher time-space demand. Additional pedestrian green time will be needed to accommodate the pedestrian crossing.

6. Pass-Through Pedestrian Traffic and Holding Area:

   The higher the proportion of pass-through traffic, i.e., pedestrian traffic crossing the corner area only from adjoining sidewalks without crossing the street, the smaller the holding area available to accommodate waiting pedestrians.

An understanding of these interrelationships is important in the tasks of planning and design of a "LOS balanced" pedestrian system at signalized intersections.



INTERRELATIONSHIP BETWEEN CROSSWALK WIDTH
AND PEDESTRIAN RED TIME

Figure 14

5.3 DEVELOPMENT OF A SYSTEMS METHODOLOGY PROCEDURE

A planning methodology is needed to link the three key elements (sidewalk, corner area, and crosswalk) by LOS. In the descriptions provided of the LOS criteria, LOS "C" is the lowest LOS that allows normal walking speeds and reasonable maneuverability. Pedestrian behavior below this level becomes more unpredictable and stressed due to restrictions in speed and maneuverability. In Chapter 4 methodologies to evaluate LOS were discussed for each of the three key elements. The methodologies of the individual key elements did not recognize the need to provide a balanced system LOS. The LOS of the system and its elements should be the same to optimize and balance pedestrian flow.

LOS (Pedestrian Traffic System at Signalized Intersection) =

LOS (Sidewalks) = LOS (Corner Area) = LOS (Crosswalks)

The sidewalk at a signalized intersection is similar to the roadway leg of the signalized intersection. Volumes of approaching vehicles are used to determine adequate levels of service for vehicles. Similarly, the volumes of pedestrians proceeding to and from a signalized intersection provide the basis on which the pedestrian traffic system elements (sidewalk, corner area, and crosswalk) should be designed. The sidewalk is the uninterrupted pedestrian flow segment of the pedestrian traffic system.

The corner areas and crosswalk areas are analyzed using the time-space concept. This must be done due to interruptions in pedestrian flow caused by the operation of the traffic signal. The cycle length of the traffic signal and the time provided for the pedestrian phase intervals (WALK, FLASHING DON'T WALK, and DON'T WALK) directly affect the LOS of the crosswalk and corner area. With an assumed or selected LOS, effective sidewalk width, signal cycle, and the following assumptions, the pedestrian traffic system can be planned.

Various assumptions must be made in this methodology. Most are the same assumptions used in the HCM methodologies for each element.

1. The bi-directional pedestrian traffic flow on crosswalks is approximately equal (52). In Figure 11 the inbound pedestrian flows to the corner are identified as v_{ci} and v_{di}. The pedestrian flows outbound from the corner are identified as v_{co} and v_{do}. It is assumed in the Highway Capacity Manual (1994) (52) that $v_{ci} = v_{co}$ and $v_{di} = v_{do}$.
2. Platooning does occur in the pedestrian flow due to the interruption of the operation of the traffic signal.
3. On corner areas either pedestrians are standing and holding, or circulating and moving.
4. A standing pedestrian on a corner occupies an average area of 5 square feet per pedestrian, according to the Highway Capacity Manual (1994 edition).
5. The average time that moving pedestrians occupy the corner, i.e., passing through, is in the range of 3 to 5 seconds, according to the Highway Capacity Manual (1994 edition). The time taken by a pedestrian to pass through the corner is a function of intersection geometry and walking speed.

6. The average walking speed, in the crosswalk identified as S_p in this report, is assumed to be 4.5 feet per second in accordance with the Highway Capacity Manual (1994 edition)..

7. The platoon start up time of pedestrians is 3 seconds.

8. The pedestrian traffic, or called pass-by or pass-through traffic in this report, between adjoining sidewalks, but not crossing the street is identified as v_{ab}. Further research is needed to refine this planning procedure value.

9. Uniform arrivals of crossing queues in the corner area.

10. The same effective width of sidewalk is used for both sidewalks intersecting at a corner. The larger effective width is used for both sidewalks A and B in the planning procedure.

With these assumptions the following methodology is used.

STEP 1: If it is desired to balance the LOS of an assumed effective sidewalk width (W_E), then use the following planning procedure.

PLANNING PROCEDURE:

Determine the high end of the flow rate (v) from Table 5. For example, at LOS "C" it would be 10 ped/min/ft. Assume that this flow rate represents platoon conditions, where v_p (ped/min/ft) = v + 4. The average flow rate would be lower, but we are designing for platoon conditions, because a signalized intersection is nearby. For the total flow of the sidewalk A, calculate:

(1) $(W_{EA})(v_{PA}) = V_{TA}$

For sidewalk B:

(2) $(W_{EB})(v_{PB}) = V_{TB}$

Where:

W_{EA} = effective walkway width of sidewalk A

W_{EB} = effective walkway width of sidewalk B

v_{PA} = flow rate of pedestrians on sidewalk A per foot of width

v_{PB} = flow rate of pedestrians on sidewalk B per foot of width

V_{TA} = pedestrian flow for sidewalk A

V_{TB} = pedestrian flow for sidewalk B

The total volume of the two sidewalks to and from the street corner is:

(3) $V_{TA} + V_{TB} = V_{TOTAL} = V_t$

ACTUAL CONDITIONS:

If the actual volumes are known, then the sidewalks need to be sized in width for the LOS desired for platoon conditions where:

(4) v_p (ped/min/ft) = v + 4, so,

(5) $$W_E = \frac{V_t}{15\,(v_p - 4)}$$

where v_p is the higher flow rate from Table 5 for the selected LOS and represents the platoon flow rate.

STEP 2: If planning is based on an effective walkway width (W_E), then use the planning procedure.

PLANNING PROCEDURE:

The total volume of the two sidewalks equals v_t. $v_t = v_{ab} + v_{ci} + v_{co} + v_{di} + v_{do}$. Assuming equal bi-directional flow, then $v_{ci} = v_{co}$ and $v_{di} = v_{do}$.

Assumptions can be made from whatever information is known of the values of v_{ab}, v_{ci}, v_{co}, v_{di}, and v_{do}. Use these relationships to calculate the volumes in and out of the corner area and the passby pedestrian volume (v_{ab}).

ACTUAL CONDITIONS:

If actual values of v_{ab}, v_{co}, v_{ci}, v_{di}, and v_{do} are available, then use these values.

STEP 3 (Crosswalk): Calculate the crossing time. The roadway widths must be known or assumed to determine L_c and L_d. Assume a walking speed (S_p) of 4.5 feet per second per the HCM (52). Use the following formulae:

(6) t_{wc} (sec) = L_c/S_p

(7) t_{wd} (sec) = L_d/S_p

STEP 4 (Crosswalk): Calculate the crosswalk occupancy time (ped/cycle)

(8) T_{wc} (ped-min.) = $(v_{ci} + v_{co})(t_{wc}/60)$

(9) T_{wd} (ped-min) = $(v_{di} + v_{do})(t_{wd}/60)$

STEP 5 (Crosswalk): Calculate the maximum surge (ped/min)

(10) $V_{mc} = (v_{ci} + v_{co})\ (R_{mi} + 3 + t_{wc})/60$

(11) $V_{md} = (v_{di} + V_{do})(R_{mj} + 3 + t_{wd})/60$

STEP 6 (Crosswalk): Calculate the crosswalk needed for LOS (average ped. space and LOS) by the following process:

The following values are given, known or calculated:

L_c, L_d, G_{mi}, G_{mj}, M_c, M_d, M_c(max), M_d(max), T_{wc}

L_c and L_d are the known roadway widths. G_{mi} and G_{mj} are the known WALK intervals. M_c, M_d, M_c (max), and M_d (max) in terms of square feet per pedestrian, which are taken from Table 5 (52). T_{wc} is calculated in Step 4. For example, for crosswalk C, the equations given are as follows:

(12) $A_c = L_c W_c$

Substituting for A_c, $TS_c = L_c\, W_c\, (G_{mj} - 3)/60$

Rearranging gives:

(13) $$W_c = \frac{60\, TS_c}{L_c(G_{mj} - 3)}$$

(14) $M_c = TS_c/T_{wc}$, therefore

(15) $TS_c = M_c T_{WC}$

If there is a significant right turn movement, a deduction from the crosswalk time space available (TS_c) should be considered. Using an average "swept-path of 8 feet (52) and an approximation that the right turn vehicle occupies the crosswalk for 5 seconds" (52) a preemption per vehicle can be estimated:

(16) $$[\, 8 \text{ ft.} \times W_c \times 5 \text{ sec.}]/60 = \frac{\text{sq. ft. min.}}{\text{veh.}} = \frac{2}{3} W_c \;\frac{\text{sq. ft. min}}{\text{veh.}}$$

The total available time space deduction equals the product of the number of right turn vehicles during the pedestrian phase and the preemption per vehicle. This number is subtracted from TS_c.

(17) $T_{wc} = TS_c - n \frac{2}{3} W_c$, where n = number of right turn vehicles

Substituting equation (15) into equation (13) gives:

(18) $$W_c = \frac{60\, M_c T_{wc}}{L_c(G_{mj} - 3)} = \text{CROSSWALK WIDTH (AVERAGE)}$$

STEP 7 (Crosswalk): Calculating the crosswalk width for the higher value of pedestrian space at the LOS follows:

For example for crosswalk "C":

(19) $M_c(max) = A_c/V_{mc}$

V_{mc} was calculated in Step 5

(20) $A_c = L_cW_c$, therefore substituting gives,

(21) $M_c(max) = L_cW_c/V_{mc}$

Rearranging terms gives,

(22) $W_c = \dfrac{M_c(max)\ V_{mc}}{L_c}$ = CROSSWALK WIDTH

Use the higher value of the square feet per pedestrian for the LOS selected from Table 5. From this analysis the appropriate crosswalk width for the LOS operation on the sidewalk can be determined. This provides a balanced LOS operation for two of the elements of the pedestrian traffic signal system at a signalized intersection. The corner analysis procedure follows.

STEP 3 (Corner): Calculate the total circulation volume. From Step 2 the values of v_{ci}, v_{co}, v_{di}, v_{do}, and v_{ab} are known.

PLANNING PROCEDURE:

(23) $v_c(ped) = v_{ci} + v_{co} + v_{do} + v_{di} + v_{ab}$

ACTUAL CONDITIONS:

If actual volumes are known, use them.

STEP 4 (Corner): Calculate the total circulation time.

(24) t_c (ped-min) = v_c x $C_{av}/60$ where C_{av} according to the HCM (52) is assumed to be four (4) seconds.

STEP 5 (Corner): Calculate the hold area waiting times, using ped/cycle.

(25) Q_{tco} (ped-min.) = $[(v_{co})(R_{mj}/C)(R_{mj}/2)]/60$

(26) Q_{tdo} (ped-min.) = $[(v_{do})(R_{mi}/C(R_{mi}/2)]/60$

STEP 6 (Corner): Calculate the hold area time space.

(27) TS_h (sq. ft. min.) = $5\ (Q_{tco} + Q_{tdo})$

STEP 7 (Corner): Calculate the gross corner area and net corner area. Determine M (sq. ft./ped) from Table 5 (52). t_c and TS_h have been previously calculated.

C, W_a, W_b, R are known.

(28) $TS_c = M(t_c)$

(29) $TS = TS_c + TS_h$

(30) $AG = \dfrac{60TS}{C}$ = GROSS CORNER AREA

The net corner formula calculation:

(31) $A = W_a W_b - 0.215 R^2$,

Where:

W_a = width of sidewalk A

W_b = width of sidewalk B

R = radius of corner

was found not to be useful, because it results in negative numbers. The formula does not take into account the typical geometric design on a street corner where the sidewalks intersect.

A “Step-by-Step” Pedestrian Systems Methodology Flow Chart” has been developed to summarize the process described, as shown in Figures 15 and 16. After the second step, i.e., at the third step and after either the corner area (gross) or the crosswalk width (average or surge) can be calculated to provide a balanced LOS pedestrian transportation system.

STEP BY STEP PEDESTRIAN SYSTEMS METHODOLOGY FLOW CHART

S/W LOS
Ped/Min/Ft

CORNER AREA DETERMINATION

CROSSWALK WIDTH DETERMINATION

Use LOS Flow for v_{di}, v_{do}, v_{co}, v_{ci}, v_{ab} or actual

Provide Signal Cycle Length (C)

Calculate Crossing Times:
$t_{wc}(\text{sec.}) = L_c/S_p$
$t_{wd}(\text{sec.}) = L_d/S_p$

Determine or assume roadway widths L_c, L_d

Calculate crosswalk occupancy time (ped/cycle):
$T_{wc}(\text{ped-min}) = (v_{ci} + v_{co})(t_{wc}/60)$
$T_{wd}(\text{ped-min}) = (v_{di} + v_{do})(t_{wd}/60)$

Calculate max. Surge (ped/min.):
$V_{mc} = (v_{ci} + v_{co})(R_{mj} + 3 + t_{wc})/60$
$V_{md} = (v_{di} + v_{do})(R_{mi} + 3 + t_{wd})/60$

Calculate crosswalk width for average ped. space and LOS.
M_c from Table 5
$$W_c = \frac{60\,M_c T_{wc}}{L_c(G_{mj}-3)} = \text{CROSSWALK WIDTH (AVG)}$$

Calculate crosswalk width for higher value of M_c for LOS:
$$W_c = \frac{M_c(\max)\,V_{mc}}{L_c} = \text{CROSSWALK WIDTH}$$

Figure 15

CORNER AREA DETERMINATION

From Step 2 the values of
v_{ci} , v_{co} , v_{dI} , v_{do} , v_{ab}
are known so calculate the total circulation volume.
v_c (ped) = $v_{ci} + v_{co} + v_{do} + v_{di} + v_{ab}$

↓

Calculate the total circulation time.
t_c(ped-min) = $v_c \times C_{av}/60$

↓

Calculate the hold area waiting time, using ped/cycle.
Q_{tco} (ped-min) = $[(v_{co})(R_{mj}/C)(R_{mj}/2)]/60$
Q_{tdo} (ped-min) = $[v_{do})(R_{mi}/c)(R_{mi}/2)]/60$

↓

Calculate the hold area time space
TS_h (sq. ft.-min.) = $5\ (Q_{tco} + Q_{tdo})$

↓

Calculate the gross corner area.
Determine M (sq. ft./ped)
from Table 5 (T-1).
$TS_c = Mt_c$
$TS = TS_c + TS_h$
$A = \frac{60\ TS}{C}$ = GROSS CORNER AREA

Figure 16

CHAPTER 6

A CASE STUDY: THE PEDESTRIAN TRAFFIC SYSTEM AT THE INTERSECTION OF FLAMINGO ROAD AND LAS VEGAS BOULEVARD SOUTH IN CLARK COUNTY, NEVADA

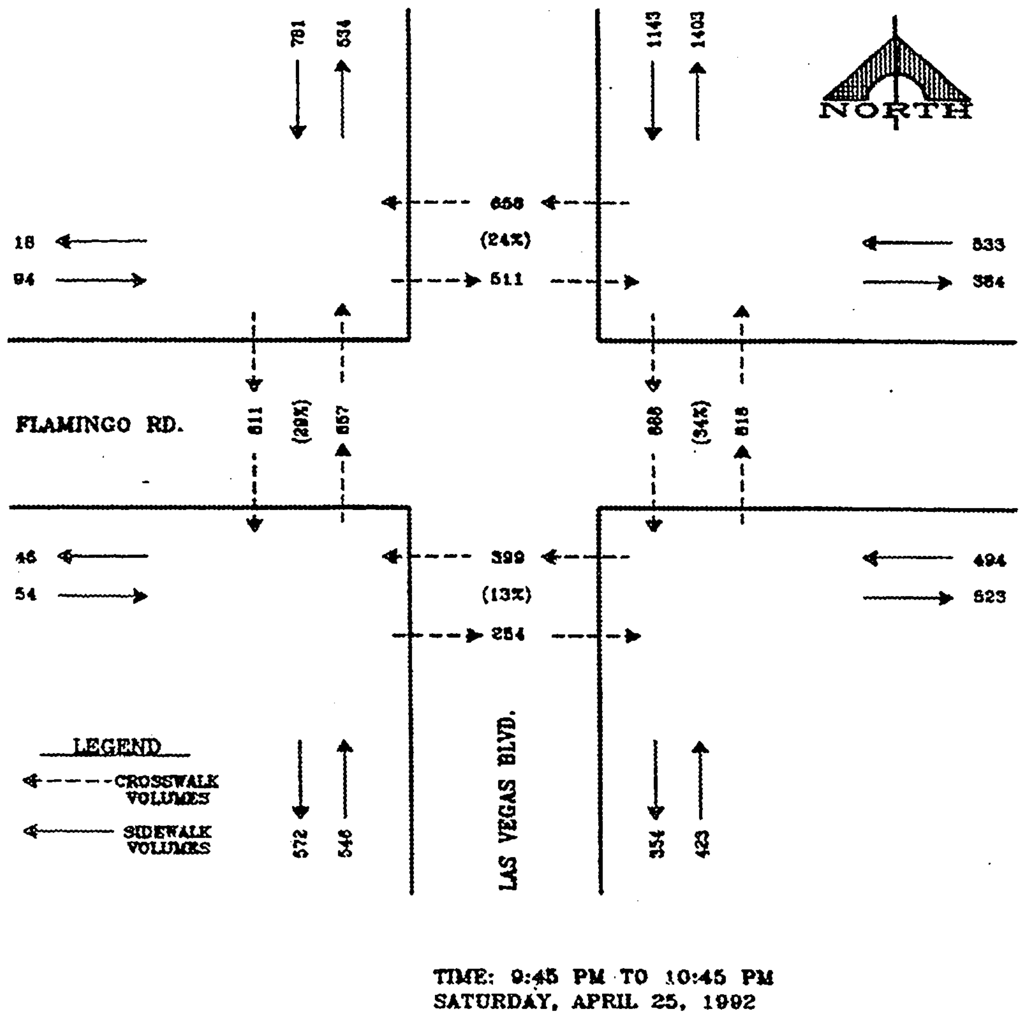
6.1 INTRODUCTION

The intersection of Flamingo Road and Las Vegas Boulevard South was selected as the case study site. Both intersecting streets are functionally classified as major arterials. The intersection is controlled by an eight phase traffic signal that is part of a computerized traffic signal system. The cycle length is 140 seconds during the peak period.

The average daily traffic volumes in 1993 were as follows (16):

Location	ADT
Las Vegas Blvd. S. north of Flamingo Rd.	58,000
Las Vegas Blvd. S. south of Flamingo Rd.	48,000
Flamingo Road between I-15 and Koval Ln.	60,000

Pedestrian volumes on the four marked crosswalks at the intersection are also very heavy. Data from peak hour pedestrian counts conducted at the intersection on Saturday, April 25, 1992 from 9:45 p.m. to 10:45 p.m. have been used in the case study. These pedestrian counts are shown in Figure 17 (16). The counts have been divided by four to obtain



PEAK HOUR PEDESTRIAN MOVEMENTS AT LAS VEGAS BLVD./FLAMINGO RD.

Figure 17

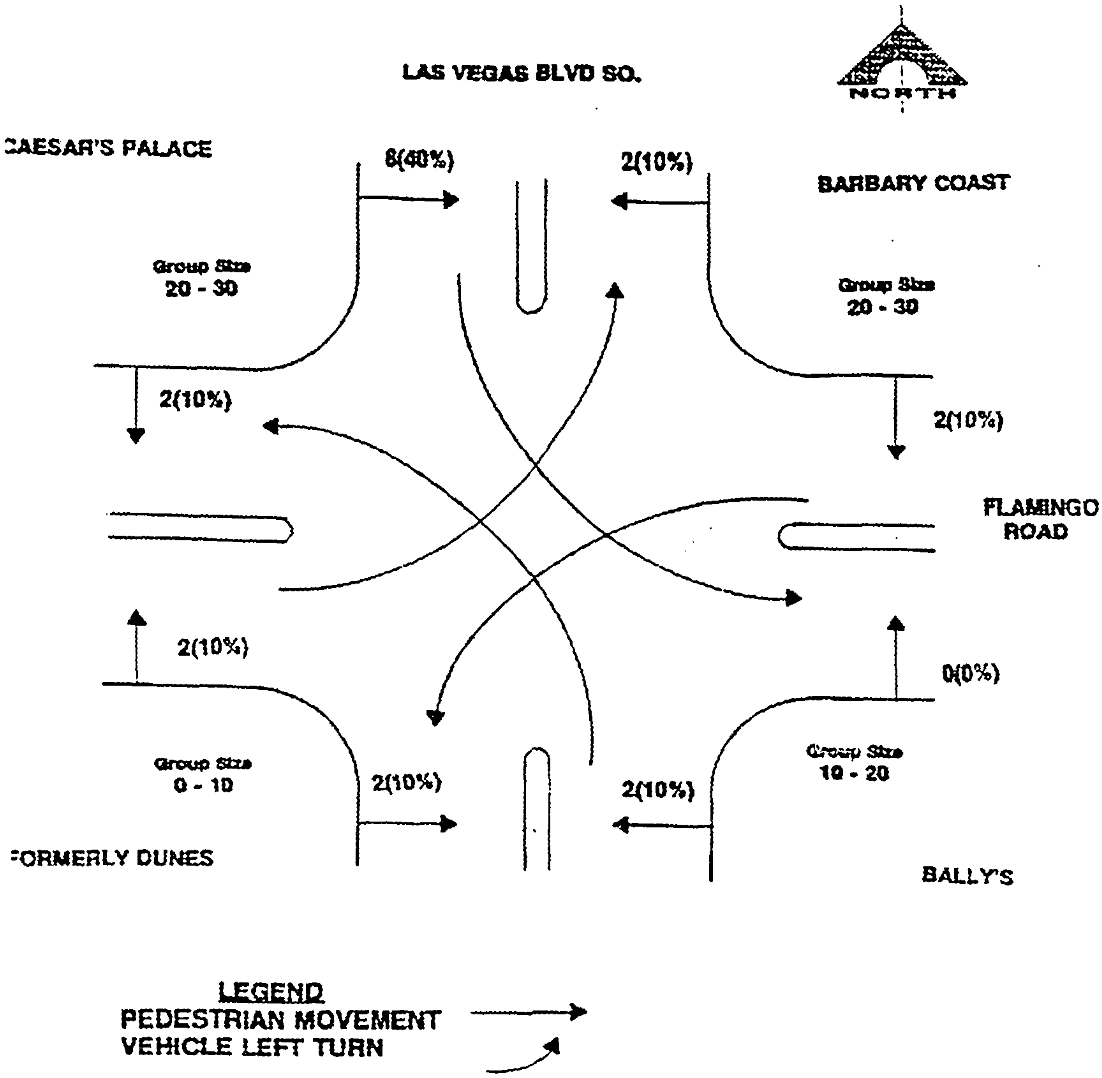
15 minute counts that will be used in the case study. The southeast corner of the intersection was selected for the case study.

6.2 FIELD OBSERVATIONS

In addition to the literature review, direct field observations of pedestrian behavior were conducted at the intersection of Las Vegas Boulevard South and Flamingo Road to provide local validity. This intersection was selected due to its heavy vehicular and pedestrian volumes during peak periods and lighter volumes during off-peak periods.

The intersection was observed at various time periods with the last observation period on Saturday, April 30, 1994, from 5:00 p.m. to 6:30 p.m. During this time period the signal cycle length was 140 seconds under control by the Las Vegas Area Computer Traffic System (LVACTS). Conflicts were observed on almost every cycle between vehicles attempting to make right turns on the vehicle green interval which ran concurrently with the corresponding pedestrian interval, when the pedestrian push-button was activated for that pedestrian phase. Usage of the pedestrian push-button was rather high with only one observance of a pedestrian phase out of ten that was not activated, although about 10 to 20 pedestrians were waiting on each opposite corner.

Pedestrian behavior at the intersection was observed for approximately 20 signal cycles (see Figure 18). In addition to the observations already mentioned regarding high push-button utilization and numerous right turn vehicle-pedestrian conflicts, left turn conflicts were studied. The left turn conflict occurred when pedestrians would initiate a crossing about halfway to the median in violation of a red HAND symbol, while a conflicting left turn movement was in operation, as shown in Figure 18.



LEFT TURN VEHICLE - PEDESTRIAN CONFLICTS

Figure 18

Generally, it was observed that there were few pedestrian violations, when pedestrians had to cross directly from the curb into the path of the left turning vehicle. This varied from zero to ten percent. Normally this occurred when the first vehicle in the left turn queue was slow in initiating movement, so the pedestrian quickly crossed before arrival of the first vehicle.

As can be seen in Figure 18, a higher proportion of pedestrian violations occurred when pedestrians crossed against a steady red HAND indication from the corner to the median, at which there was potential conflict with the left turn movement. This occurred between 10 percent to forty percent of the time with the highest violation involving the Caesars Palace corner (northwest) to the Barbary Coast corner (northeast). The largest group sizes per cycle were also observed on these two corners. The group size relates to the highest number of pedestrians observed in a platoon waiting on the corner.

Violations were initiated by one or two persons about sixty percent of the time. Usually, one or two people would begin to cross while the left turn movement was still proceeding, but the pedestrian group on the originating corner would remain. About forty percent of the time a few pedestrians would initiate the action and the remaining group would follow to the median.

Pedestrian behavior was also observed in the marked crosswalk. When the group size crossing from each corner could be contained within the crosswalk lines, pedestrians generally observed the "walk to the right half" rule. When pedestrian volumes exceeded the capacity of the crosswalk, the interface of the two opposing crossing groups of pedestrians was less orderly with numerous conflicts. In addition, a flaring out or widening of the width of the combined pedestrian groups (surge) occurred in the middle of the leg. This induced some pedestrians to walk behind the first vehicles waiting on the queue or to walk closer to the parallel stream of vehicular traffic. Although this sample is very small, the probability that a pedestrian movement in conflict with a left turn movement seemed to increase with an increase in the waiting pedestrian group size.

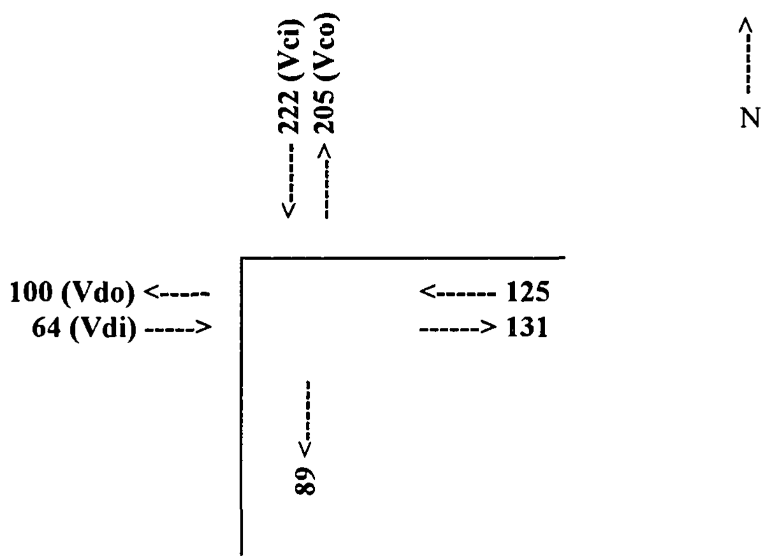
Observations of the pedestrian traffic system at this signalized intersection revealed that a balanced pedestrian traffic system was not in place. The crosswalks were inadequate in width. The corner holding areas appeared to have adequate area, but the effective or clear width of the sidewalk seemed inadequate.

6.3 CASE STUDY

The actual conditions that exist on the southeast corner of Las Vegas Boulevard South and Flamingo Road are used in this case study. It is desired to know the sidewalk width (W_E), the crosswalk widths, and the corner area necessary to satisfy LOS "C". Figure 19 shows the 15 minute pedestrian volumes on the crosswalks to the southeast corner and the sidewalk volumes toward and away from the corner. The analysis follows.

Figure 19

(Ped/15 min)



STEP 1: On the sidewalk to the east there is a volume of 125 + 131 = 256 ped/15 min. At LOS "C" the flow rate (v) can equal 10 ped/min./ft. at the less desirable end of the range.

ACTUAL CONDITIONS:

Calculations follow.

$V_p = V_1 + V_2 = 125 + 131 =$ <u>256 ped/15 min.</u>

For sidewalk to east:

$W_E = 3$ feet (preemptions subtracted)

For average walkway LOS:

v (ped/min./ft.) $= V_p/15W_E$

$v = 256/15\ (3)$

$v = 5.68 \cong 5.7$

For platooning:

$v_p = v + 4 = 5.7 + 4 = 9.7 \cong$ <u>10 ped/min./ft.</u>

Sidewalk operates at LOS "C".

For the sidewalk to the south there is a volume of 89 + 106 = 195 ped/15 min. At LOS "C" the flow rate (v) can equal 10 ped/min./ft. at the less desirable end of the range. At the time the pedestrian counts were taken, the effective walkway width (W_E) equaled 3 feet.

ACTUAL CONDITIONS:

$V_p = V_1 + V_2 = 89 + 106 =$ <u>195 ped/15 min.</u>

W_E = 3 feet (preemptions subtracted

For average walkway LOS:

v (ped/min./ft.) = $V_p/15\ W_E$

v = 195/15(3) = 4.3

For platooning:

$v_p = v + 4 = 4.3 + 4 =$ <u>8.3 ped/min./ft.</u>

Sidewalk operates at LOS "C".

STEP 2: Using actual volumes.

Ped/15 min.	Ped/min.	Ped/Cycle*
v_{ci} = 222	15	36
v_{co} = 205	14	33
v_{di} = 64	5	11
v_{do} = 100	7	16
v_{ab} = 8	1	2
v_{tot} = 599	42	98

*140 second cycle. 25 cycles/hour
Numbers rounded up.

The crosswalk analysis will be conducted first, then the corner area.

STEP 3 (Crosswalk): Calculate the crossing time. 4.5 feet per second is assumed for S_p.

$L_c = 84$ ft.

$L_d = 84$ ft.

t_{wc} (sec) = $L_c/S_p = 84/4.5 = \underline{18.7s}$

t_{wd} (sec) = $L_d/S_p = 84/4.5 = \underline{18.7s}$

STEP 4 (Crosswalk): Calculate the crosswalk occupancy time (ped/cycle).

T_{wc} (ped-min.) = $(v_{ci} + v_{co})(t_{wc}/60)$

$T_{wc} = (36 + 33)\ (18.7/60) = \underline{21.5 \text{ ped min}}$

$T_{wd} = (v_{di} + v_{do})(t_{wd}/60)$

$T_{wd} = (11 + 16)\ (18.7/60) = \underline{8.4 \text{ ped min}}$

STEP 5 (Crosswalk): Calculate the maximum surge (ped/min)

$V_{mc} = (v_{ci} + v_{co})(R_{mj} + 3 + t_{wc})/60$

$V_{mc} = (15 + 14)\ (119s + 3 + 18.7s)/60 = \underline{68 \text{ ped.}}$

$V_{md} = (v_{di} + v_{do})\ (R_{mi} + 3 + t_{wd})/60$

$V_{md} = (5 + 7)\ (119s + 3 + 18.7s)/60 = \underline{28 \text{ ped}}$

STEP 6 (Crosswalk): Calculate the crosswalk needed for the LOS desired, in this case LOS"C":

$$W_c = \frac{60\ M_c\ T_{wc}}{L_c\ (G_{mj} - 3)}$$

M_c from Table 5 equals 24 sq.ft./ped.

$$W_c = \frac{60\ (24\ \text{sq.ft/ped})(21.5\ \text{ped.-min.})}{84\ \text{ft.}\ (21 - 3)}$$

W_c = 20.5 feet for CROSSWALK "C".

$$W_d = \frac{60\ M_d\ T_{wd}}{L_d\ (G_{mi} - 3)}$$

$$W_d = \frac{60\ (24\ \text{sq.ft./ped})(8.4\ \text{ped-min.})}{84\ \text{ft.}\ (21 - 3)}$$

W_d = 8 feet for CROSSWALK "D".

STEP 7 (Crosswalk): Calculate the crosswalk width for the pedestrian space at the higher value of the LOS. In this step the highest value of M_c is assumed from the LOS table, i.e., 39.9 at the upper end of LOS "C" from Table 5.

$$W_c = \frac{M_c(\text{max})(V_{mc})}{L_c}$$

$$W_c = \frac{39.9\ \text{ft}^2/\text{ped}(68\ \text{ped}/)}{84\ \text{ft.}} =$$

W_c = 32.3 ft. For CROSSWALK "C".

$$W_d = \frac{M_d(\text{max})(v_{md})}{L_d}$$

$$W_d = \frac{(39.9\ \text{ft}^2/\text{ped})(28\ \text{ped})}{84\ \text{ft.}} =$$

W_d = 13.3 ft. For CROSSWALK "D".

At LOS "C" the crosswalk width for crosswalk "C"should be from 20.5 feet at the low end to 32.3 feet at the high end. Crosswalk "D" should be from 8 feet in width at the low end of LOS "C" to 13.3 feet in width at the high end of LOS "C". Now, calculate the corner area needed for LOS "C".

STEP 3 (Corner): Calculate the total circulation volume (ped/cycle).

$v_c(ped) = v_{ci} + v_{co} + v_{do} + v_{di} + v_{ab}$

$v_c(ped) = 36 + 33 + 11 + 16 + 2 = \underline{98}$

STEP 4 (Corner): Calculate the total circulation time. 4 seconds is assumed for C_{av}.

t_c (ped.min.) $= v_c \times C_{av}/60$

$t_c = 98 \times 4/60 = 6.53$ ped.min.

STEP 5 (Corner): Calculate the hold area waiting times, using ped/cycle.

Q_{tco}(ped.min) $= [(v_{co})(R_{mj}/C)(R_{mj}/2)]/60$

$Q_{tco} = [(33)(119/140)(119/2)]/60 = \underline{27.8 \text{ ped.min.}}$

$Q_{tdo} = [(v_{do})(R_{mi}/C)(R_{mi}/2)]/60$

$Q_{tdo} = [(16)(119/140)(119/2)]/60 = \underline{13.5 \text{ ped.min.}}$

STEP 6 (Corner): Calculate the hold area time space.

TS_h (sq.ft.-min.) $= 5\ (Q_{tco} + Q_{tdo})$

$TS_h = 5(27.8 + 13.5) = \underline{206.5 \text{ sq.ft.min.}}$

STEP 7 (Corner): Calculate the gross corner area.

$TS_c = Mt_c$, M at LOS "C" from Table 5.

TS_c = (24 sq.ft./ped.)(6.53 ped.min.) = $\underline{156.7 \text{ sq.ft.min.}}$

$TS = TS_c + TS_h$

$TS = 156.7 + 206.5 = 363.2$ sq. ft.min.

$$A_G = \frac{\underline{60\ TS}}{C} = \underline{\text{GROSS CORNER AREA}}$$

$A_G = \frac{60(363.2 \text{ sq.ft.min.})}{140 \text{ sec.}} = 155.7$ sq. ft.

GROSS CORNER AREA = 155.7 sq. ft.

Using the systems methodology, the crosswalk widths and corner area have been sized to complement the LOS "C" width of the sidewalks. To recap the sidewalks used in this example are operating at LOS "C". LOS "C" was chosen as the LOS to be used in the design of the crosswalks and corner areas. The crosswalk widths at LOS "C" were determined to need widths of 20.5 feet and eight feet, respectively. The existing crosswalks are approximately ten feet in width, so one crosswalk width is adequate, but one is grossly inadequate. The values calculated confirm the general field observations discussed in Section 6.2. The gross corner area was used rather than the net corner area due to misleading results that the HCM formula (31), $A = W_a W_b - 0.215 R^2$, will give. For example, in this case $W_a = W_b = 6$ feet and the radius is about 30 feet. If that formula is used, the result is 36 - 0.215(900) = -157.5 square feet.

This systems methodology provides a balanced pedestrian transportation system at the signalized intersection. This can be accomplished at any of the levels of service from A to F. Further discussion of the potential applications occurs in Chapter 7.

CHAPTER 7

CONCLUSIONS, RECOMMENDATIONS AND GUIDELINES

7.1 CONCLUSIONS

Intermodalism will be the key to solving transportation problems in the future. The walking mode of the pedestrian is one important part of what ISTEA proposes to be an integrated, balanced transportation system. The balancing of the pedestrian transportation system at the urban signalized intersection becomes more significant with core land uses of higher densities, such as central business districts or areas of intense pedestrian activity, such as the "Strip" in the Las Vegas valley area of Clark County, Nevada, and congested overloaded transportation systems.

The three elements (sidewalks, corner area, and crosswalks) must be balanced to improve the level of service, capacity, and safety of the pedestrian system. A review of previous research revealed a disproportionate number of pedestrian accidents at signalized intersections during peak periods within the zone from the stop line to within 150 feet of the stop line. Compliance and understanding of pedestrian signals and messages are low. This suggests that there is a need for the design of balanced pedestrian facilities at urban signalized intersections. A review of walking speeds revealed that elderly pedestrians, a growing segment, walk slower. In addition, pedestrians tend to walk slower under congested conditions, i.e., as pedestrian volume and density increases pedestrian speed declines.

Some past research discussed the concept of quality of service to describe a more qualitative "environmental" assessment of pedestrian facilities. The level of service (LOS) concept and evaluative criteria, as discussed in Chapter 13 of the HCM, is still the mainstay of actual practice throughout the nation. In the HCM there are methodologies to evaluate the performance of sidewalks, corner areas, and crosswalk, but there exists no integrated systems methodology for the planning or evaluation of the three elements to ensure a balanced pedestrian transportation system at a signalized intersection.

An integrated systems methodology has been developed and applied to a case study. The integrated systems approach realizes that the sidewalk and signal phasing are the keys to the balanced system. Generally, the sidewalk provides an uninterrupted pedestrian flow that interfaces with the corner area, where interrupted and uninterrupted conditions exist, and the crosswalk area, where interrupted pedestrian flow conditions exist due to the operation of the traffic signal. The sidewalk element, especially "effective" sidewalk width at an acceptable LOS, probably LOS "C", sets the basic criteria for the system, whereas the signal phasing and timing affects the design of both the corner area and crosswalk width.

In recognition of the importance of the "effective" sidewalk width, and signal phasing and timing, an integrated step-by-step systems methodology was developed. This systems methodology could be used to develop a balanced LOS system based on a chosen LOS, corresponding pedestrian flow rate and effective walkway width (planning procedure) or could be used if actual conditions are known. The assumptions of the pedestrian volumes can be varied depending on engineering or planning judgment. Both, a step-by-step methodology and flow chart were developed. In the case study it was shown that commonly accepted practices, such as ten foot wide crosswalks, did not necessarily provide an adequate LOS or corner area. It was also concluded that the "net corner area" formula was flawed in that it did not take into account the geometric design of a sidewalk around an intersection curb return.

The methodology does recognize the effect of right turning vehicles although further refinement in this area is needed. The HCM methodology assumes a 4.5 feet per second walking speed in the crosswalk, which seems too high based on the findings of various other research efforts cited earlier in Chapter 2.

7.2 RECOMMENDATIONS AND GUIDELINES

The integrated systems methodology provides a tool from which various tables or charts can be generated. As mentioned previously, the sidewalk LOS and the signal phasing and timing directly affect the corner area and crosswalk width needed. Through iterations of various sidewalk widths and signal phasing, charts can be developed that indicate the appropriate corner area and crosswalk width. From a review of past research this type of guideline or decision support tool does not exist.

The current common practice of sizing crosswalks by MUTCD minimums, typically ten feet, and the sizing of the corner areas and sidewalk widths by minimum AASHTO criteria can be replaced by this support tool that provides a design tool for the planning of an integrated, balanced, systems pedestrian traffic system at urban signalized intersections. The charts can be developed in recognition of local practices that, perhaps, accept LOS "C" or "D" for the design of pedestrian facilities. Other local parameters can also be established, so the methodology allows for flexibility.

At heavily traveled intersections, the conflicts of heavy pedestrian volumes and heavy vehicular traffic volumes can quickly overcome the ability of a traffic signal with pedestrian signal indications to efficiently and safely control both flows. Heavy pedestrian traffic can severely limit the level of service and capacity of the vehicular traffic at signalized intersections. This methodology can be used as a decision support tool to guide in the evaluation and decision-making process regarding the consideration of pedestrian grade separations. When restrictions or constraints prevent the development or attainment of LOS "E" with one or more of the three elements by physical limitations for example, i.e., sidewalk, corner area, or crosswalk, then alternatives, such as pedestrian grade separations, should be considered. Obviously, other constraints, especially fiscal factors, reduce the potential application of this option. The use of systems methodology can show that, despite attempts at LOS "E" to balance signal phasing and timing, with the other elements, that LOS "F" conditions exist, then support is provided for other alternatives, such as pedestrian grade separations or a decision to prohibit and prevent pedestrian crossings. The construction of a pedestrian grade separation can provide the obvious improvements by the elimination of vehicle-pedestrian conflicts and significant benefits by the reduction of vehicle delay. An unpublished study (Appendix "D") of the benefits of the construction of the pedestrian grade separation at the intersection of Las Vegas Boulevard South and Tropicana Avenue on the "Strip" revealed a reduction in P.M. peak hour delay of about 41 percent.

Further research is needed to evaluate the relationship between pedestrian accident experience at urban signalized intersections and the LOS of the pedestrian elements, i.e., sidewalk, corner area, and crosswalk. It may be found that there is a definite relationship between significant pedestrian accident experience locations and pedestrian facilities with deficient LOS.

APPENDIX A

WALKWAY ANALYSIS WORKSHEET

Location: ______________________ COUNTS

City, State: ______________________ Date: __________

Time: __________

Curb Line/Sidewalk Edge

PEAK 15-MIN FROM

________ to ________

W_T = ____	W_{B1} (curb) =	ft
	W_{B2} (street furn.) =	ft
	W_E (effective width) =	ft
	W_{B3} (window shop) =	ft
	W_{B4} (bldg protrusions) =	ft
	W_{B5} (inside clearance =	ft

← V_1 = ________

→ V_2 = ________

(ped/15 min)

Wall Line/Sidewalk Edge

Pedestrian Volume

V_1 = ________ ped/15 min

V_2 = ________ ped/15 min

$V_p = V_1 + V_2$ = ________ ped/15 min

Walkway Width

W_T = ________ ft

$W_B = W_{B1} + W_{B2} + W_{B3} + W_{B4} + W_{B5}$ = ________ ft

$W_E = W_T - W_B$ = ________ ft

Average Walkway LOS

$v = V_p/15W_E$ = ________ ped/min/ft

Average LOS = ________ (Table 13-3)

Platoon Walkway LOS

$v_p = v + 4$ = ________ ped/min/ft

Platoon LOS = ________ (Table 13-3)

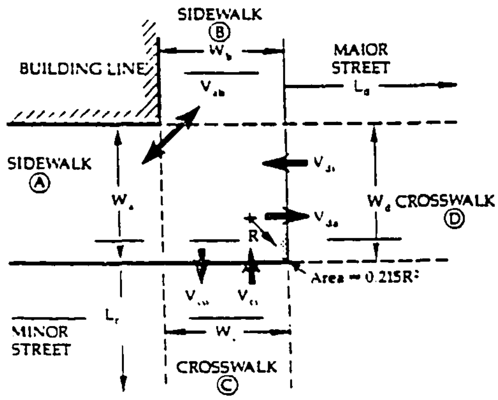
APPENDIX 'A' Source: Highway Capacity Manual: Special Report No. 209 (1994 edition)

APPENDIX B

STREET CORNER ANALYSIS WORKSHEET

Location: ______________________________

City, State: ______________________________



SIGNAL TIMING (sec)

C = ______

G_{mi} = ______ R_{mi} = ______

G_{mi} = ______ R_{mi} = ______

PEDESTRIAN VOLUMES

Flow	Ped/Min	Ped/Cyc
v_{ci}		
v_{co}		
v_{di}		
v_{do}		
$v_{a,b}$		
v_{tot}		

NET CORNER AREA	$A = W_a W_b - 0.215R^2 =$	______ sq ft
AVAILABLE TIME-SPACE	$TS = A \times C/60 =$	______ sq ft-min
HOLD AREA WAITING TIMES (use ped/cycle)	$Q_{tco} = [(v_{co})(R_{mi}/C)(R_{mi}/2)]/60 =$ $Q_{tdo} = [(v_{do})(R_{mi}/C)(R_{mi}/2)]/60 =$	______ ped-min ______ ped-min
HOLD AREA TIME-SPACE	$TS_h = 5(Q_{tco} + Q_{tdo}) =$	______ sq ft-min
CIRCULATION TIME-SPACE	$TS_c = TS - TS_h =$	______ sq ft-min
TOTAL CIRCULATION VOLUME	$v_c = v_{ci} + v_{co} + v_{do} - v_{di} + v_{a,b} =$	______ ped
TOTAL CIRCULATION TIME	$t_c = v_c \times 4/60 =$	______ ped-min
PEDESTRIAN SPACE AND LOS	$M = TS_c/t_c =$ ______ sq ft/ped; LOS = ______ (Table 13-3)	

APPENDIX 'B'

Source: Highway Capacity Manual: Special Report No. 209 (1994 edition)

APPENDIX C

CROSSWALK ANALYSIS WORKSHEET

Location: ____________________

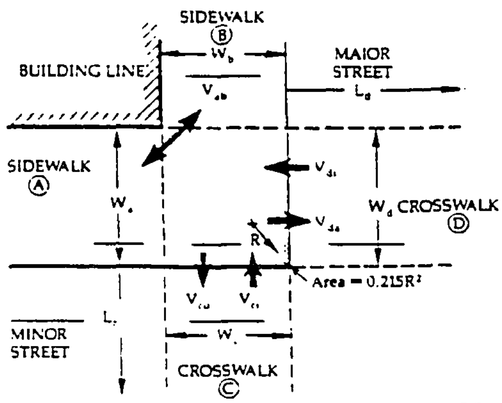
City, State: ____________________

SIGNAL TIMING (sec)

C = ______

G_{mi} = ______ R_{mi} = ______

G_{mi} = ______ R_{mi} = ______



PEDESTRIAN VOLUMES

Flow	Ped/Min	Ped/Cyc
v_{ci}		
v_{co}		
v_{di}		
v_{do}		
$v_{a,b}$		
v_{tot}		

CROSSWALK AREAS

$A_c = L_c W_c =$ ______ sq ft

$A_d = L_d W_d =$ ______ sq ft

CROSSWALK TIME-SPACE

$TS_c = A_c (G_{mi} - 3)/60 =$ ______ sq ft-min

$TS_d = A_d (G_{mi} - 3)/60 =$ ______ sq ft-min

CROSSING TIMES

$t_{wc} = L_c/4.5 =$ ______ sec

$t_{wd} = L_d/4.5 =$ ______ sec

CROSSWALK OCCUPANCY TIME
(use ped/cycle)

$T_{wc} = (v_{ci} + v_{co})(t_{wc}/60) =$ ______ ped-min

$T_{wd} = (v_{di} + v_{do})(t_{wd}/60) =$ ______ ped-min

AVERAGE PEDESTRIAN SPACE AND LOS

$M_c = TS_c/T_{wc} =$ ______ sq ft/ped: LOS = ______ (Table 13-3)

$M_d = TS_d/T_{wd} =$ ______ sq ft/ped: LOS = ______ (Table 13-3)

MAXIMUM SURGE
(use ped/min)

$V_{mc} = (v_{ci} + v_{co})(R_{mi} + 3 + t_{wc})/60 =$ ______ ped

$V_{md} = (v_{di} + v_{do})(R_{mi} + 3 + t_{wd})/60 =$ ______ ped

SURGE PEDESTRIAN SPACE AND SURGE LOS

$M_c(Max) = A_c/V_{mc} =$ ______ sq ft/ped: LOS = ______ (Table 13-3)

$M_d(Max) = A_d/V_{md} =$ ______ sq ft/ped: LOS = ______ (Table 13-3)

APPENDIX 'C' Source: Highway Capacity Manual: Special Report No. 209 (1994 edition)

APPENDIX D

A VEHICULAR DELAY ANALYSIS
FOR THE INTERSECTION OF
LAS VEGAS BOULEVARD SOUTH AND TROPICANA AVENUE

APPENDIX 'D'

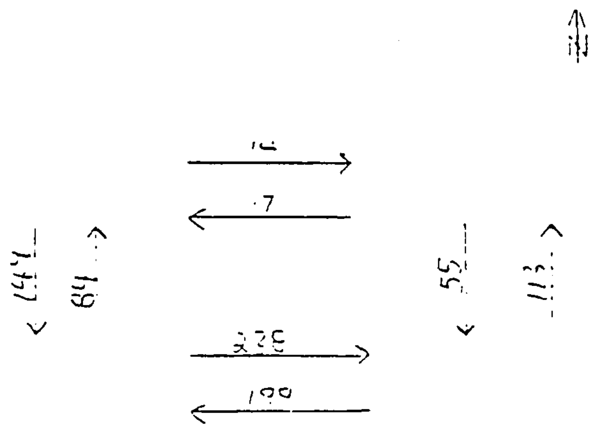
I. DETERMINATION OF HIGHEST PEAK HOUR INTERSECTION VOLUME

1.	Weekday A.M.	=	8051	(See Exhibit A1)
2.	Weekday P.M.	=	8457	*(See Exhibit A2)
3.	Weekend A.M.	=	7575	(See Exhibit A3)
4.	Weekend P.M.	=	8277	(See Exhibit A4)

*Highest peak. occurs 4:00 p.m. to 5:00 p.m.

II. ESTIMATION OF PEDESTRIAN VOLUMES

The following volumes are from MGM traffic study and were counted Wednesday, April 17, 1991. At that time, neither the Luxor nor the MGM were open for business.



The MGM has 5005 rooms.

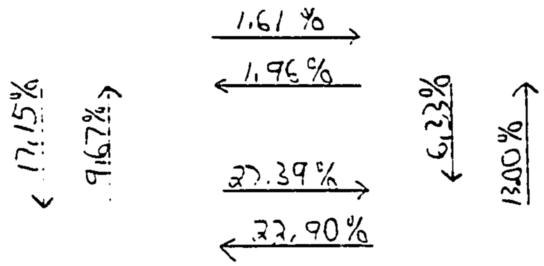
The Luxor has 2450 rooms.

The total room count near the intersection is therefore 7455 higher than when the 4/91 counts were conducted.

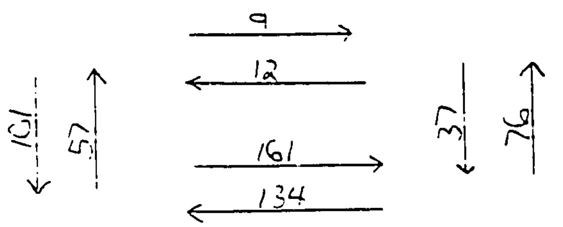
According to the Luxor's traffic study, the peak hour pedestrian generation rate is 0.07875 pedestrians/hotel room.

The new peak hour pedestrian volume generated by the MGM and Luxor is: (0.07875)(7455) = 587

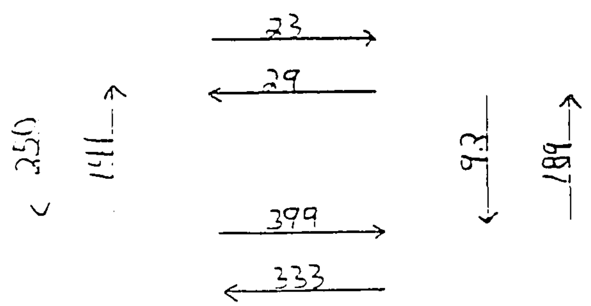
Assume that trip distribution for these pedestrians will follow the pattern as observed in the April 1991 counts. The trip distribution percentages therefore are as follows:



The trip assignment diagram for these pedestrians is as follows:



The total peak hour pedestrian volumes at this intersection, reflecting the MGM and Luxor, are as follows:



III. SCENARIO 1 - PEDESTRIANS ARE ASSUMED TO CROSS INTERSECTION AT-GRADE

A. Assumptions

1. Due to high pedestrian volumes and number of jaywalkers, only westbound vehicles can execute a right turn on red.

2. Capacity software is capable of recognizing only six lanes in each direction. Therefore, on east and west legs, three through lanes were assumed. Volumes utilized for LOS calculations are on a per lane basis for the eastbound and westbound through movements.

   On the north and south legs, three through lanes and two left turn lanes were assumed. Volumes utilized for LOS calculations are on a per lane basis for both the northbound and southbound through and left turn movements. See Exhibit B for volumes used in LOS calculations.

3. Total delay calculations were based on total observed vehicular volumes.

B. SUMMARY OF P.M. PEAK HOUR DELAY

APPROACH	DELAY/VEH. (SEC)	TOTAL VEH.	TOTAL DELAY (HR)
East	102.1	2469	70.02
North	57.0	1472	23.31
West	97.9	1896	51.56
South	47.1	2620	34.28
Total Delay - 179.17 Hr.			

See Exhibit C for LOS calculations.

IV. SCENARIO 2 - PEDESTRIAN CROSS OVER THE INTERSECTION ON STRUCTURES

A. Assumptions

1. Due to elimination of pedestrians at-grade, 25% of all right turn movements on the north, west and south legs can be made on red. On the east leg, 35% of all right turn movements can be made on red.

2. See Items A2 and A3 from Scenario 1.

B. Summary of P.M. Peak Hour Delay

APPROACH	DELAY/VEH. (SEC)	TOTAL VEH.	TOTAL DELAY (HR)
East	49.6	2469	34.02
North	38.8	1472	15.86
West	49.4	1896	26.02
South	41.3	2620	30.06
Total Delay = 105.96			

See Exhibit D for LOS calculations.

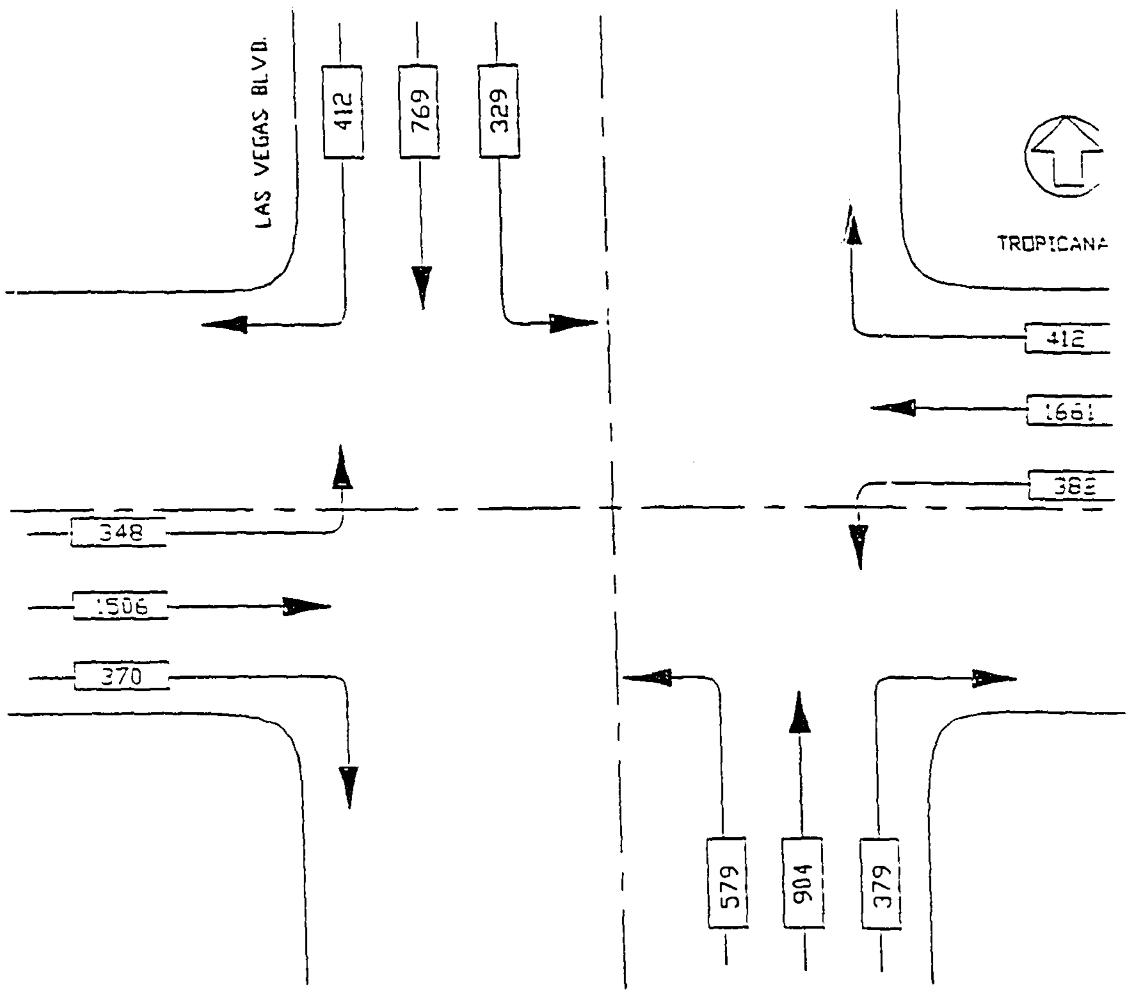
V. COMPARISON OF SCENARIOS

A. P.M. peak hour delay for the intersection is reduced by 73.21 hours by employing the pedestrian grade separation.

B. P.M. peak hour delay percent reduction due to pedestrian bridges:

$$\frac{(179.17 - 105.96)}{179.17} 100 = 40.9\%$$

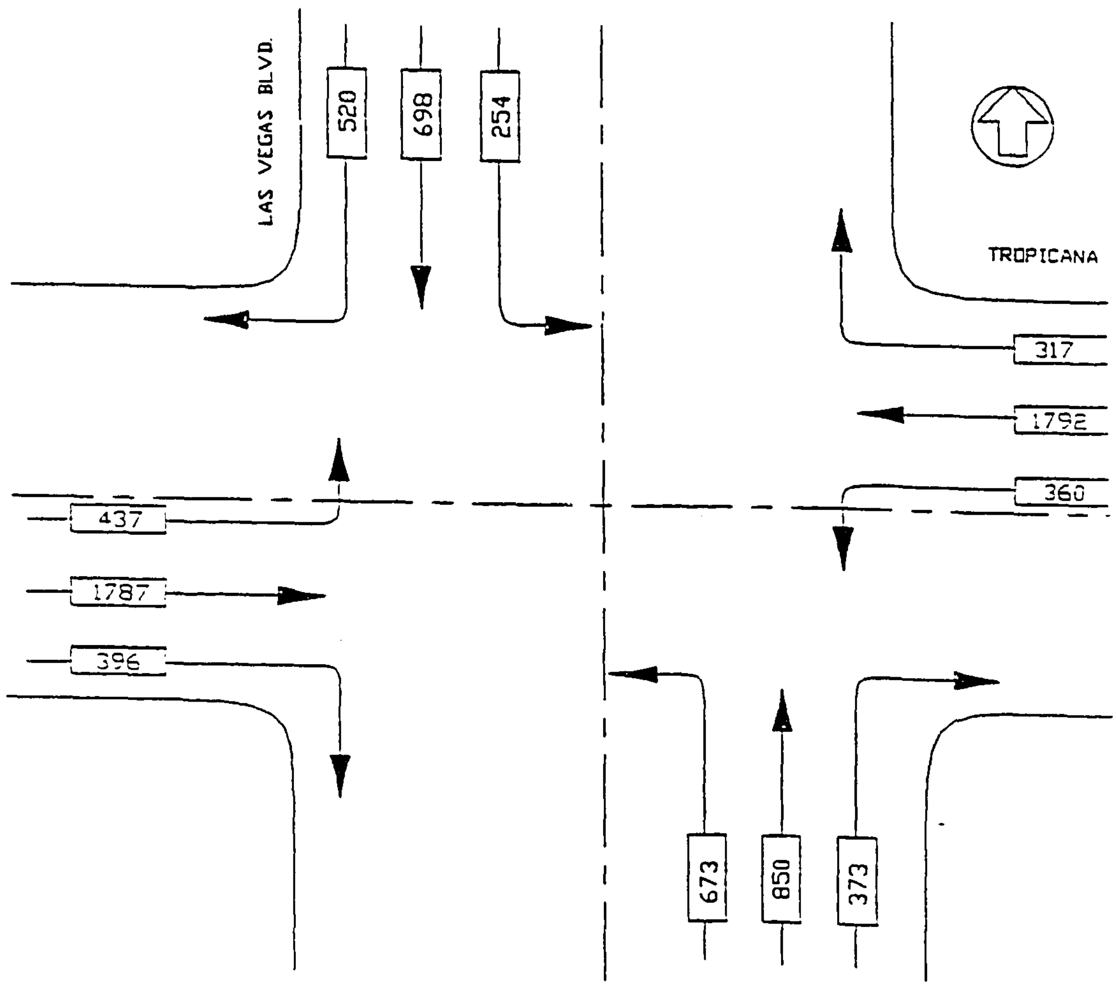
WEEK DAY AM PEAK HOUR COUNTS



LAS VEGAS BLVD & TROPICANA AVE.
DATE OF COUNT: FRIDAY JULY 22, 1994
PEAK HOUR: 11:00 am to 12:00 pm

EXHIBIT A1

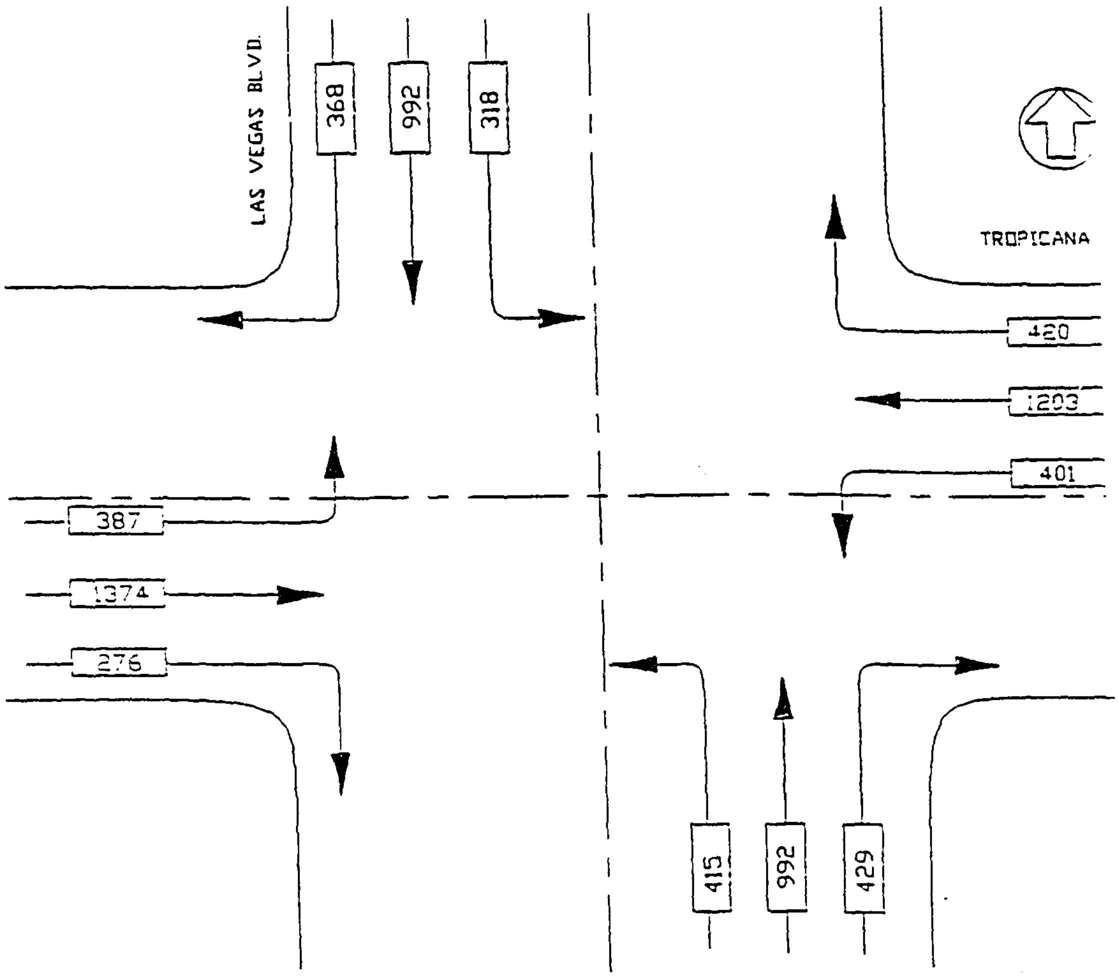
WEEK DAY PM PEAK HOUR COUNTS



LAS VEGAS BLVD & TROPICANA AVE.
DATE OF COUNT: FRIDAY JULY 22, 1994
PEAK HOUR: 4:00 pm to 5:00 pm

EXHIBIT A2

WEEKEND AM PEAK HOUR COUNTS



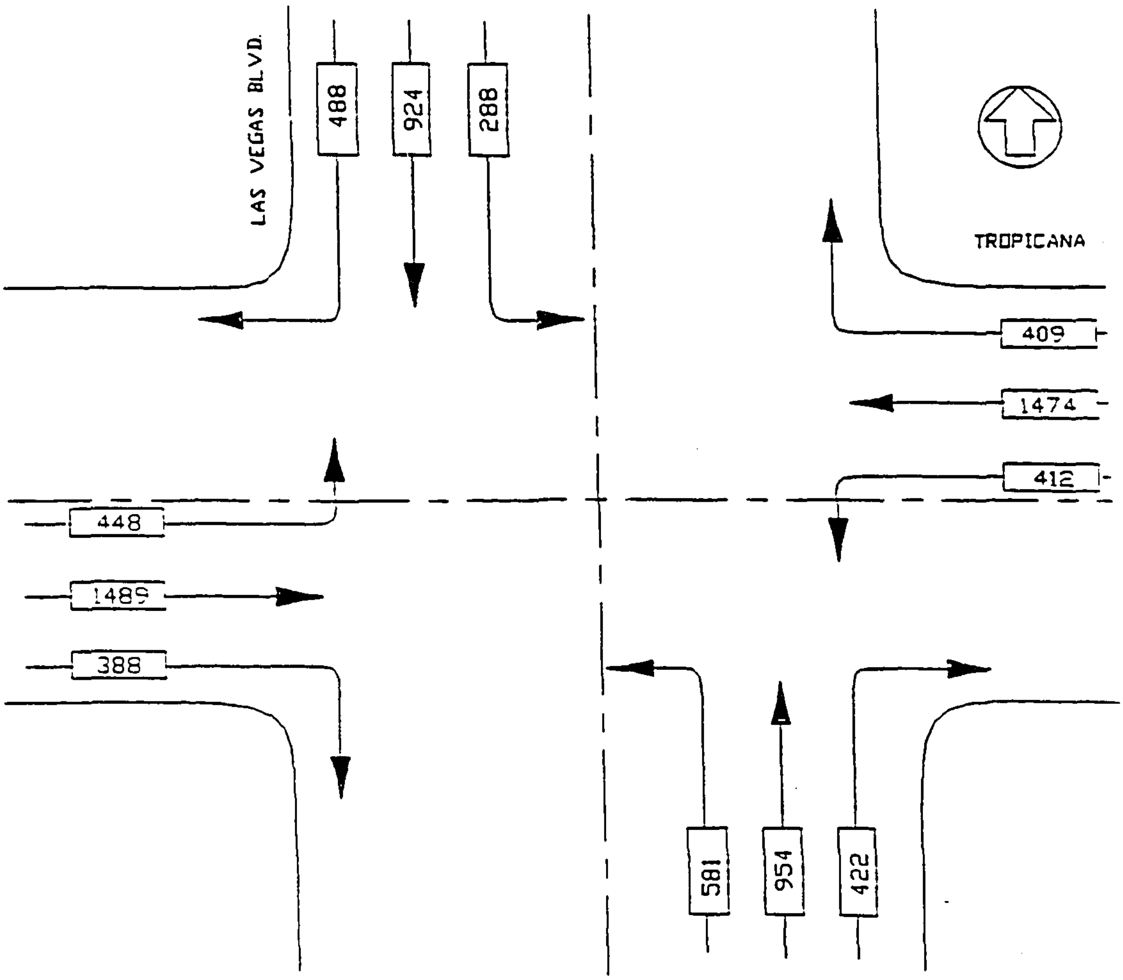
LAS VEGAS BLVD & TROPICANA AVE.

DATE OF COUNT: SATURDAY JULY 23, 1994
SUNDAY JULY 24, 1994

PEAK HOUR: 11:00 pm to 12:00 pm

EXHIBIT A3

WEEKEND PM PEAK HOUR COUNTS



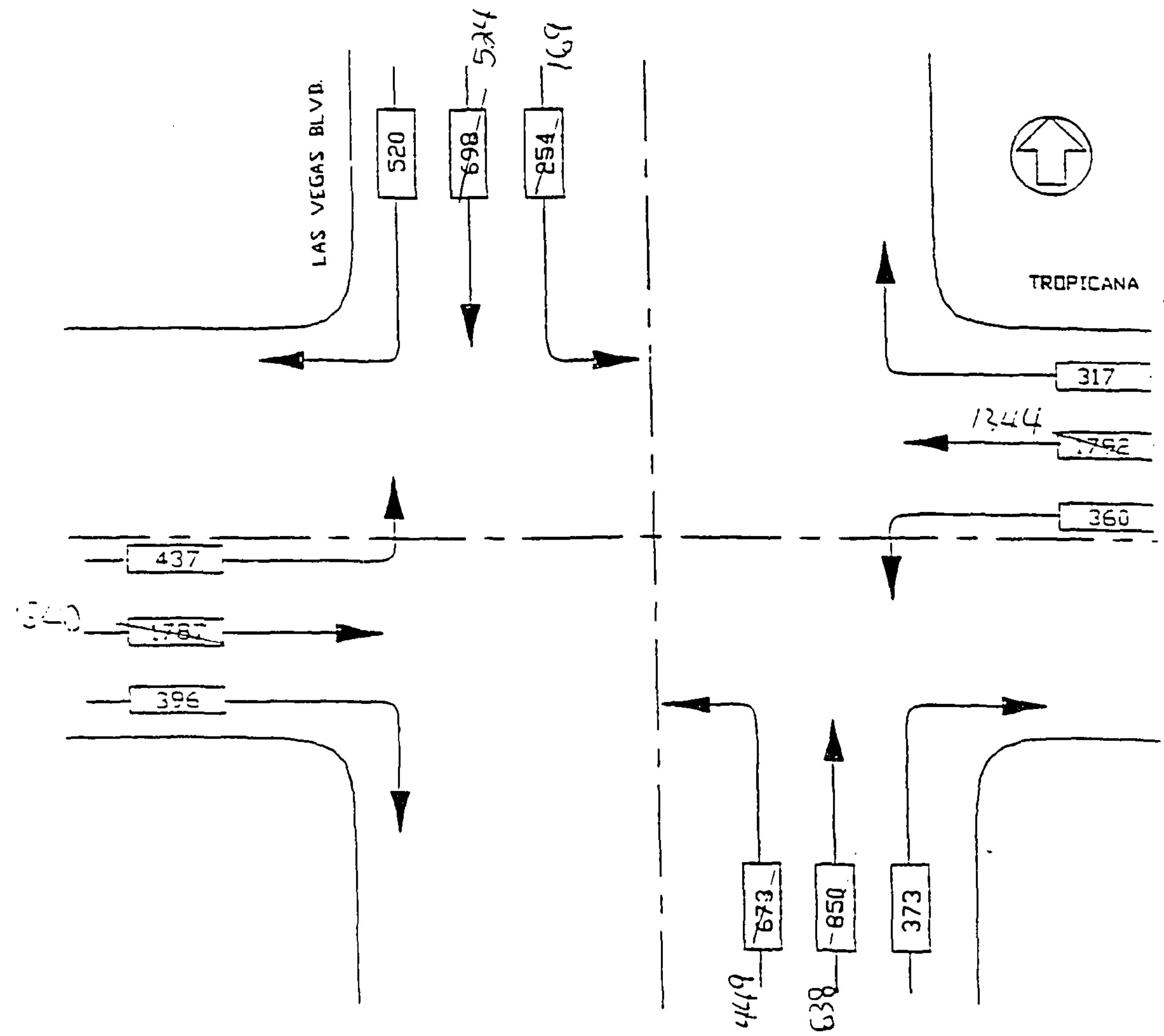
LAS VEGAS BLVD & TROPICANA AVE.

DATE OF COUNT: SATURDAY JULY 23, 1994
SUNDAY JULY 24, 1994

PEAK HOUR: 3:00 pm to 4:00 pm

EXHIBIT A4

WEEK DAY PM PEAK HOUR COUNTS



LAS VEGAS BLVD & TROPICANA AVE.

DATE OF COUNT: FRIDAY JULY 22, 1994

PEAK HOUR: 4:00 pm to 5:00 pm

EXHIBIT B

1985 HCM: SIGNALIZED INTERSECTIONS
SUMMARY REPORT

INTERSECTION..Tropicana Ave./Las Vegas Boulevard S.
AREA TYPE.....OTHER
ANALYST.......jt
DATE..........09-06-1994
TIME..........p.m. peak
COMMENT.......Scenario 1 (PEDS AT GRADE)

	VOLUMES EB	WB	NB	SB	:	GEOMETRY EB		WB		NB		SB	
LT	437	360	449	169	:	L	12.0	L	12.0	L	12.0	L	12.0
TH	1340	1344	638	524	:	L	12.0	L	12.0	L	12.0	L	12.0
RT	396	317	373	520	:	T	12.0	T	12.0	T	12.0	T	12.0
RR	0	32	0	0	:	T	12.0	T	12.0	T	12.0	T	12.0
					:	T	12.0	T	12.0	T	12.0	T	12.0
					:	R	12.0	R	12.0	R	12.0	R	12.0

ADJUSTMENT FACTORS

	GRADE (%)	HV (%)	ADJ PKG Y/N	Nm	BUSES Nb	PHF	PEDS	PED. BUT. Y/N	min T	ARR. TYPE
EB	0.00	2.00	N	0	1	0.90	422	Y	38.5	3
WB	0.00	2.00	N	0	1	0.90	362	Y	38.5	3
NB	0.00	2.00	N	0	5	0.90	330	Y	38.5	3
SB	0.00	2.00	N	0	5	0.90	342	Y	38.5	3

SIGNAL SETTINGS CYCLE LENGTH = 160.0

		PH-1	PH-2	PH-3	PH-4			PH-1	PH-2	PH-3	PH-4
EB	LT	X				NB	LT	X			
	TH		X				TH		X		
	RT		X				RT		X		
	PD		X				PD	X			
WB	LT	X				SB	LT	X			
	TH		X				TH		X		
	RT		X				RT		X		
	PD		X				PD	X			
GREEN		35.0	46.0	0.0	0.0	GREEN		31.0	28.0	0.0	0.0
YELLOW		5.0	5.0	0.0	0.0	YELLOW		5.0	5.0	0.0	0.0

LEVEL OF SERVICE

	LANE GRP.	V/C	G/C	DELAY	LOS	APP. DELAY	APP. LOS
EB	L	0.786	0.237	47.9	E	*	*
	T	1.200	0.306	*	*		
	R	0.384	0.519	32.2	D		
WB	L	0.647	0.237	43.4	E	*	*
	T	1.204	0.306	*	*		
	R	0.593	0.519	18.4	C		
NB	L	0.902	0.213	59.0	E	47.1	E
	T	0.903	0.194	48.5	E		
	R	0.777	0.431	29.3	D		
SB	L	0.340	0.213	40.8	E	57.0	E
	T	0.742	0.194	41.3	E		
	R	1.083	0.431	79.9	F		

INTERSECTION: Delay = * (sec/veh) V/C = 1.372 LOS = *

EXHIBIT C

INTERSECTION GEOMETRY Page-2

NUMBER OF LANES PER DIRECTION INCLUDING TURN BAYS:
EASTBOUND = 6 WESTBOUND = 6 NORTHBOUND = 6 SOUTHBOUND = 6

	EB		WB		NB		SB	
LANE	TYPE	WIDTH	TYPE	WIDTH	TYPE	WIDTH	TYPE	WIDTH
1	L	12.0	L	12.0	L	12.0	L	12.0
2	L	12.0	L	12.0	L	12.0	L	12.0
3	T	12.0	T	12.0	T	12.0	T	12.0
4	T	12.0	T	12.0	T	12.0	T	12.0
5	T	12.0	T	12.0	T	12.0	T	12.0
6	R	12.0	R	12.0	R	12.0	R	12.0

L - EXCLUSIVE LEFT LANE
LT - LEFT/THROUGH LANE
LR - LEFT/RIGHT ONLY LANE
LTR - LEFT/THROUGH/RIGHT LANE
T - EXCLUSIVE THROUGH LANE
TR - THROUGH/RIGHT LANE
R - EXCLUSIVE RIGHT LANE

ADJUSTMENT FACTORS

	GRADE (%)	HEAVY VEH. (%)	ADJACENT PKG Y/N	(Nm)	BUSES (Nb)	PHF
EASTBOUND	0.00	2.00	N	0	1	0.90
WESTBOUND	0.00	2.00	N	0	1	0.90
NORTHBOUND	0.00	2.00	N	0	5	0.90
SOUTHBOUND	0.00	2.00	N	0	5	0.90

Nm = number of parking maneuvers/hr; Nb = number of buses stopping/hr

	CONFLICTING PEDS (peds/hour)	PEDESTRIAN BUTTON (Y/N)	(min T)	ARRIVAL TYPE
EASTBOUND	422	Y	38.5	3
WESTBOUND	362	Y	38.5	3
NORTHBOUND	330	Y	38.5	3
SOUTHBOUND	342	Y	38.5	3

min T = minimum green time for pedestrians

IDENTIFYING INFORMATION

NAME OF THE EAST/WEST STREET..... Tropicana Ave.
NAME OF THE NORTH/SOUTH STREET... Las Vegas Boulevard S.
DATE AND TIME OF THE ANALYSIS.... 09-06-1994 ; p.m. peak
OTHER INFORMATION:
Scenario 1

SIGNAL SETTINGS - OPERATIONAL ANALYSIS

ACTUATED   LOST TIME/PHASE = 2.0   CYCLE LENGTH = 160.0

EAST/WEST PHASING

	PHASE-1	PHASE-2	PHASE-3	PHASE-4
EASTBOUND				
LEFT	X			
THRU		X		
RIGHT		X		
PEDS		X		
WESTBOUND				
LEFT	X			
THRU		X		
RIGHT		X		
PEDS		X		
NORTHBOUND RT	X			
SOUTHBOUND RT	X			
GREEN	35.0	46.0	0.0	0.0
YELLOW + ALL RED	5.0	5.0	0.0	0.0

NORTH/SOUTH PHASING

	PHASE-1	PHASE-2	PHASE-3	PHASE-4
NORTHBOUND				
LEFT	X			
THRU		X		
RIGHT		X		
PEDS	X			
SOUTHBOUND				
LEFT	X			
THRU		X		
RIGHT		X		
PEDS	X			
EASTBOUND RT	X			
WESTBOUND RT	X			
GREEN	31.0	28.0	0.0	0.0
YELLOW + ALL RED	5.0	5.0	0.0	0.0

IDENTIFYING INFORMATION

NAME OF THE EAST/WEST STREET..... Tropicana Ave.
NAME OF THE NORTH/SOUTH STREET... Las Vegas Boulevard S.
DATE AND TIME OF THE ANALYSIS.... 09-06-1994 ; p.m. peak
OTHER INFORMATION:
Scenario 1

VOLUME ADJUSTMENT WORKSHEET Page-4

		MVT. VOL.	PHF	ADJ. VOL.	LANE GRP.	LANE GRP. VOL.	NO. LN	LANE UTIL. FACT.	GROWTH FACT.	ADJ. GRP. VOL.	PROP LT	PROP RT
EB												
	LT	437	0.90	486	L	486	2	1.050	1.000	510	1.00	0.00
	TH	1340	0.90	1489	T	1489	3	1.100	1.000	1638	0.00	0.00
	RT	396	0.90	440	R	440	1	1.000	1.000	440	0.00	1.00
WB												
	LT	360	0.90	400	L	400	2	1.050	1.000	420	1.00	0.00
	TH	1344	0.90	1493	T	1493	3	1.100	1.000	1643	0.00	0.00
	RT	317	0.90	316	R	316	1	1.000	1.000	316	0.00	1.00
NB												
	LT	449	0.90	499	L	499	2	1.050	1.000	524	1.00	0.00
	TH	638	0.90	709	T	709	3	1.100	1.000	780	0.00	0.00
	RT	373	0.90	414	R	414	1	1.000	1.000	414	0.00	1.00
SB												
	LT	169	0.90	188	L	188	2	1.050	1.000	197	1.00	0.00
	TH	524	0.90	582	T	582	3	1.100	1.000	640	0.00	0.00
	RT	520	0.90	578	R	578	1	1.000	1.000	578	0.00	1.00

* Denotes a Defacto Left Turn Lane Group

IDENTIFYING INFORMATION

NAME OF THE EAST/WEST STREET..... Tropicana Ave.
NAME OF THE NORTH/SOUTH STREET... Las Vegas Boulevard S.
DATE AND TIME OF THE ANALYSIS.... 09-06-1994 ; p.m. peak
OTHER INFORMATION:
Scenario 1

SATURATION FLOW ADJUSTMENT WORKSHEET

	IDEAL SAT. FLOW	NO. LNS	f W	f HV	f G	f p	f BB	f A	f RT	f LT	ADJ. SAT. FLOW
EB											
L	1500	2	1.000	0.990	1.000	1.000	1.000	1.000	1.000	0.920	2732
T	1500	3	1.000	0.990	1.000	1.000	1.000	1.000	1.000	1.000	4455
R	1500	1	1.000	0.990	1.000	1.000	0.996	1.000	0.649	1.000	960
WB											
L	1500	2	1.000	0.990	1.000	1.000	1.000	1.000	1.000	0.920	2732
T	1500	3	1.000	0.990	1.000	1.000	1.000	1.000	1.000	1.000	4455
R	1500	1	1.000	0.990	1.000	1.000	0.996	1.000	0.695	1.000	1028
NB											
L	1500	2	1.000	0.990	1.000	1.000	1.000	1.000	1.000	0.920	2732
T	1500	3	1.000	0.990	1.000	1.000	1.000	1.000	1.000	1.000	4455
R	1500	1	1.000	0.990	1.000	1.000	0.980	1.000	0.850	1.000	1237
SB											
L	1500	2	1.000	0.990	1.000	1.000	1.000	1.000	1.000	0.920	2732
T	1500	3	1.000	0.990	1.000	1.000	1.000	1.000	1.000	1.000	4455
R	1500	1	1.000	0.990	1.000	1.000	0.980	1.000	0.850	1.000	1237

IDENTIFYING INFORMATION

NAME OF THE EAST/WEST STREET..... Tropicana Ave.
NAME OF THE NORTH/SOUTH STREET... Las Vegas Boulevard S.
DATE AND TIME OF THE ANALYSIS.... 09-06-1994 ; p.m. peak
OTHER INFORMATION:
Scenario 1

CAPACITY ANALYSIS WORKSHEET Page-6

	ADJ. FLOW RATE (v)	ADJ. SAT. FLOW RATE (s)	FLOW RATIO (v/s)	GREEN RATIO (g/C)	LANE GROUP CAPACITY (c)	v/c RATIO	
EB							
L	510	2732	0.187	0.237	649	0.786	*
T	1638	4455	0.368	0.306	1364	1.200	
R	440	960	0.458	0.519	498	0.884	*
WB							
L	420	2732	0.154	0.237	649	0.647	
T	1643	4455	0.369	0.306	1364	1.204	
R	316	1028	0.308	0.519	533	0.593	
NB							
L	524	2732	0.192	0.213	581	0.902	*
T	780	4455	0.175	0.194	863	0.903	
R	414	1237	0.335	0.431	533	0.777	
SB							
L	197	2732	0.072	0.213	581	0.340	
T	640	4455	0.144	0.194	863	0.742	
R	578	1237	0.467	0.431	533	1.083	*

Cycle Length, C = 160.0 sec. Sum (v/s) critical = 1.304
Lost Time Per Cycle, L = 8.0 sec. X critical = 1.372

IDENTIFYING INFORMATION

NAME OF THE EAST/WEST STREET..... Tropicana Ave.
NAME OF THE NORTH/SOUTH STREET... Las Vegas Boulevard S.
DATE AND TIME OF THE ANALYSIS.... 09-06-1994 ; p.m. peak
OTHER INFORMATION:
Scenario 1

LEVEL-OF-SERVICE WORKSHEET Page-7

	v/c RATIO	g/C RATIO	CYCLE LEN.	DELAY d 1	LANE GROUP CAP.	DELAY d 2	PROG. FACT.	LANE GRP. DELAY	LANE GRP. LOS	DELAY BY APP.	LOS BY APP.
EB											
L	0.786	0.237	160.0	43.5	649	4.4	1.00	47.9	E	*	*
T	1.200	0.306	160.0	*	1364	*	0.85	*	*	(47.9)	
R	0.884	0.519	160.0	26.0	498	11.9	0.85	32.2	D		
WB											
L	0.647	0.237	160.0	41.8	649	1.6	1.00	43.4	E	*	*
T	1.204	0.306	160.0	*	1364	*	0.85	*	*	(102.1)	
R	0.593	0.519	160.0	20.3	533	1.3	0.85	18.4	C		
NB											
L	0.902	0.213	160.0	46.6	581	12.4	1.00	59.0	E	47.1	E
T	0.903	0.194	160.0	47.9	863	9.2	0.85	48.5	E		
R	0.777	0.431	160.0	29.6	533	4.9	0.85	29.3	D		
SB											
L	0.340	0.213	160.0	40.6	581	0.1	1.00	40.8	E	57.0	E
T	0.742	0.194	160.0	46.2	863	2.4	0.85	41.3	E		
R	1.083	0.431	160.0	36.9	533	57.1	0.85	79.9	F		

Intersection Delay = * (sec/veh)   Intersection LOS = *

* Delay and LOS not meaningful when any v/c is greater than 1.2

IDENTIFYING INFORMATION

NAME OF THE EAST/WEST STREET..... Tropicana Ave.
NAME OF THE NORTH/SOUTH STREET... Las Vegas Boulevard S.
DATE AND TIME OF THE ANALYSIS.... 09-06-1994 ; p.m. peak
OTHER INFORMATION:
Scenario 1

1985 HCM: SIGNALIZED INTERSECTIONS
SUMMARY REPORT

INTERSECTION..Tropicana Ave./Las Vegas Boulevard S.
AREA TYPE.....OTHER
ANALYST.......jt
DATE..........09-06-1994
TIME..........p.m. peak
COMMENT.......Scenario 2 [illegible]

	VOLUMES EB	WB	NB	SB	:	GEOMETRY EB		WB		NB		SB	
LT	437	360	449	169	:	L	12.0	L	12.0	L	12.0	L	12.0
TH	1349	1344	638	524	:	L	12.0	L	12.0	L	12.0	L	12.0
RT	396	317	373	520	:	T	12.0	T	12.0	T	12.0	T	12.0
RR	99	111	93	130	:	T	12.0	T	12.0	T	12.0	T	12.0
					:	T	12.0	T	12.0	T	12.0	T	12.0
					:	R	12.0	R	12.0	R	12.0	R	12.0

ADJUSTMENT FACTORS

	GRADE (%)	HV (%)	ADJ Y/N	PKG Nm	BUSES Nb	PHF	PEDS	PED. Y/N	BUT. min T	ARR. TYPE
EB	0.00	2.00	Y	20	1	0.90	0	N	0.0	3
WB	0.00	2.00	Y	20	1	0.90	0	N	0.0	3
NB	0.00	2.00	Y	20	5	0.90	0	N	0.0	3
SB	0.00	2.00	Y	20	5	0.90	0	N	0.0	3

SIGNAL SETTINGS CYCLE LENGTH = 160.0

		PH-1	PH-2	PH-3	PH-4			PH-1	PH-2	PH-3	PH-4
EB	LT	X				NB	LT	X			
	TH		X				TH		X		
	RT		X				RT		X		
	PD						PD				
WB	LT	X				SB	LT	X			
	TH		X				TH		X		
	RT		X				RT		X		
	PD						PD				
GREEN		35.0	46.0	0.0	0.0	GREEN		31.0	28.0	0.0	0.0
YELLOW		5.0	5.0	0.0	0.0	YELLOW		5.0	5.0	0.0	0.0

LEVEL OF SERVICE

	LANE GRP.	V/C	G/C	DELAY	LOS	APP. DELAY	APP. LOS
EB	L	0.672	0.231	44.2	E	49.4	E
	T	1.028	0.300	57.3	E		
	R	0.540	0.506	18.0	C		
WB	L	0.554	0.231	41.9	E	49.6	E
	T	1.024	0.300	56.3	E		
	R	0.375	0.506	15.7	C		
NB	L	0.775	0.206	49.5	E	41.3	E
	T	0.778	0.188	42.3	E		
	R	0.626	0.419	25.2	D		
SB	L	0.292	0.206	40.8	E	38.8	D
	T	0.639	0.188	39.6	D		
	R	0.872	0.419	36.8	D		

INTERSECTION: Delay = 46.0 (sec/veh) V/C = 1.069 LOS = E

EXHIBIT D

IDENTIFYING INFORMATION

NAME OF THE EAST/WEST STREET........ Tropicana Ave.

NAME OF THE NORTH/SOUTH STREET...... Las Vegas Boulevard S.

AREA TYPE........................... OTHER

NAME OF THE ANALYST................. jt

DATE OF THE ANALYSIS................ 09-06-1994

TIME PERIOD ANALYZED................ p.m. peak

OTHER INFORMATION:
Scenario 2

TRAFFIC VOLUMES

	EB	WB	NB	SB
LEFT	437	360	449	169
THRU	1349	1344	638	524
RIGHT	396	317	373	520
RTOR	99	111	93	130

(RTOR volume must be less than or equal to RIGHT turn volumes.)

INTERSECTION GEOMETRY Page-2

NUMBER OF LANES PER DIRECTION INCLUDING TURN BAYS:
EASTBOUND = 6 WESTBOUND = 6 NORTHBOUND = 6 SOUTHBOUND = 6

	EB		WB		NB		SB	
LANE	TYPE	WIDTH	TYPE	WIDTH	TYPE	WIDTH	TYPE	WIDTH
1	L	12.0	L	12.0	L	12.0	L	12.0
2	L	12.0	L	12.0	L	12.0	L	12.0
3	T	12.0	T	12.0	T	12.0	T	12.0
4	T	12.0	T	12.0	T	12.0	T	12.0
5	T	12.0	T	12.0	T	12.0	T	12.0
6	R	12.0	R	12.0	R	12.0	R	12.0

L - EXCLUSIVE LEFT LANE
LT - LEFT/THROUGH LANE
LR - LEFT/RIGHT ONLY LANE
LTR - LEFT/THROUGH/RIGHT LANE
T - EXCLUSIVE THROUGH LANE
TR - THROUGH/RIGHT LANE
R - EXCLUSIVE RIGHT LANE

ADJUSTMENT FACTORS

	GRADE (%)	HEAVY VEH. (%)	ADJACENT Y/N	PKG (Nm)	BUSES (Nb)	PHF
EASTBOUND	0.00	2.00	Y	20	1	0.90
WESTBOUND	0.00	2.00	Y	20	1	0.90
NORTHBOUND	0.00	2.00	Y	20	5	0.90
SOUTHBOUND	0.00	2.00	Y	20	5	0.90

Nm = number of parking maneuvers/hr; Nb = number of buses stopping/hr.

	CONFLICTING PEDS (peds/hour)	PEDESTRIAN BUTTON (Y/N)	(min T)	ARRIVAL TYPE
EASTBOUND	0	N	0.0	3
WESTBOUND	0	N	0.0	3
NORTHBOUND	0	N	0.0	3
SOUTHBOUND	0	N	0.0	3

min T = minimum green time for pedestrians

IDENTIFYING INFORMATION

NAME OF THE EAST/WEST STREET..... Tropicana Ave.
NAME OF THE NORTH/SOUTH STREET... Las Vegas Boulevard S.
DATE AND TIME OF THE ANALYSIS.... 09-06-1994 ; p.m. peak
OTHER INFORMATION:
Scenario 1

SIGNAL SETTINGS - OPERATIONAL ANALYSIS Page-3

ACTUATED LOST TIME/PHASE = 3.0 CYCLE LENGTH = 160.0

EAST/WEST PHASING

	PHASE-1	PHASE-2	PHASE-3	PHASE-4
EASTBOUND				
LEFT	X			
THRU		X		
RIGHT		X		
PEDS				
WESTBOUND				
LEFT	X			
THRU		X		
RIGHT		X		
PEDS				
NORTHBOUND RT	X			
SOUTHBOUND RT	X			
GREEN	35.0	46.0	0.0	0.0
YELLOW + ALL RED	5.0	5.0	0.0	0.0

NORTH/SOUTH PHASING

	PHASE-1	PHASE-2	PHASE-3	PHASE-4
NORTHBOUND				
LEFT	X			
THRU		X		
RIGHT		X		
PEDS				
SOUTHBOUND				
LEFT	X			
THRU		X		
RIGHT		X		
PEDS				
EASTBOUND RT	X			
WESTBOUND RT	X			
GREEN	31.0	28.0	0.0	0.0
YELLOW + ALL RED	5.0	5.0	0.0	0.0

IDENTIFYING INFORMATION

NAME OF THE EAST/WEST STREET..... Tropicana Ave.
NAME OF THE NORTH/SOUTH STREET... Las Vegas Boulevard S.
DATE AND TIME OF THE ANALYSIS.... 09-06-1994 ; p.m. peak
OTHER INFORMATION:
Scenario 2

VOLUME ADJUSTMENT WORKSHEET Page-4

		MVT. VOL.	PHF	ADJ. VOL.	LANE GRP.	LANE GRP. VOL.	NO. LN	LANE UTIL. FACT.	GROWTH FACT.	ADJ. GRP. VOL.	PROP LT	PROP RT
EB												
	LT	437	0.90	486	L	486	2	1.050	1.000	510	1.00	0.00
	TH	1349	0.90	1499	T	1499	3	1.100	1.000	1649	0.00	0.00
	RT	396	0.90	330	R	330	1	1.000	1.000	330	0.00	1.00
WB												
	LT	360	0.90	400	L	400	2	1.050	1.000	420	1.00	0.00
	TH	1344	0.90	1493	T	1493	3	1.100	1.000	1643	0.00	0.00
	RT	317	0.90	229	R	229	1	1.000	1.000	229	0.00	1.00
NB												
	LT	449	0.90	499	L	499	2	1.050	1.000	524	1.00	0.00
	TH	638	0.90	709	T	709	3	1.100	1.000	780	0.00	0.00
	RT	373	0.90	311	R	311	1	1.000	1.000	311	0.00	1.00
SB												
	LT	169	0.90	188	L	188	2	1.050	1.000	197	1.00	0.00
	TH	524	0.90	582	T	582	3	1.100	1.000	640	0.00	0.00
	RT	520	0.90	434	R	434	1	1.000	1.000	434	0.00	1.00

* Denotes a Defacto Left Turn Lane Group

IDENTIFYING INFORMATION

NAME OF THE EAST/WEST STREET..... Tropicana Ave.
NAME OF THE NORTH/SOUTH STREET... Las Vegas Boulevard S.
DATE AND TIME OF THE ANALYSIS.... 09-06-1994 ; p.m. peak
OTHER INFORMATION:
Scenario 2

SATURATION FLOW ADJUSTMENT WORKSHEET

		IDEAL SAT. FLOW	NO. LNS	f W	f HV	f G	f p	f BB	f A	f RT	f LT	ADJ. SAT. FLOW
EB												
	L	1800	2	1.000	0.990	1.000	1.000	1.000	1.000	1.000	0.920	3279
	T	1800	3	1.000	0.990	1.000	1.000	1.000	1.000	1.000	1.000	5346
	R	1800	1	1.000	0.990	1.000	0.800	0.996	1.000	0.850	1.000	1207
WB												
	L	1800	2	1.000	0.990	1.000	1.000	1.000	1.000	1.000	0.920	3279
	T	1800	3	1.000	0.990	1.000	1.000	1.000	1.000	1.000	1.000	5346
	R	1800	1	1.000	0.990	1.000	0.800	0.996	1.000	0.850	1.000	1207
NB												
	L	1800	2	1.000	0.990	1.000	1.000	1.000	1.000	1.000	0.920	3279
	T	1800	3	1.000	0.990	1.000	1.000	1.000	1.000	1.000	1.000	5346
	R	1800	1	1.000	0.990	1.000	0.800	0.980	1.000	0.850	1.000	1188
SB												
	L	1800	2	1.000	0.990	1.000	1.000	1.000	1.000	1.000	0.920	3279
	T	1800	3	1.000	0.990	1.000	1.000	1.000	1.000	1.000	1.000	5346
	R	1800	1	1.000	0.990	1.000	0.800	0.980	1.000	0.850	1.000	1188

IDENTIFYING INFORMATION

NAME OF THE EAST/WEST STREET..... Tropicana Ave.
NAME OF THE NORTH/SOUTH STREET... Las Vegas Boulevard S.
DATE AND TIME OF THE ANALYSIS.... 09-06-1994 ; p.m. peak
OTHER INFORMATION:
Scenario 2

CAPACITY ANALYSIS WORKSHEET

	ADJ. FLOW RATE (v)	ADJ. SAT. FLOW RATE (s)	FLOW RATIO (v/s)	GREEN RATIO (g/C)	LANE GROUP CAPACITY (c)	v/c RATIO
EB						
L	510	3279	0.155	0.231	758	0.672 •
T	1649	5346	0.308	0.300	1604	1.028 •
R	330	1207	0.273	0.506	611	0.540
WB						
L	420	3279	0.128	0.231	758	0.554
T	1643	5346	0.307	0.300	1604	1.024
R	229	1207	0.190	0.506	611	0.375
NB						
L	524	3279	0.160	0.206	676	0.775 •
T	780	5346	0.146	0.188	1002	0.778
R	311	1188	0.262	0.419	497	0.626
SB						
L	197	3279	0.060	0.206	676	0.292
T	640	5346	0.120	0.188	1002	0.639
R	434	1188	0.365	0.419	497	0.872 •

Cycle Length, C = 160.0 sec. Sum (v/s) critical = 0.989
Lost Time Per Cycle, L = 12.0 sec. X critical = 1.069

IDENTIFYING INFORMATION

NAME OF THE EAST/WEST STREET..... Tropicana Ave.
NAME OF THE NORTH/SOUTH STREET... Las Vegas Boulevard S.
DATE AND TIME OF THE ANALYSIS.... 09-06-1994 ; p.m. peak
OTHER INFORMATION:
Scenario 2

LEVEL-OF-SERVICE WORKSHEET Page-7

	v/c RATIO	g/C RATIO	CYCLE LEN.	DELAY d 1	LANE GROUP CAP.	DELAY d 2	PROG. FACT.	LANE GRP. DELAY	LANE GRP. LOS	DELAY BY APP.	LOS BY APP.
EB											
L	0.672	0.231	160.0	42.5	758	1.6	1.00	44.2	E	49.4	E
T	1.0[illegible]8	0.300	160.0	43.1	1604	24.3	0.85	57.3	E		
R	0.540	0.506	160.0	20.4	611	0.8	0.85	18.0	C		
WB											
L	0.554	0.231	160.0	41.2	758	0.7	1.00	41.9	E	49.6	E
T	1.024	0.300	160.0	43.0	1604	23.3	0.85	56.3	E		
R	0.375	0.506	160.0	18.3	611	0.2	0.85	15.7	C		
NB											
L	0.775	0.206	160.0	45.6	676	3.9	1.00	49.5	E	41.3	E
T	0.778	0.188	160.0	47.0	1002	2.8	0.85	42.3	E		
R	0.626	0.419	160.0	27.8	497	1.8	0.85	25.2	D		
SB											
L	0.292	0.206	160.0	40.8	676	0.1	1.00	40.8	E	38.8	D
T	0.639	0.188	160.0	45.6	1002	1.0	0.85	39.6	D		
R	0.872	0.419	160.0	32.4	497	10.9	0.85	36.8	D		

Intersection Delay = 46.0 (sec/veh) Intersection LOS = E

IDENTIFYING INFORMATION

NAME OF THE EAST/WEST STREET..... Tropicana Ave.
NAME OF THE NORTH/SOUTH STREET... Las Vegas Boulevard S.
DATE AND TIME OF THE ANALYSIS.... 09-06-1994 ; p.m. peak
OTHER INFORMATION:
Scenario 2

APPENDIX E

LIST OF ACRONYMS

AASHTO	American Association of State Highway and Transportation Officials
HCM	Highway Capacity Manual: Special Report No. 209
ITE	Institute of Transportation Engineers
LOS	Level of Service
LVACTS	Las Vegas Area Computer Traffic System
MUTCD	Manual on Uniform Traffic Control Devices
QOS	Quality of Service
RTOR	Right Turn on Red
TRB	Transportation Research Board
USDOT	United States Department of Transportation

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