A CONGESTION COST INDEX

FOR URBAN TRAFFIC

by

Ronald Robert Asta

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APPROVAL BY THESIS DIRECTOR

This thesis has been approved on the date shown below:

David J. Hall
DAVID J. HALL
Professor of Civil Engineering

Apr 30, 1965
Date

PREFACE

While doing graduate work at The University of Arizona, I have become very interested in the interrelationship of traffic engineering, urban development, and government. A matter of importance to these three subjects is the allocation of public funds for roadway improvement. Congestion indexes characterized by high traffic volumes, high traffic densities, long travel times, low vehicle speeds, and frequent and large speed changes have been developed to determine priority schedules of improvement for a number of roadways. But do these indexes all yield the same schedules?

It is the purpose of this thesis to first, develop a congestion index characterized by high costs of vehicle movement, and second, to determine, for selected roadways in Tucson, if there is a difference in priority schedules of improvement based on this index and the indexes mentioned in the previous paragraph. Before continuing, I would like to acknowledge the following people and organizations for their contributions to this thesis:

William G. Ealy, Director, and the staff of the Tucson Area Transportation Study who permitted me to use their traffic records. Without their travel time, capacity, and accident rate data, this thesis would not have been prepared.

The National Bureau of Casualty Underwriters, the Fireman's Fund American Insurance Group, and the Hartford Insurance Group who provided necessary data to determine average accident costs for Tucson.

The Engineering Division of the Department of Public Works for the City of Tucson who allowed me to study their engineering plans to determine grades for some of the roadways in Tucson.

Edward A. Mueller, Engineer of Traffic and Operations for the Highway Research Board, who compiled and sent me a list of references on traffic congestion.

James A. Archer and Glen L. Martin, graduate students at The University of Arizona, who took time from their work to improve the quality of mine by helping me prepare a computer program for the calculation of congestion cost indexes.

Finally, I wish to express appreciation to my thesis director, Professor David J. Hall, Assistant to the Dean of Engineering, for letting me make the decisions regarding purpose, scope, procedure, and final presentation of this thesis.

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Ronald R. Asta

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ABSTRACT

A congestion cost index was developed to rate roadways for improvement according to their degree of congestion. This index was developed to equal the following for passenger car travel: roadway costs at the existing level of service speed ÷ roadway costs at the acceptable level of service speed.

Roadway costs consisted of three components: (1) vehicle operation cost, (2) accident cost and (3) travel time cost.

Two other congestion indexes were considered in this thesis. One concerned hourly "vehicle minutes of delay," and the other concerned "hourly volume to practical capacity" ratios. Priority schedules for 90 roadway sections in Tucson were determined according to these three indexes; none of the schedules were similar.

The congestion cost index was concluded to be the most accurate indicator of functional obsolescence.

Chapter I

URBAN AREAS

> If we could first know where we are,
> And whither we are tending,
> We could better judge what to do,
> And how to do it.
>
> Abraham Lincoln

Before any problem can be solved, it must be defined; and before the problem can be defined it must be located. The title of this thesis suggests the problem to be traffic congestion and its location to be in urban areas. But what is traffic congestion? What are urban areas? How can the problem be solved?

In this chapter the nature of urban areas is presented, the needed services of urban areas are listed, roadways as a needed service are discussed, and the responsibility and task of government is described. The remaining chapters will discuss the questions concerning traffic congestion and the solution to this problem.

The Nature of Urban Areas

The distinction between rural and urban areas used to be a clear one. Beegle, Firey, and Loomis (1950) called the two activities of human endeavor "field" and "center." "Field" activities were the taking of foods, fibers, ores, and raw materials from the land while "center" activities were the processing and distribution of the products of "field" activities. Thus, settlements around field activities were termed "rural," and settlements around center activities were called "urban." Today the mobility of the highway is bringing these two activities and settlements together such that a distinction of rural and urban areas based on this definition is not readily apparent.

A more appropriate definition of an urban area is: a limited geographical area containing a high concentration of people and a multiplicity of land uses. The following is a list of land uses that would normally be found in urban areas:

1. residential
    a. single-family
    b. two-family
    c. multi-family
2. commercial
    a. central business district
    b. shopping centers
3. industrial
    a. light
    b. heavy
    c. industrial parks
4. public and quasi-public
    a. government buildings
    b. civic centers
    c. libraries
    d. schools
    e. fire stations
    f. parks and playgrounds

In contrast, the following list of predominant land uses in rural areas illustrates one of the distinguishing characteristics of this definition:

1. residential
    a. ranch
    b. farm
2. open space
    a. agriculture
    b. recreation

Three purposes of urban areas are: living, working, and recreation. For these purposes to be fulfilled in areas densely populated and in spaces demanded by wide ranges of land use, many services have to be provided.

Needed Services of Urban Areas

In general terms, the health, safety, welfare, and morals of the community must be advanced and protected. In detailed terms, the following list of services are needed in urban areas:

1. roadways and bridges
2. water supply and treatment
3. sewage collection and disposal
4. garbage collection and disposal
5. mass transit
6. airports
7. police protection
8. fire protection

9. control and abatement of nuisances
10. schools
11. libraries
12. museums
13. parks and playgrounds
14. welfare services
15. public health programs
16. public hospitals
17. safety programs
18. housing
19. gas
20. electricity
21. planning, zoning, and subdivision controls
22. churches
23. licensing and registration
24. administration of records
25. drainage and flood control
26. administration of elections
27. cemeteries
28. mail

The provision of these services requires many other duties. For instance, the provision of roadways requires planning, design, construction, and maintenance activities, methods of finance, the employment of a staff, and a consideration of gas, electricity, water and sewerage lines. This list of services, then, is even more extensive.

The needed service and subject of this thesis is the roadway system.

Roadways as a Needed Service

The primary function of roadways in an urban area is to link the land uses together. The city dweller cannot satisfy his wants within the confines of his own lot. If he wants to work he may have to travel to industrial land, if he wants to educate his children he must travel to public and quasi-public land, and if he wants to shop he has to travel to commercial land. If people could not travel to these lands within a reasonable amount of time or with an adequate degree of ease, these land uses would have no reason for existence. Thus an urban area would lose its character and would become rural in nature.

Roadways are a necessity to the provision of other services. The transportation of materials to construct a sewage treatment plant, the transportation of people and goods to an airport, and the movement of fire trucks to burning buildings all require a system of roadways.

To accomplish its purposes, the system must move traffic, provide land access, and provide spaces for parking or access to off-street parking. The elements of the roadway system, their service functions and other characteristics are displayed in Table 1 on page 7 (Van Cleve, 1964). The variations in service functions and other characteristics are particularly important in the design and the determination of functional obsolescence of these elements. For instance, considering the adequacy of traffic movement, a major arterial street would be more obsolete than a collector street if both failed to provide this service.

Regarding roadway systems, the necessity for distinguishing between rural and urban areas now becomes clear. Rural areas would not contain major arterial and local streets although they would contain highways and probably collector roads to transport people and goods from residences, agricultural, and recreational areas to the highway. However, the collector roads would not serve neighborhoods, commercial or industrial districts, would not necessarily provide trip lengths of under 1 mile, would not be marked as through streets, would not be spaced at one-half mile intervals, and would not feature intersections at one block spacings.

Responsibility for roadways and the other needed services of urban areas usually lies with the units of local government.

TABLE 1. FUNCTIONAL ROADWAY SYSTEMS

Element	Primary System		Secondary System	
	Highway	Major Arterial Street	Collector Street	Local Street
Service Functions:				
Traffic Movement	Primary	Primary	Same relative importance as access	Secondary
Land Access	Controlled	Secondary	Same relative importance as movement	Primary
Parking	None	Limited	Tertiary	Tertiary
Other Characteristics:				
Land Use Served	Major Regional Traffic Generators[1]	Major Urban Area Traffic Generators[2]	Neighborhoods, commercial or industrial districts	Individual properties
Trip Length	Over 3 miles	Over 1 mile	Under 1 mile	Under ½ mile
Marked as Through Street	Always	Always	Usually	Never
Spacing of Streets	----	1 mile	One-half mile	----
Spacing of Intersections	1 mile or more[3]	1/4 to 1/2 mile	One block	----

1 Including central business districts, major employment centers.
2 Including neighborhood shopping centers, high schools and similar uses.
3 Closer spacing necessary in high traffic areas such as central business districts.

The Task of Government

To provide a good roadway system, local government must: (1) plan, design, and construct new facilities when and where they are needed and (2) maintain the level of service of existing facilities. Maintaining the level of service of existing facilities involves the correction of: (1) physical obsolescence (pavement, subgrade, curbs, etc.) and (2) functional obsolescence (traffic movement, land access, and parking). The specific task of local government which concerns this thesis is the correction of functional obsolescence. This task is difficult, and some of the reasons for this difficulty are discussed in the following three paragraphs.

The responsibilities of local government are many. Its responsibility for the multiplicity of needed services has already been mentioned, and these services must be provided in areas characterized by changing population densities and changing commercial, industrial and other land use activities. Furthermore, they must be provided within the boundaries of a limited budget.

The units of government that are responsible for these services are many. They include not only municipal governments but county governments and single-purpose special districts such as school, park and playground, sanitary, flood control, water, fire, airport, irrigation and weed control. Regarding roadways, the Federal and state governments plan and construct freeways through urban areas, counties construct roads on the periphery of urban areas, flood control districts desire proposed roadways to be located in one place and airport districts desire them to be located in another, and all the while the urban area limits are extending into other counties and other municipalities.

The units of responsibility within a local government are many. The construction of roadways may be the responsibility of the department of public works, the design of roadways may be the responsibility of the city engineer, the planning of roadways may be the responsibility of the planning department and/or a special area transportation planning agency. The maintenance of level of service may be the responsibility of the traffic engineer, and traffic law enforcement will probably be the responsibility of the police department.

In the light of this multitude of required services and this multitude of responsible public bodies, the question asked is how can an efficient program of roadway improvement be established? The term "efficient program" means correcting the functional obsolescence of those roadway elements that will provide the greatest service benefits to the entire system and will make the best use of public funds.

The Task of This Thesis

To help meet the goal implied in the previous paragraph, this thesis developes a systematic method of determining priority schedules of improvement for functionally obsolete roadways having traffic movement as their primary service function. Other methods have been derived for this purpose, and this thesis compares their resulting priority schedules with the resulting schedule of this new method.

The methods previously derived make use of a technique called the congestion index. Chapter II examines some of these congestion indexes.

Chapter II

TRAFFIC CONGESTION INDEXES

Rothrock (1954) stated that traffic congestion actually begins whenever there is any impedance to free vehicular movement. He then proposed three concepts--an operational characteristics concept, a freedom of movement concept, and a volume to capacity concept--to be used as bases for developing congestion indexes. It was his reasoning that a congestion index would:

1. provide a means of comparing congestion in one place with congestion in another.
2. provide a measurement of trends in congestion for any subject of study.
3. provide an indicator of traffic potential.
4. provide a means of setting up priorities for remedial expenditures.

Operational Characteristics Concept

The operational characteristics concept was to involve studies of travel speeds, travel times, and travel delays. Delays were to be slowdowns in movement at or between intersections due to the following causes:

1. traffic signals
2. a single slow passenger car ahead
3. a single slow truck ahead
4. a slow bus ahead

5. a vehicle making a left turn
6. a double-parked vehicle
7. traffic encroaching from opposite lanes
8. pedestrians
9. generally slow traffic

Somewhat related to this concept was a study by Greenshields (1955) concerning a quality index number. He reasoned that the quality of traffic flow depended on the average speed(s), the magnitude of total speed change (Δs), and the frequency of speed changes (f). These variables were related to a quality index number as follows:

$\theta = F(s/\Delta s \cdot f)$, where θ is the quality index and F means "function of."

This was to say that the quality of traffic flow increased with an increase in average speed, decreased with an increase in the magnitude of total speed change, and decreased with an increase in the number of speed changes.

However, Greenshields further reasoned that since small speed changes were not as annoying to drivers as large changes and since the size of the changes decreased as the frequency of change increased, it was reasonable to reduce the weight given to larger frequencies. Also, since the ratio in the previous paragraph yielded very small values, a factor of 1000 was added which resulted in the following quality index number:

$$\theta = 1000 \cdot s/\Delta s \cdot \sqrt{f}$$

To collect data for this number, Greenshields proposed making test runs with an Esterline-Angus recorder attached to the test car.

From the recorder's charts, values for average speed, total speed change, and frequency of speed changes could be determined.

Rothrock and Keefer (1957) followed up Rothrock's original proposal of the operational characteristics concept of a congestion index by studying vehicle time-of-occupancy. The theory was that when a number of vehicles could move through a section of roadway in the average optimum travel time, there was no congestion. Any excess vehicle time-of-occupancy was the measurement of time lost due to congestion. Values for this congestion index (CI) were determined from the following relationship:

$$CI = \frac{\text{actual vehicle minutes-of-occupancy}}{\text{optimum vehicle minutes-of-occupancy}}.$$

Two ways were suggested to obtain actual vehicle time-of-occupancy. The first involved taking photographs of the study section at periodic intervals for a given time of observation. The average density (density is the number of vehicles in a section of roadway at any instant of time) was found by counting the number of vehicles in each of the photographs and dividing by the number of photographs. The actual vehicle time-of-occupancy was then found by multiplying this density by the time of observation. The second method involved counting the number of vehicles entering the section while a test car made a sufficient number of runs through the section to determine an average travel time. The actual vehicle time-of-occupancy was then found by multiplying the volume of vehicles that entered the section by the average travel time to get through the section.

A suggested criteria for determining the optimum vehicle time-of-occupancy was to find that travel time in the field that corresponded to the largest volume of traffic moving through the section without any restrictions to movement except for those due to traffic signals. Multiplying this travel time by its corresponding volume yielded the optimum vehicle time-of-occupancy. It was difficult, however, to determine this optimum condition and to obtain a consistent value for a particular roadway section; therefore, two other ways for determining the optimum vehicle time-of-occupancy were proposed. The first considered a roadway's practical capacity as the optimum volume, and six-minute volume counts were taken in the field. The travel time corresponding to the six-minute volume closest to one-tenth of the practical capacity was selected. (Practical capacity is the maximum number of vehicles that can pass a point on a roadway or enter an intersection in one hour without causing unnecessary hazard and delay.) The second method used the volume during the peak hour and the average travel time for the hour of best travel conditions.

Rothrock and Keefer further suggested that the congestion index be expressed per lane per mile or one-tenth mile to facilitate the comparison of congestion for roadway sections of different lengths or number of lanes.

Somewhat related to Rothrock and Keefer's work was an investigation by Hall and George (1959) of travel time as an effective measure of congestion. They considered an optimum travel time corresponding to a standard level of service speed (National Committee on Urban Transportation, 1958). This level of service speed was defined to be a desirable and obtainable speed for a particular roadway element that was practical of achievement through the use of various restrictive and constructive techniques. Hall and George used "vehicle minutes of delay" as a measurement of congestion; this measurement equaled the product of peak hour volume and the difference between actual travel time and the assigned level of service speed.

The second of Rothrock's original three concepts for determining congestion indexes was the freedom of movement concept.

Freedom of Movement Concept

Rothrock stated that this method required measurements of traffic densities to determine whether the movements of vehicles were restricted and to determine the changing percentages, magnitudes and durations of restrictions. He stated that density could be measured in terms of vehicle occupancy per unit width and length of roadway, or that perhaps an occupancy figure by time periods would suffice. An index might be developed, he suggested, to show the duration of time that a given percentage of the vehicles were restricted from moving or from free movement.

Rothrock's third concept was the volume to capacity concept.

Volume to Capacity Concept

This concept considered that congestion was caused by a lack of capacity in the roadway to handle the demands of traffic. Therefore the ratio of actual traffic volumes to the so-called design volumes, otherwise known as the practical capacity, constituted the congestion index.

Gardner's (1960) congestion approach to rational programming considered a relationship of actual traffic volumes to capacities. His thinking was that the functional obsolescence date of a roadways occurred when traffic volumes equaled capacities at desirable operating speeds.

The year of equality (x) of the two was expressed as:

$$x = y + \frac{\log.\ c/v}{\log.\ (1+e)},$$

where y = year of known average daily traffic
c = capacity of road section
v = average daily traffic of known year
e = annual expansion factor for the region

and was derived as follows:

$$c = v(1+e)^{x-y}$$

$$c/v. = (1+e)^{x-y}$$

$$\log.\ c/v = (x-y)\log.\ (1+e)$$

$$x = y + \frac{\log.\ c/v}{\log.\ (1+e)}.$$

In the light of these numerous ways to measure congestion, the question asked is how accurately do they measure congestion?

The Accurate Measurement of Congestion

Other factors being equal, a roadway section having a higher ratio of green time to total traffic signal cycle time (green, red, and yellow) has a higher practical capacity than a roadway section having a lower ratio of green to total cycle time. Consider two roadway sections of equal length having an equal number of signalized intersections with the same ratios of green to total cycle time. Let one section be characterized by a progressive signal system and the other be characterized by independent signals (in a progressive signal system, a driver is able to travel at a specified constant speed and approach every intersection at a green signal). It is possible that these two sections could encounter the same traffic volumes and, therefore, have the same volume to capacity ratios. However, the travel time on the section featuring the progressive signal system would be less than the other section's travel time. Then which is the more accurate measurement of congestion--the operational characteristics concept or the volume to capacity concept?

Consider two roadway sections having equal capacities and handling equal traffic volumes. Suppose that the vehicle arrival rate to one section was fairly uniform while the arrival rate to the other section was sporadic with many vehicles arriving at the same time in some instances and no vehicles arriving in others. The volume to capacity ratios would be the same, but the roadway sections would feature different degrees of restricted movement. Then which is the more accurate measurement of congestion--the freedom of movement concept or the volume to capacity concept?

The answer to questions concerning the most accurate indexes or concepts has not been resolved as yet. It has been suggested that an index might be developed which would be based on all three concepts. If many roadway sections were tested for congestion by various indexes and each index yielded the same relative degree of congestion among the roadways, it could be said that these concepts shared the same degree of accuracy.

This thesis develops another congestion index; it develops an index characterized by roadway costs. It is proposed on the premise that high or excessive roadway costs are indicators of congestion. It is suspected that a comparison of congestion ratings by this index and an index based on travel time may differ; a low travel time or fast speed might indicate congestion due to high gasoline costs on the one hand, but might indicate no congestion on the other.

The first stage of development of the congestion cost index listed all the possible roadway costs and selected the pertinent ones. This is the subject matter of Chapter III.

Chapter III

ROADWAY COSTS

Ogelsby and Hewes (1963) introduced a chapter on highway economy in their textbook, Highway Engineering, with the following paragraph:

> Governments devote public funds to highway improvement because they provide benefits to society either as a whole or as individuals. Good transportation facilities raise the level of the entire economy by providing for ready transportation of goods; they are of assistance in problems of national defense; they make easier the provision of community services such as police and fire protection, medical care, schooling, and delivery of the mails; they open added opportunities for recreation and travel. Highways benefit the landowner because ready access makes his property more valuable. They benefit the motor-vehicle user through reduced cost of vehicle operation, savings in time, reduction in accidents, and increased comfort and ease of driving. On the other hand, road improvements take money that might be used for other productive purposes by individuals or by government.....

This paragraph suggested that there were costs which were not necessarily related to the road user. It also suggested that costs or consequences existed which were not easily expressed in monetary terms. With a recognition of these characteristics, roadway costs that could be considered in comparing level of service were grouped into four classifications: market costs to road users, extra-market costs to road users, market costs to other than road users, and extra-market costs to other than road-users. Market costs were considered to be those where the market provided a place for money valuations; extra-market costs were those where it did not. The results of the grouping and a discussion of the costs follow.

Market Costs to Road Users

These costs include motor vehicle operating costs, time costs to commercial vehicles, and direct cost of motor vehicle accidents. Some motor vehicle operating costs such as fuel, oil, tires, maintenance and mileage depreciation are dependent on the distance of travel. Others such as license and registration fees, garage rent, insurance and obsolescent depreciation are dependent on time; these cost elements vary inversely with mileage. The time costs to commercial vehicles vary inversely with speed. Those cost elements that vary with distance are also affected by speed and congestion.

The costs of fuel, oil, tires, maintenance and mileage depreciation vary with pavement conditions (paved, gravel, or unsurfaced), roadway alinement (tangents or horizontal curves), roadway profile (level or sloped), and the age, weight, and type of vehicle (passenger cars, single-unit trucks, or combination truck and trailers). Additional costs arise when a vehicle comes to a stop, remains idle, and regains its initial speed. Tire wear and maintenance, in particular, are affected; in fact, Gibbons and Proctor (1954) stated that all the maintenance costs of brakes and clutches were due to traffic stops.

In addition to all these factors, motor vehicle operating cost elements are affected or determined by factors unique to their particular natures. For instance, fuel costs vary, also, with operator skill, engine and transmission adjustment, side friction of the vehicle, super-elevation of the roadway, temperature, and elevation. When congestion exists, drivers travel at speeds less than their desirable speeds and, therefore, undergo speed changes trying to exceed their congestion rate. The number and degree of these changes significantly affect fuel consumption. Marcellus (1963) stated that fuel consumption and tire wear were less on divided than on undivided two, three, and four-lane highways because passing maneuvers could be made with less changes in speed. However, he stated that it was not necessary to consider this factor in urban areas because very few urban streets were separated by wide enough medians to reduce costs.

Tire costs also vary with the degree of inflation, tire rotation, wheel balance and overload control. Vehicle repair and maintenance costs include the cost of labor plus parts and depend on the maintenance practices of the owner. Maintenance costs are difficult to establish because the results of hard usage may not require repairs for a long time afterwards. Oil costs depend on the average miles between oil changes. Though the cost per mile decreases as the length of time between changes increases, the cost of other factors such as engine maintenance and fuel increases as a result.

Depreciation costs are determined with a consideration to the number of ownership changes, the length of time between changes, appearance and running conditions. For instance, the average difference between ownership and purchase prices can be found and divided by the mileage accumulation. Ogelsby and Hewes (1963) revealed current practice to be that of allocating one-half of the total depreciation cost to mileage and one-half to time. However, they stated that for certain trucks all the depreciation could conceivably be charged to mileage.

Their annual mileage could be high such that they would be completely worn out before major improvements in design or marked changes in first cost occurred.

The cost of time for commercial vehicles such as trucks and buses has a value in direct ratio to the wages of drivers and the rental of equipment. Another way to evaluate time is to consider the net operating profits of commercial carriers; congestion delay time is then considered as time that could be used for making profits. In computing net operating profits, losses due to the spoilage of goods in delayed commercial carriers could be considered as well as wages and rental charges.

The direct costs of accidents arise from property damage, injury and death. As yet, methods are lacking for relating accidents to such design elements as intersections, medians, curves, number of lanes, and access control. Accidents depend not only on these design elements but on human and vehicular failures as well. Thus to determine accident costs for any roadway, records of accident frequency and severity have to be consulted.

Extra-market Costs to Road Users

Some roadway effects such as the travel time of non-commercial vehicles, the strain and discomfort of non-uniform driving, the circumstances resulting from the deaths and permanently disabling injuries of accidents, and the accessibility to parks, recreational facilities, and cultural and historical areas, have a basis for an arbitrary assignment of money valuations. Others such as the joy of sightseeing and driving for pleasure cannot (at least at present) be assigned money values.

In discussing the costs of time for non-commercial vehicles, Ogelsby and Hewes (1963) stated that the conditions for determining time costs for commercial vehicles also applied to passenger cars used for business purposes by delivery men, salesmen, and others; however, serious difficulties had arisen in assigning the proper money value to them. They further stated:

> The greater part of private passenger-car use is devoted to necessity travel such as trips for work and business, and for family services. Without question, drivers and passengers place a money value on the time given to these purposes, since it otherwise could be made available for business, pleasure, or rest. However, this time, if saved, will not produce goods or services and, therefore, will have no specific economic value, measurable by market standards. Rather, if a money value is assigned, it must be on an arbitrary basis or by assessing in a subjective way what people will pay to free such time for other purposes.
>
> ......Research to establish factually the value that noncommercial motorists place on time has been proposed. One approach is to relate time saved to the extra costs incurred to save the time. For example, many drivers are willing to pay tolls to save time. In other cases, they will incur greater costs by driving longer distances in order to save time.

In discussing the costs of strain and discomfort of nonuniform or difficult driving, Ogelsby and Hewes (1963) stated:

> Origin and destination surveys have shown that many drivers choose routes along freeways and expressways in preference to those along conventional highways or streets, even though overall distances are longer and travel times greater on the former. Also, many drivers are willing to use toll roads even though they can reach their destinations in fewer miles and with little time difference on a free but congested route. Thus, there is substantial evidence that drivers place a money value on

the comfort and convenience provided by modern highway facilities.

......At present, if a money value is assigned, it must be done arbitrarily......

Research has been proposed to determine the subjective money values that drivers assign to discomfort, inconvenience, and strain. Measurements would be made of the extra time and distance that drivers would expend to travel at a uniform rate on a free-flowing artery in order to avoid the speed changes, starting, and stopping encountered on congested streets. Among the ways that results might be expressed are (a) assigning premium money values to the time devoted to speed changes or (b) assigning money values directly to speed changes as a measure of strain, discomfort, and annoyance. It has also been suggested that the greater visual comfort and reduction in strain to nighttime drivers brought about by improved roadway illumination bring humanitarian, traffic, and economic gains that should be considered in economy studies.

Market Costs to Other Than Road Users

The operating costs of public services can vary considerably with varying roadway conditions. If a segment of a community becomes severed from the remainder by a fully access-controlled highway and travel to it becomes circuitous, the costs of police and fire protection and school bus operation increase. However, if this highway provides a direct link between a residential area and a working area, the patronage of public transit may be enhanced.

The location of roadways usually affects the drainage conditions in an area. A roadway may provide flood protection to adjacent land, or it may increase the flood hazard if improperly designed. The value of land is largely determined by its accessibility to modes of transportation. Thus, some roadways may be characterized by higher values of adjacent land, agricultural crops, and natural resources than others.

Economic gains are realized also to land improvements and business establishments when their accessibility is improved.

Engineering and administrative manpower and maintenance labor and materials are allocated to the various elements of a roadway system. However, it is sometimes difficult to determine when these operating costs are being used to maintain the existing level of service or being used to construct new facilities. For instance, it might be argued that the widening of a major arterial street should be considered construction of a new facility, because the capacity is being increased, instead of maintenance of its traffic movement function.

Extra-Market Costs to Other Than Road Users

The overall economic and social well-being of a community can be traced to the roadway system although it can't be described in monetary terms. The mobilization of the automobile has an effect on individuals' social life, community environment, and political organization. The effects are not always favorable. For instance, the decentralization of business activity in urban areas results in the flight of trade from the central business district. In many cases, this flight of trade, also caused by bad traffic conditions, results in slum development, increased crime rates, and disease.

Table 2 on page 26 presents the market and extra-market costs of roadways in summary form. Only some of these costs were considered pertinent to the development of a congestion cost index.

TABLE 2. ROADWAY COSTS

To Road Users	To Other Than Road Users
I. Market Costs A. Vehicle operation 1. fuel 2. oil 3. tires 4. maintenance 5. depreciation (mileage) 6. depreciation (time) 7. license fees 8. garage rent 9. insurance B. Travel time of commercial vehicles 1. wages 2. equipment rental 3. profits 4. spoilage C. Accident 1. property damage 2. injury 3. death	I. Market Costs A. Public services B. Drainage C. Land and improvements D. Business activity E. Roadway operation
II. Extra-Market Costs A. Travel time of non-commercial vehicles B. Strain and discomfort C. Recreation D. Sightseeing	II. Extra-Market Costs A. Social life B. Environment C. Political organization D. Urban blight

Selected Roadway Costs for a Congestion Cost Index

The selection of the particular cost elements was made on the basis of their applicability to the function of the congestion cost index. It has been stated that the intended use of this index is to measure the level of service afforded traffic movement. Roadway costs "to other than road users" were not selected then because:

1. The market costs of public services, land and improvements, and business activity, and the extra-market costs of social life, environment, political organization and urban blight are related to the "access" function of roadways rather than the "traffic movement" function.
2. Drainage costs are related to the design and location of a roadway.
3. There is difficulty in distinguishing between the construction activity and maintenance activity of roadway operation costs. Much of the maintenance activity is for repairing structural and underground utility obsolescence, not for repairing functional obsolescence. It is difficult to assess the monetary value of the engineering and administrative manpower that is used for correcting such traffic movement devices as signs and signals for a particular roadway.
4. Although traffic congestion may be the cause of urban blight or decreased business activity, it is only a secondary cause since it acts to prevent proper access, the primary cause.

The "vehicle operation" costs of fuel, oil, tires, maintenance and mileage depreciation were selected because they are related to the speed and speed changes of travel. The vehicle operation costs of depreciation due to time, license fees and garage rent were not selected, however, because their costs would remain the same regardless of the level of traffic service. Though insurance rates fluctuate with accident frequency, their incremental increases or decreases due to the accident ratings of individual streets or highways is difficult to determine, and thus the vehicle operation costs of insurance were not selected. Though the "travel time of commercial vehicles" is directly related to the rate of movement, it was not selected as a cost factor because, as is indicated in Chapter IV, accurate data was not available to determine the type of commercial vehicles traveling on the selected roadways. Accident costs were selected because their frequency of occurrence is related to the conditions of traffic flow as well as to vehicle and driver capabilities.

The only "extra-market cost to road users" selected for use in the congestion cost index was the travel time cost of non-commercial vehicles. The difficulty of measuring recreation and sightseeing values for particular roadways was apparent, and there wasn't a substantial enough basis for arbitrarily selecting values of strain and discomfort. The American Association of State Highway Officials (1960) set values for discomfort and inconvenience in terms of traffic volumes and practical capacity. However, this thesis considers congestion from a volume vs. capacity viewpoint as one separate from that of roadway costs for comparison purposes. There seemed to be a reasonable basis, however, for arbitrarily setting a value of time for non-commercial vehicles in terms of the occupants' incomes.

The following is a summarized list of the selected roadway costs:

I. Vehicle operation

a. fuel

b. oil

c. tires

d. maintenance

e. depreciation (mileage)

II. Accident

a. property damage

b. injury

c. death

III. Travel time of non-commercial vehicles

The selection of these costs was the first stage of development of the congestion cost index. The remaining stages are discussed in Chapter IV.

Chapter IV

A CONGESTION COST INDEX

This congestion cost index (CCI) concerns itself with two rates of travel--running speed and nominal speed. Running speed is equal to the distance traveled divided by the time a vehicle is in motion. Nominal speed is defined as the speed at which a driver operates in the absence of traffic interference. Thus, nominal speed is a theoretical, desirable speed while running speed is an actual, measurable rate of traffic movement. CCI is defined as the ratio of roadway costs at the running speed to roadway costs at the nominal speed of a roadway section. A roadway "section" is that portion of the roadway located between two signalized intersections which contains one direction of travel. The following is the symbolic expression of CCI:

$$CCI = CVMR/CVMN$$

$$= \frac{OCVMR + ACVMR + TCVMR}{OCVMN + ACVMN + TCVMN},$$

CVMR = roadway costs per vehicle-mile at running speed

CVMN = roadway costs per vehicle-mile at nominal speed

OCVMR = operating costs per vehicle-mile at running speed

ACVMR = accident costs per vehicle-mile at running speed

TCVMR = time costs per vehicle-mile at running speed

OCVMN = operating costs per vehicle-mile at nominal speed

ACVMN = accident costs per vehicle-mile at nominal speed

TCVMN = time costs per vehicle-mile at nominal speed

A description of the procedure of development, data, and calculations follows.

Procedure of Development

Figure 1 on page 34 portrays the procedure that was followed to develop this congestion cost index. STAGE 1--the selection of cost elements was described in Chapter III.

STAGE 2--the selection of roadway sections was determined by the availability of accident records for Tucson as reported by the Tucson Area Transportation Study (1960). Accident records were available from 22nd Street to Pima Street and Main Avenue to Craycroft Road; this roadway network is shown in Figures 2 and 3. Of the 67 signalized intersections indicated in Figures 2 and 3, 25 were selected at random for study. Since some intersections did not allow four approaches for study, a total of 90 roadway sections were analyzed in this thesis. The following is a list of the intersections which allowed less than four approaches for study with the reasons enclosed in parenthesis:

1. Speedway-Jones (no accident data available for Jones)
2. Speedway-Craycroft (limit of study area at Craycroft)
3. 5th Street-Craycroft (limit of study area at Craycroft)
4. Pennington-Stone (Pennington a one-way street)
5. Broadway-Scott (no speed data for Scott)
6. Broadway-Craycroft (limit of study area at Craycroft)
7. 22nd Street-Tucson (limit of study area at 22nd Street)
8. 22nd Street-Swan (limit of study area at 22nd Street)

Data

STAGE 3--the determination of the required variables needed to calculate costs was made after studying published cost data and the available traffic data of the Tucson Area Transportation Study (TATS). Roadway costs as determined by the American Association of State Highway Officials (1960), McGraw-Hill (1960), and Claffey (1960) were given for commercial vehicles by type and weight; such designations as single-unit trucks, combination vehicles, and dump trucks 50 percent loaded were used. In a capacity study made by TATS in 1960-61, the percentage of trucks and buses during evening peak-hour travel was measured in the field; however, this percentage was not broken down into the number of single-unit trucks, buses, etc. Therefore, CCI's were calculated for passenger cars only. The effect of more commercial vehicles on one roadway section than on another was still taken into account for comparison purposes, however, because commercial traffic influences the travel behavior of passenger cars.

TATS assigned local standard speeds to the elements of the Tucson roadway system. These local standard speeds were selected with a consideration to recommended standard speeds by the National Committee on Urban Transportation with adjustments to reflect local conditions; these standard speeds are shown in Table 3 on the next page.

TABLE 3. STANDARD SPEEDS

Street Classification	National Standard Speed	Local Standard Speed
Expressway	35 MPH	35 MPH
Outside CBD		
Major Arterial	25 MPH	30 MPH
Collector	20 MPH	25 MPH
Inside CBD		
Major Arterial	25 MPH	15 MPH
Collector	20 MPH	15 MPH

Since these local standard speeds were considered by TATS to be desirable speeds that could reasonably be attained on Tucson roadways, they were adopted as nominal speeds in this thesis. The 90 roadway sections studied in this thesis contained outside and inside CBD major arterials and collectors; thus the use of three nominal speeds was required. It was stated in Chapter I that a congestion cost index was being developed to define the functional obsolescence of roadways having traffic movement as their primary function. This statement ruled out the consideration of collector streets. However, it was very difficult to distinguish between major arterial and collector streets in the Central Business District of Tucson and in the study area outside the Central Business District.

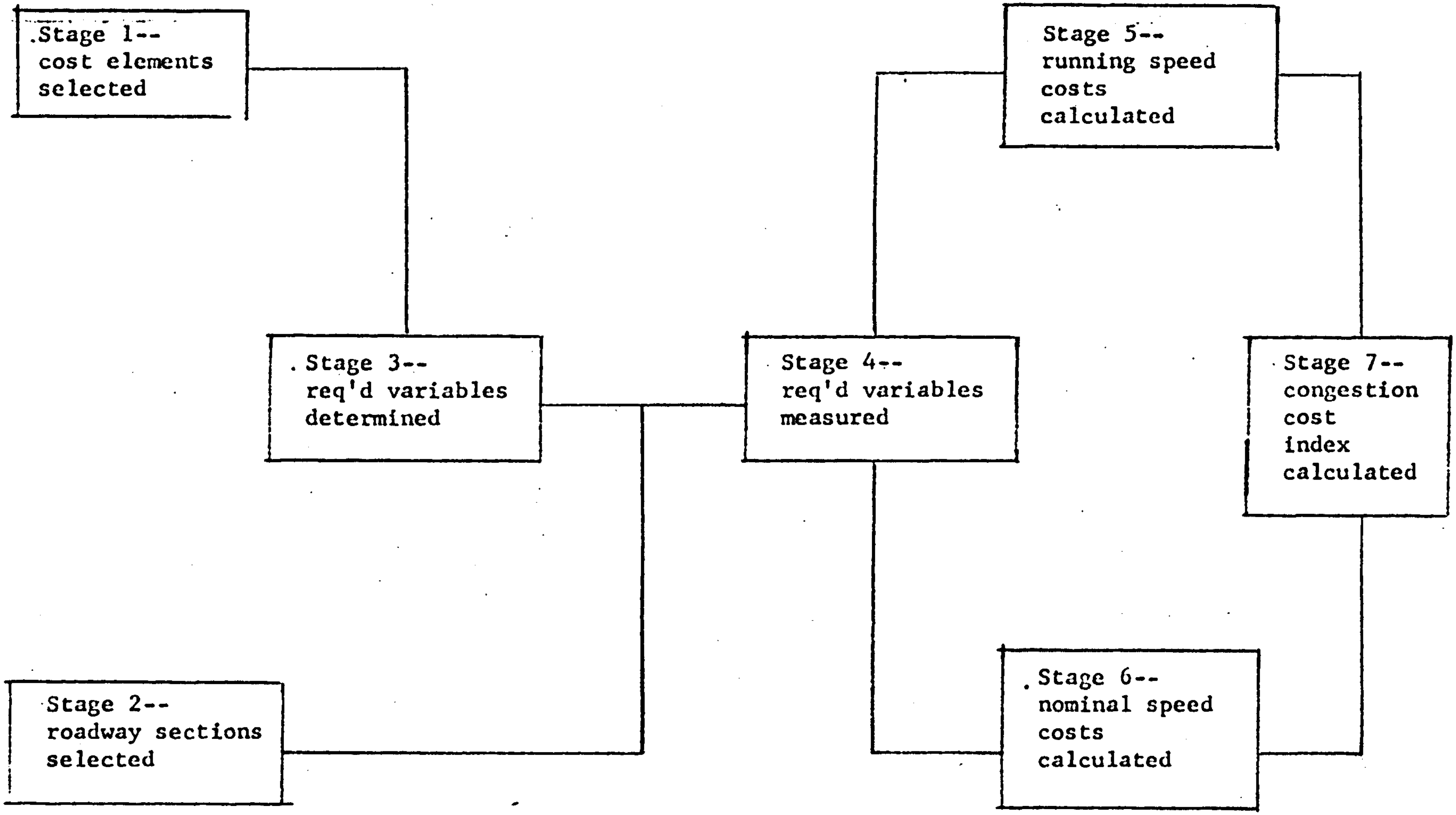


FIGURE 1. DEVELOPMENT PROCEDURE

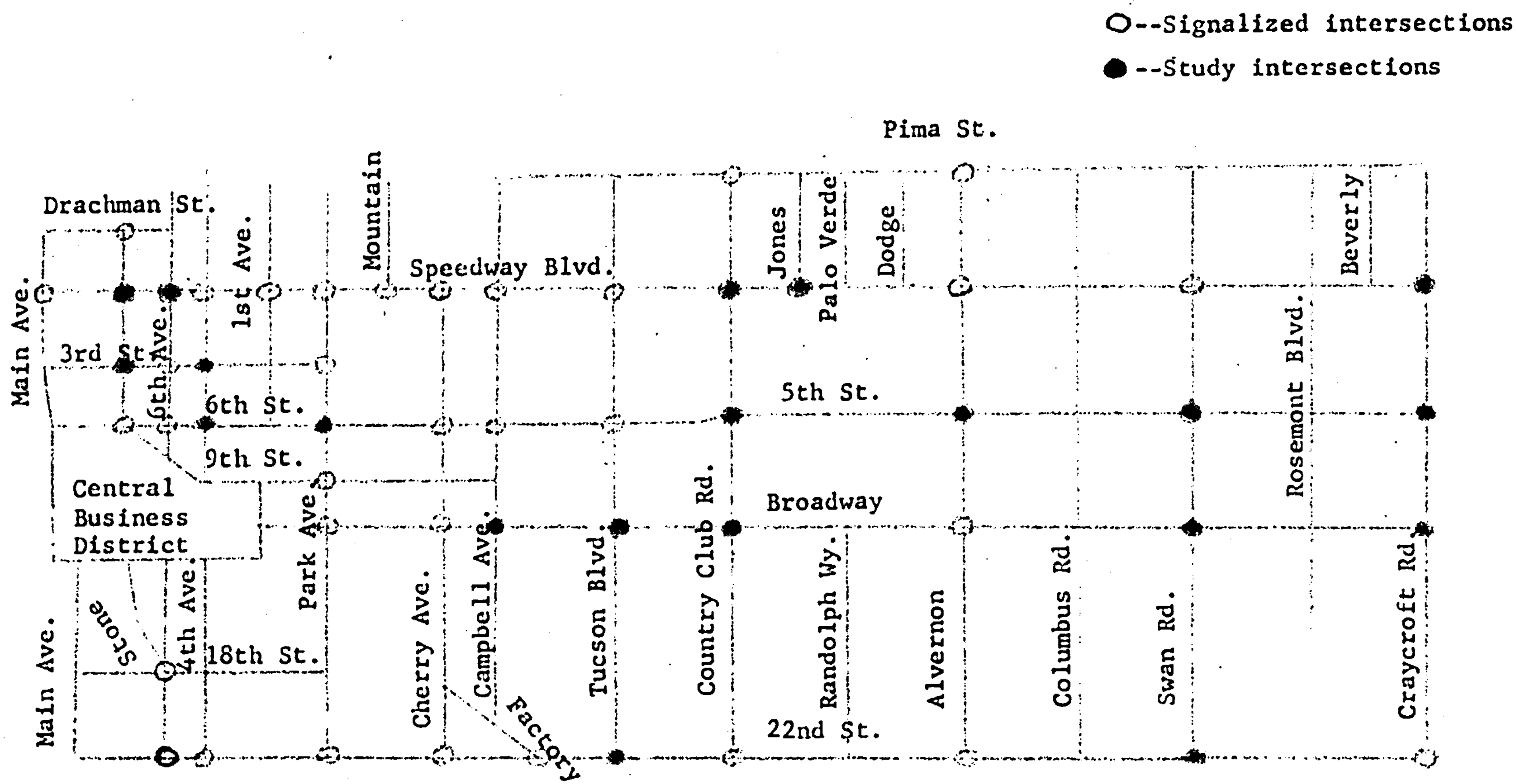


FIGURE 2. ROADWAY NETWORK

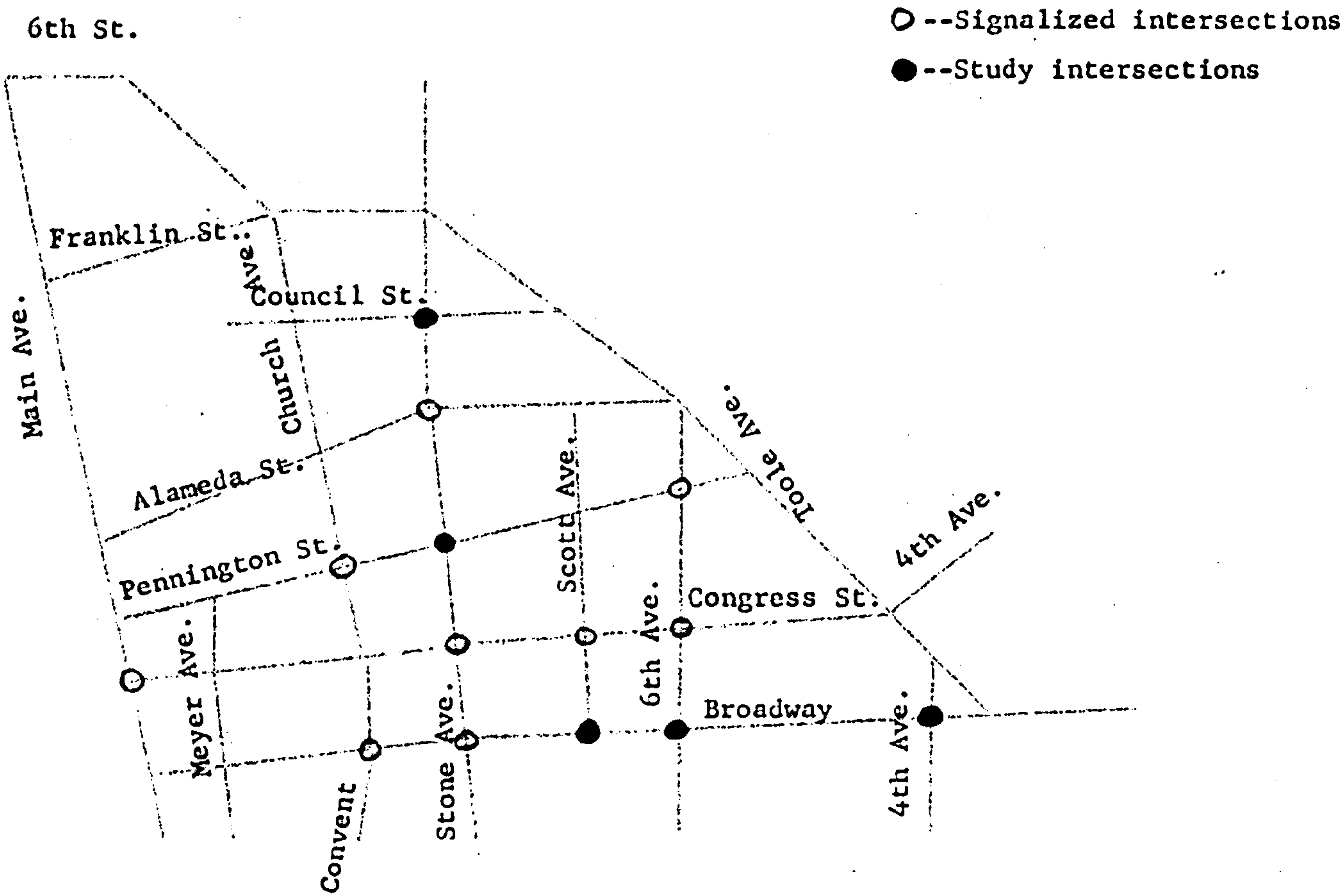


FIGURE 3. CENTRAL BUSINESS DISTRICT

The McGraw-Hill (1960) vehicle operating cost data which was used in this thesis and which applied to passenger cars and the three selected nominal speeds is presented in Table 4 on pages 38, 39, and 40. Additional data was available for the running costs of passenger cars on paved horizontal curves in good condition; however, none of the study roadways contained horizontal curves. The McGraw-Hill operating cost data was selected for use in this thesis for two reasons:

1. It included the effects of many of the cost dependent factors listed in Chapter III.
2. The author felt that the grouping of running speed costs under various nominal speeds indirectly included the effects of strain and discomfort to drivers.

To determine operating costs, it was necessary to find values of running speed, nominal speed and grade for each roadway section. To determine the additional running costs due to vehicle-stops and idling, it was necessary to find the number of stops per vehicle and the idling time per stop.

Accident costs depended on the accident rates of the roadway sections and the corresponding values per accident. The determination of time costs required a knowledge of the total speed of travel and the value of car occupants' time. Total speed, unlike running speed, is the total travel time, including stops and delays, divided by the length of travel.

TABLE 4. McGRAW-HILL OPERATING COSTS

RUNNING COST OF PASSENGER CARS ON PAVED-LEVEL TANGENTS IN GOOD CONDITION. (Costs in cents per vehicle-mile for gasoline, oil, tires, maintenance, and depreciation attributable to mileage)

Average Running Speed, mph	15 MPH Nominal Speed	25 mph Nominal Speed	30 mph Nominal Speed
9	4.770		
10	4.458		
11	4.289		
12	4.161	5.245	
13	4.053		
14	3.953	4.869	
15	3.861		
16		4.548	4.762
17			
18		4.271	4.517
19			
20		4.035	4.301
21			
22		3.853	4.121
23			
24		3.720	3.973
25		3.681	
26			3.852
27			
28			3.758
29			
30			3.709

Table 4--continued

RUNNING COST OF PASSENGER CARS ON PAVED COMPOSITE GRADES IN GOOD CONDITION. (Costs in cents per vehicle-mile for gas, oil, tires, maintenance, and mileage depreciation)

Average Running Speed, mph	Level Tangent	1% Grade	2% Grade
10	4.093	4.111	4.165
11	4.039	4.056	4.108
12	3.988	4.003	4.053
13	3.942	3.956	4.003
14	3.899	3.912	3.970
15	3.861	3.873	3.917
16	3.827	3.838	3.880
17	3.796	3.807	3.847
18	3.768	3.778	3.818
19	3.744	3.753	3.793
20	3.725	3.733	3.773
21	3.708	3.716	3.755
22	3.695	3.702	3.740
23	3.686	3.693	3.730
24	3.682	3.689	3.725
25	3.681	3.688	3.724
26	3.682	3.689	3.725
28	3.690	3.697	3.734
30	3.709	3.717	3.754
32	3.734	3.742	3.780
34	3.770	3.779	3.818

Table 4--continued

COST TO STOP AND REGAIN INITIAL SPEED OF PASSENGER CARS ON PAVED LEVEL TANGENTS IN GOOD CONDITION. (Cost in cents per vehicle-stop additional to cost of operation per mile at initial speed)	
Initial Speed, mph	Cents Per Vehicle-stop
10	0.345
11	0.342
12	0.333
13	0.327
14	0.322
15	0.318
16	0.316
17	0.315
18	0.314
19	0.314
20	0.314
21	0.316
22	0.317
23	0.320
24	0.323
25	0.328
26	0.335
28	0.356
30	0.383
32	0.416
34	0.462

COST OF MOTOR-VEHICLE OPERATION WITH IDLING MOTOR FOR PASSENGER CARS	0.280 cents per vehicle-minute

The components of roadway costs, then, and the variables necessary for their determination were:

I. Operating costs

A. Running costs

1. running speed

2. nominal speed

3. grade

B. Stopping costs

4. stops per vehicle

C. Idling costs

5. idling time per stop

II. Accident costs

A. Accident rate

B. Cost per accident

III. A. Total speed

B. Value of occupants' time

STAGE 4--the measurement of the required variables necessitated a closer look at the variables themselves. Nominal speeds were easily attained from TATS traffic data of 1960, but running speeds were not. In conducting a travel time study of the roadway network, the TATS staff measured the total time, including stops and delays, that it took a test car to travel from the middle of one intersection to the next. A method derived by May and Wagner (1959) was used in this thesis to reduce these total travel times to running times. This method required values for total rate of travel in minutes per mile which was, as has been indicated, available from TATS. Grades were determined from the construction plans of Tucson roadways as furnished by the Engineering

Division of the Tucson Department of Public Works. Composite grades (the average of plus and minus grades) were measured and rounded to the nearest whole percent. The author felt that the roadway sections were not, necessarily, constructed to the exact design grades and that the desired accuracy of the CCI's did not warrant the usage of fractional grades.

The average number of stops per vehicle was assumed equal to one for running speeds. It was reasoned that some vehicles did not have to stop for a particular traffic signal while others had to stop once or more than once to clear the signalized intersection. Also, it was reasoned that the average vehicle did not have to stop for traffic entering or leaving the roadway section between intersections; therefore, since no data regarding stops for 1960 was available, one stop per vehicle seemed to be the logical choice. The lengths of the roadway sections were necessary to compute the idling time per stop.

The average number of stops per vehicle was assumed equal to zero for nominal speeds. This was assumed in light of the definition of nominal speed which pertained to travel in the absence of traffic interference. For a progressive signal system, a vehicle could, in the absence of traffic interference, travel at a constant speed such that it would never have to stop for a red signal. It should be mentioned that none of the roadway sections contained stop signs which, of course, would require every vehicle to stop.

Table 5 on pages 44, 45, 46 and 47 presents the values of operating cost variables for each of the ninety roadway sections. The travel time data was compiled from 4:00 p.m. to 6:00 p.m. for the weekdays of April and May, 1960. Negative composite grades were considered equal to zero for calculation purposes because no operating costs were available which included their effects.

The accident rates at running speeds were considered to be the existing accident rates as determined by TATS. TATS had researched the Tucson Police Department's accident record files, which included fatality, injury, and property damage accidents, for 1957 through 1960 and computed annual rates for the accidents which occurred on the intersection approaches and inside the intersections themselves. For the purposes of this thesis, the accidents which occurred inside the intersections were equally distributed among their respective approaches. The resulting accident rates for the running speeds of each roadway section are shown in Table 6 on pages 48, 49, 50 and 51. Table 6 also lists the total speeds which were necessary for the determination of travel time costs.

TABLE 5. VALUES OF OPERATING COST VARIABLES

Section Name (including direction of travel)	Total Rate of Travel (min./mile)	Nominal Speed (mile/hr.)	Positive Composite Grade (percent)	Section Length (miles)
Speedway-Stone				
1. west	2.44	30	0	0.18
2. east	5.31	30	1	0.36
3. north	2.55	30	0	0.29
4. south	3.07	30	0	0.24
Speedway-6th Ave.				
5. west	2.88	30	0	0.18
6. east	4.29	30	2	0.18
7. north	3.17	30	0	0.29
8. south	2.50	30	1	0.24
Speedway-Country Club				
9. west	2.63	30	0	0.35
10. east	3.55	30	0	0.50
11. north	2.43	30	0	0.50
12. south	3.31	30	1	0.50
Speedway-Jones				
13. west	2.32	30	0	0.65
14. east	2.83	30	0	0.35
Speedway-Craycroft				
15. east	2.11	30	0	1.00
16. north	3.09	30	0	0.50
17. south	2.19	30	1	0.50
3rd St.-Stone				
18. west	2.53	25	0	0.17
19. east	2.66	25	1	0.36
20. north	2.88	30	0	0.27
21. south	2.85	30	0	0.29
3rd St.-4th Ave.				
22. west	3.19	25	0	0.27
23. east	2.39	25	0	0.18
24. north	2.76	30	1	0.26
25. south	2.06	30	0	0.29

Table 5--Continued

Section Name (including direction of travel)	Total Rate of Travel (min./mile)	Nominal Speed (mile/hr.)	Positive Composite Grade (percent)	Section Length (miles)
6th St.-4th Ave.				
26. west	3.24	30	0	0.54
27. east	8.10	30	1	0.18
28. north	5.94	30	0	0.21
29. south	3.22	30	0	0.26
6th St.-Park Ave.				
30. west	2.83	30	0	0.48
31. east	2.37	30	1	0.54
32. north	2.45	30	1	0.26
33. south	4.22	30	0	0.26
5th St.-Country Club				
34. west	2.23	30	0	0.98
35. east	3.29	30	1	0.48
36. north	1.85	30	0	0.50
37. south	2.12	30	0	0.50
5th St.-Alvernon				
38. west	1.89	30	0	1.00
39. east	2.70	30	0	1.00
40. north	2.71	30	0	0.50
41. south	2.59	30	1	0.50
5th St.-Swan				
42. west	2.26	30	0	1.00
43. east	2.09	30	0	1.00
44. north	3.31	30	0	0.50
45. south	2.18	30	0	0.50
5th St.-Craycroft				
46. east	2.25	30	0	1.00
47. north	2.29	30	1	0.50
48. south	2.94	30	1	0.50

Table 5--Continued

Section Name (including direction of travel)	Total Rate of Travel (min./mile)	Nominal Speed (mile/hr.)	Positive Composite Grade (percent)	Section Length (miles)
Council-Stone				
49. west	8.13	15	0	0.11
50. east	7.27	15	1	0.14
51. north	8.21	30	0	0.05
52. south	2.88	30	0	0.18
Pennington-Stone				
53. east	10.16	15	0	0.07
54. north	8.33	30	1	0.07
55. south	6.00	30	0	0.10
Broadway-Scott				
56. west	9.09	15	0	0.06
57. east	5.66	15	1	0.08
Broadway-6th Ave.				
58. west	3.94	15	0	0.18
59. east	13.63	15	1	0.06
60. north	2.94	30	0	0.63
61. south	5.50	30	1	0.06
Broadway-4th Ave.				
62. west	3.40	30	0	0.54
63. east	5.12	15	1	0.18
64. north	2.89	30	0	0.63
65. south	6.52	30	1	0.08
Broadway-Campbell				
66. west	2.04	30	0	0.50
67. east	7.79	30	1	0.25
68. north	2.09	30	0	0.91
69. south	3.43	30	0	0.42
Broadway-Tucson				
70. west	1.94	30	0	0.50
71. east	3.46	30	1	0.50
72. north	2.37	30	0	1.00
73. south	3.10	30	0	0.44

Table 5--Continued

Section Name (including direction of travel)	Total Rate of Travel (min./mile)	Nominal Speed (mile/hr.)	Positive Composite Grade (percent)	Section Length (miles)
Broadway-Country Club				
74. west	1.93	30	0	1.00
75. east	4.16	30	1	0.50
76. north	2.07	30	0	1.00
77. south	2.64	30	0	0.50
Broadway-Swan				
78. west	2.05	30	0	1.00
79. east	2.07	30	0	1.00
80. north	2.21	30	0	1.00
81. south	2.73	30	1	0.50
Broadway-Craycroft				
82. east	1.59	30	0	1.00
83. north	2.23	30	0	1.00
84. south	2.00	30	0	0.50
22nd St.-Tucson				
85. west	2.29	30	0	0.50
86. east	2.84	30	0	0.38
87. south	2.18	30	0	1.00
22nd St.-Swan				
88. west	1.63	30	0	1.00
89. east	1.82	30	1	1.00
90. south	2.18	30	0	1.00

TABLE 6. RUNNING SPEED ACCIDENT RATES AND TOTAL SPEEDS

Section Name (including direction of travel)	Annual Accidents per 10,000,000 Vehicle-miles	Total Speed (miles/hr.)
Speedway-Stone		
1. west	53.0	24.5
2. east	75.5	11.3
3. north	50.0	23.5
4. south	81.6	19.5
Speedway-6th Ave.		
5. west	28.7	20.8
6. east	53.5	14.0
7. north	35.6	18.9
8. south	44.8	24.0
Speedway-Country Club		
9. west	102.7	22.8
10. east	53.7	16.9
11. north	43.3	24.6
12. south	28.5	18.1
Speedway-Jones		
13. west	58.2	25.8
14. east	104.1	21.2
Speedway-Craycroft		
15. east	83.6	28.7
16. north	16.0	19.4
17. south	5.3	27.3
3rd St.-Stone		
18. west	114.7	23.7
19. east	54.7	22.5
20. north	79.0	20.9
21. south	49.0	21.0
3rd St.-4th Ave.		
22. west	89.7	18.8
23. east	24.1	25.1
24. north	129.0	21.7
25. south	38.7	29.0

Table 6--Continued

Section Name (including direction of travel)	Annual Accidents per 10,000,000 Vehicle-miles	Total Speed (miles/hr.)
6th St.-4th Ave.		
26. west	42.3	18.5
27. east	148.6	7.4
28. north	127.0	10.1
29. south	129.7	18.6
6th St.-Park		
30. west	78.6	21.2
31. east	42.8	25.3
32. north	84.7	24.4
33. south	123.5	14.2
5th St.-Country Club		
34. west	24.8	28.3
35. east	69.4	18.2
36. north	50.4	32.3
37. south	41.4	28.3
5th St.-Alvernon		
38. west	36.8	31.6
39. east	26.4	24.2
40. north	41.5	22.1
41. south	38.9	23.1
5th St.-Swan		
42. west	33.1	27.2
43. east	35.7	29.0
44. north	43.8	18.1
45. south	25.9	27.5
5th St.-Craycroft		
46. east	32.2	27.2
47. north	12.2	26.1
48. south	16.2	20.4

Table 6--Continued

Section Name (including direction of travel)	Annual Accidents per 10,000,000 Vehicle-miles	Total Speed (miles/hr.)
Council-Stone		
49. west	822.1	12.5
50. east	145.3	9.5
51. north	97.5	6.5
52. south	65.6	20.5
Pennington-Stone		
53. east	299.0	5.8
54. north	192.2	7.0
55. south	178.9	11.2
Broadway-Scott		
56. west	147.2	6.0
57. east	282.5	10.6
Broadway-6th Ave.		
58. west	178.0	16.0
59. east	148.1	4.4
60. north	112.9	20.4
61. south	92.9	10.2
Broadway-4th Ave.		
62. west	171.1	17.6
63. east	177.0	11.7
64. north	74.2	20.7
65. south	29.0	12.2
Broadway-Campbell		
66. west	278.6	29.4
67. east	22.6	7.7
68. north	31.9	28.6
69. south	113.2	18.2
Broadway-Tucson		
70. west	64.2	30.9
71. east	279.4	17.3
72. north	42.1	25.3
73. south	59.0	19.3

Table 6--Continued

Section Name (including direction of travel)	Annual Accidents per 10,000,000 Vehicle-miles	Total Speed (miles/hr.)
Broadway-Country Club		
74. west	32.1	31.0
75. east	64.9	14.4
76. north	37.1	28.9
77. south	52.1	22.7
Broadway-Swan		
78. west	36.0	29.3
79. east	44.7	29.0
80. north	31.6	27.1
81. south	44.0	21.9
Broadway-Craycroft		
82. east	35.6	32.5
83. north	17.4	26.9
84. south	12.9	30.0
22nd St.-Tucson		
85. west	30.7	26.1
86. east	27.1	21.1
87. south	41.7	27.5
22nd St.-Swan		
88. west	18.9	36.7
89. east	48.2	33.4
90. south	31.4	27.5

The National Committee on Urban Transportation (1957) specified maximum annual fatality and personal injury accident rates that should not be exceeded on the various types of roadways. However, before these rates could be used as the accident rates for nominal speeds in this thesis, a determination of property damage accidents without injury or death was needed. The author consulted the Traffic Division of the Tucson Police Department and discovered that 26 percent of the total accidents for 1959 through 1962 involved deaths and personal injuries. This percentage was applied to the sum of the fatality and personal injury accident rates specified by the National Committee on Urban Transportation which resulted in the following accident rates at nominal speeds for the roadway sections of this thesis:

TABLE 7. NOMINAL SPEED ACCIDENT RATES

Nominal Speed--miles/hr.	Annual Accidents per 10,000,000 Vehicle-miles
30	49.6
25	28.1
15	5.0

The New York office of the National Bureau of Casualty Underwriters furnished average personal injury, death, and property damage costs per accident in Tucson for 1957 through 1960. The National Bureau had collected data on liability claims for about one-third of the private passenger cars in Tucson. The average accident cost for the four years was $1,160. The average accident cost as furnished by the Los Angeles office of Fireman's Fund American Insurance Companies for this same period of time was $1,032. The National Bureau's figure was selected for this thesis, however, because Fireman's Fund's figure represented the entire State of Arizona, and did not represent as many passenger cars.

The value of time per passenger car was derived by reducing the 1960 median family income of $5,690 (Tucson-Pima County Planning Department, 1964) for the Tucson Standard Metropolitan Statistical Area, to income per person per hour. This was done by considering 3.87 persons per family (Tucson-Pima County Planning Department, 1964) and 40 working hours per week. TATS stated the car occupancy rate to be 1.57 persons per vehicle in 1960, and this figure was applied to the income per person to yield $1.11 per passenger car per hour. The value of time used in the Chicago Area Transportation Study was $1.17 per automobile per hour (Haikalis and Hyman, 1961), and the American Association of State Highway Officials (1960) recommended a value of $1.35 per hour. The Association's value was derived from a car occupancy of 1.80, however.

Calculations

The following is an outline of the schedule followed in completing STAGE 5--the calculation of running speed costs, STAGE 6--the calculation of nominal speed costs, and STAGE 7--the calculation of congestion cost indexes.

I. Operating cost parabolas derived

A. Method

1. fitted "least squares" parabolas to McGraw-Hill operating costs

2. see Appendix A

B. Results--see Table 8 on page 59

II. Running speeds calculated

A. Method

1. $RT = \frac{TT}{0.132(TT) + 0.782}$, where

RT = running rate of travel (mile/min.)

TT = total rate of travel (min./mile)

2. $RS = \frac{60 \text{ min./hr.}}{RT}$

B. Results--see Table 9 on pages 60, 61, 62 and 63

III. Vehicle operating costs calculated

A. Method

1. CVS obtained from appropriate operating cost parabola

2. D = AL(TT - RT), where

D = idling time per stop (minutes)

AL = length of roadway section (miles)

3. CVMIN = D(0.280 cents/veh.-min.), where

CVMIN = idling cost (cents/vehicle)

4. RCVMR obtained from appropriate operating cost parabola, where

RCVMR = running cost on level tangents at running speed

5. RCVMN obtained from appropriate operating cost parabola, where

   RCVMN = running cost on level tangents at nominal speed

6. GCVMR obtained from appropriate operating cost parabola, where

   GCVMR = running cost on composite grade at running speed

7. GCMRO obtained from operating cost parabola for grade = 0% at running speed

8. DGCMR = GCVMR - GCMRO, where

   DGCMR = incremental running cost of non-level tangent at running speed

9. GCVMN obtained from appropriate operating cost parabola, where

   GCVMN = running cost on composite grade at nominal speed

10. GCMNO obtained from operating cost parabola for grade = 0% at nominal speed

11. DGCMN = incremental running cost of non-level tangent at nominal speed

12. OCVMR = CVS + CVMIN + RCVMR + DGCMR, where

    OCVMR = vehicle operating costs at running speed (cents/veh.-mile)

13. OCVMN = RCVMN + DGCMN, where

OCVMN = vehicle operating costs at nominal speed (cents/veh.-mile)

B. Results--see Table 9 on pages 60, 61, 62 and 63

IV. Accident costs calculated

A. Method

1. ACVMR = AVMRS (116,000 cents/accident), where

ACVMR = accident costs at running speed (cents/veh.-mile)

AVMRS = accident rate at running speed (accidents/veh.-mile)

2. ACVMN = AVMNS (116,000 cents/accident), where

ACVMN = accident costs at nominal speed (cents/veh.-mile)

AVMNS = accident rate at nominal speed (accidents/veh.-mile)

B. Results--see Table 10 on pages 64, 65, 66 and 67

V. Time Costs Calculated

A. Method

1. $TCVMR = \frac{111.50 \text{ cents/veh.-hour}}{TS}$, where

TCVMR = time costs at running speed (cents/veh.-mile)

TS = total speed (mile/hr.)

2. $TCVMN = \frac{111.50 \text{ cents/veh.-hour)}}{NOMSP}$, where

TCVMN = time costs at nominal speed (cents/veh.-mile)

NOMSP = nominal speed (mile/hr.)

B. Results--see Table 11 on pages 68, 69, 70 and 71

VI. Roadway Costs Calculated

A. Method

1. CVMRS = OCVMR + ACVMR + TCVMR

2. CVMNS = OCVMN + ACVMN + TCVMN

B. Results--see Table 12 on pages 72, 73, 74 and 75

VII. Congestion Costs Calculated

A. Method

$$CCI = \frac{CVMRS}{CVMNS}$$

B. Results--see Table 12 on pages 72, 73, 74 and 75

This schedule was developed into a FORTRAN program (see Appendix B), and the calculations were made on an IBM 7094 Computer. The McGraw-Hill operating costs had to be fitted to curves, then, because computers work with mathematical equations, not tables. The cost tables were plotted as graphs of cents per vehicle-mile vs. running speed, and the resulting curves were easily identified as parabolas with costs decreasing to a certain speed (for instance, 25 miles/hr. for running costs on composite grades) then increasing with increasing speeds.

The formula used to reduce total rates of travel to running rates of travel was adopted from an empirical study made by May and Wagner (1959). This same method was used by the Chicago Area Transportation Study and TATS.

Since no stops were assumed for travel at nominal speed, this speed was, in effect, a running speed and its use in the operating cost parabolas was valid. Also, it was necessary to compute incremental grade costs and add them to the running costs on level tangents because the composite grade tables were not grouped under specified nominal speeds. It was assumed that the additional costs due to grades at certain speeds would be the same for any nominal speed.

The results of the congestion cost index calculations indicated only two of the 90 roadway sections to have CCI values less than 1.00 (Broadway-Craycroft southbound and 22nd St.-Swan westbound); a value of 1.00 indicates the beginning of traffic congestion.

In Chapter V, these roadway sections are analyzed by two other indexes, and the validity and usefulness of CCI is discussed.

Appendix C contains a sample calculation of CCI, without the use of a computer, for a given intersection.

TABLE 8. McGRAW-HILL OPERATING COST PARABOLAS

General Equation:

$$CVM(\text{or } CVS) = A + B(RS) + C(RS)^2, \text{ where}$$

CVM = cents per vehicle-mile
CVS = cents per vehicle-stop
RS = running speed (miles/hr.)
A, B and C = derived coefficients

	A	B	C
Running Cost on Level Tangents:			
nominal speed = 15 MPH	8.398	-0.566	0.018
nominal speed = 25 MPH	8.512	-0.345	0.006
nominal speed = 30 MPH	7.855	-0.256	0.004
Running Cost on Composite Grades:			
grade = 0%	4.801	-0.089	0.002
grade = 1%	4.838	-0.091	0.002
grade = 2%	4.919	-0.095	0.002
Cost to Stop and Regain Initial Speed	0.458	-0.015	0.000

TABLE 9. OPERATING COSTS

Section Name (including direction of travel)	Running Speed (miles/hr.)	Operating Cost at Running Speed	Operating Cost at Nominal Speed
Speedway-Stone			
1. west	27.1	4.150	3.707
2. east	16.8	5.165	3.715
3. north	26.3	4.193	3.707
4. south	23.2	4.380	3.707
Speedway-6th Ave.			
5. west	24.2	4.302	3.707
6. east	18.9	4.839	3.752
7. north	22.7	4.426	3.707
8. south	26.7	4.180	3.715
Speedway-Country Club			
9. west	25.8	4.226	3.707
10. east	21.1	4.611	3.707
11. north	27.2	4.168	3.707
12. south	22.1	4.522	3.715
Speedway-Jones			
13. west	28.1	4.142	3.707
14. east	24.5	4.302	3.707
Speedway-Craycroft			
15. east	30.2	4.104	3.707
16. north	23.1	4.424	3.707
17. south	29.1	4.109	3.715
3rd St.-Stone			
18. west	26.5	3.977	3.676
19. east	25.6	4.025	3.683
20. north	24.2	4.312	3.707
21. south	24.4	4.303	3.707
3rd St.-4th Ave.			
22. west	22.6	4.170	3.676
23. east	27.6	3.964	3.676
24. north	24.9	4.273	3.715
25. south	30.7	4.075	3.707

Table 9--Continued

Section Name (including direction of travel)	Running Speed (miles/hr.)	Operating Cost at Running Speed	Operating Cost at Nominal Speed
6th St.-4th Ave.			
26. west	22.4	4.492	3.707
27. east	13.7	5.606	3.715
28. north	15.8	5.229	3.707
29. south	22.5	4.440	3.707
6th St.-Park			
30. west	24.5	4.315	3.707
31. east	27.7	4.158	3.715
32. north	27.1	4.166	3.715
33. south	19.0	4.793	3.707
5th St.-Country Club			
34. west	29.1	4.129	3.707
35. east	22.2	4.510	3.715
36. north	33.3	4.089	3.707
37. south	30.1	4.089	3.707
5th St.-Alvernon			
38. west	32.6	4.090	3.707
39. east	25.3	4.312	3.707
40. north	25.2	4.270	3.707
41. south	26.0	4.231	3.715
5th St.-Swan			
42. west	27.1	4.203	3.707
43. east	30.4	4.100	3.707
44. north	22.1	4.514	3.707
45. south	29.4	4.099	3.707
5th St.-Craycroft			
46. east	28.8	4.146	3.715
47. north	28.4	4.126	3.707
48. south	23.9	4.369	3.715

Table 9--Continued

Section Name (including direction of travel)	Running Speed (miles/hr.)	Operating Cost at Running Speed	Operating Cost at Nominal Speed
Council-Stone			
49. west	13.7	4.399	3.883
50. east	14.4	4.368	3.896
51. north	13.6	5.470	3.707
52. south	24.2	4.302	3.707
Pennington-Stone			
53. east	12.5	4.528	3.896
54. north	13.6	5.505	3.707
55. south	15.7	5.174	3.707
Broadway-Scott			
56. west	13.1	4.419	3.883
57. east	16.2	4.237	3.896
Broadway-6th Ave.			
58. west	19.8	4.483	3.883
59. east	11.4	4.740	3.896
60. north	23.9	4.378	3.707
61. south	16.5	5.061	3.715
Broadway-4th Ave.			
62. west	21.7	4.558	3.707
63. east	17.1	4.291	3.896
64. north	24.2	4.357	3.707
65. south	15.1	5.268	3.715
Broadway-Campbell			
66. west	30.9	4.079	3.707
67. east	13.9	5.627	3.715
68. north	30.4	4.098	3.707
69. south	21.6	4.548	3.707
Broadway-Tucson			
70. west	32.1	4.078	3.707
71. east	21.5	4.583	3.715
72. north	27.7	4.177	3.707
73. south	23.1	4.420	3.707

Table 9--Continued

Section Name (including direction of travel)	Running Speed (miles/hr.)	Operating Cost at Running Speed	Operating Cost at Nominal Speed
Broadway-Country Club			
74. west	32.2	4.088	3.707
75. east	19.2	4.852	3.715
76. north	30.6	4.097	3.707
77. south	25.7	4.243	3.707
Broadway-Swan			
78. west	30.8	4.095	3.707
79. east	30.6	4.097	3.707
80. north	29.2	4.127	3.707
81. south	25.1	4.285	3.715
Broadway-Craycroft			
82. east	37.2	4.217	3.707
83. north	29.0	4.132	3.707
84. south	31.4	4.077	3.707
22nd St.-Tucson			
85. west	28.4	4.126	3.707
86. east	24.4	4.309	3.707
87. south	29.4	4.119	3.707
22nd St.-Swan			
88. west	36.7	4.192	3.707
89. east	33.7	4.111	3.715
90. south	29.4	4.119	3.707

TABLE 10. ACCIDENT COSTS
(cents/veh.-mile)

Section Name (including direction of travel)	Accident Cost at Running Speed	Accident Cost at Nominal Speed
Speedway-Stone		
1. west	0.615	0.575
2. east	0.875	0.575
3. north	0.580	0.575
4. south	0.947	0.575
Speedway-6th Ave.		
5. west	0.333	0.575
6. east	0.621	0.575
7. north	0.413	0.575
8. south	0.520	0.575
Speedway-Country Club		
9. west	1.191	0.575
10. east	0.623	0.575
11. north	0.502	0.575
12. south	0.331	0.575
Speedway-Jones		
13. west	0.675	0.575
14. east	1.208	0.575
Speedway-Craycroft		
15. east	0.970	0.575
16. north	0.186	0.575
17. south	0.062	0.575
3rd St.-Stone		
18. west	1.331	0.326
19. east	0.635	0.326
20. north	0.916	0.575
21. south	0.568	0.575
3rd St.-4th Ave.		
22. west	1.041	0.326
23. east	0.280	0.326
24. north	1.496	0.575
25. south	0.449	0.575

Table 10--Continued

Section Name (including direction of travel)	Accident Cost at Running Speed	Accident Cost at Nominal Speed
6th St.-4th Ave.		
26. west	0.491	0.575
27. east	1.724	0.575
28. north	1.473	0.575
29. south	1.505	0.575
6th St.-Park		
30. west	0.912	0.575
31. east	0.497	0.575
32. north	0.982	0.575
33. south	1.433	0.575
5th St.-Country Club		
34. west	0.288	0.575
35. east	0.805	0.575
36. north	0.585	0.575
37. south	0.480	0.575
5th St.-Alvernon		
38. west	0.427	0.575
39. east	0.306	0.575
40. north	0.481	0.575
41. south	0.451	0.575
5th St.-Swan		
42. west	0.384	0.575
43. east	0.414	0.575
44. north	0.508	0.575
45. south	0.300	0.575
5th St.-Craycroft		
46. east	0.374	0.575
47. north	0.142	0.575
48. south	0.188	0.575

Table 10--Continued

Section Name (including direction of travel)	Accident Cost at Running Speed	Accident Cost at Nominal Speed
Council-Stone		
49. west	9.536	0.058
50. east	1.686	0.058
51. north	1.131	0.575
52. south	0.761	0.575
Pennington-Stone		
53. east	3.468	0.058
54. north	2.230	0.575
55. south	2.075	0.575
Broadway-Scott		
56. west	1.708	0.058
57. east	3.277	0.058
Broadway-6th Ave.		
58. west	2.065	0.058
59. east	1.718	0.058
60. north	1.310	0.575
61. south	1.078	0.575
Broadway-4th Ave.		
62. west	1.985	0.575
63. east	2.053	0.058
64. north	0.861	0.575
65. south	0.336	0.575
Broadway-Campbell		
66. west	3.232	0.575
67. east	0.262	0.575
68. north	0.370	0.575
69. south	1.313	0.575
Broadway-Tucson		
70. west	0.745	0.575
71. east	3.241	0.575
72. north	0.488	0.575
73. south	0.684	0.575

Table 10--Continued

Section Name (including direction of travel)	Accident Cost at Running Speed	Accident Cost at Nominal Speed
Broadway-Country Club		
74. west	0.372	0.575
75. east	0.753	0.575
76. north	0.430	0.575
77. south	0.604	0.575
Broadway-Swan		
78. west	0.418	0.575
79. east	0.519	0.575
80. north	0.367	0.575
81. south	0.510	0.575
Broadway-Craycroft		
82. east	0.413	0.575
83. north	0.202	0.575
84. south	0.150	0.575
22nd St.-Tucson		
85. west	0.356	0.575
86. east	0.314	0.575
87. south	0.484	0.575
22nd St.-Swan		
88. west	0.219	0.575
89. east	0.559	0.575
90. south	0.364	0.575

TABLE 11. TIME COSTS
(cents/veh.-mile)

Section Name (including direction of travel)	Time Cost at Running Speed	Time Cost at Nominal Speed
Speedway-Stone		
1. west	4.551	3.717
2. east	9.867	3.717
3. north	4.745	3.717
4. south	5.718	3.717
Speedway-6th Ave.		
5. west	5.361	3.717
6. east	7.964	3.717
7. north	5.900	3.717
8. south	4.646	3.717
Speedway-Country Club		
9. west	4.890	3.717
10. east	6.598	3.717
11. north	4.533	3.717
12. south	6.160	3.717
Speedway-Jones		
13. west	4.322	3.717
14. east	5.259	3.717
Speedway-Craycroft		
15. east	3.885	3.717
16. north	5.747	3.717
17. south	4.084	3.717
3rd St.-Stone		
18. west	4.705	4.460
19. east	4.956	4.460
20. north	5.335	3.717
21. south	5.310	3.717
3rd St.-4th Ave.		
22. west	5.931	4.460
23. east	4.442	4.460
24. north	5.138	3.717
25. south	3.845	3.717

Table 11--Continued

Section Name (including direction of travel)	Time Cost at Running Speed	Time Cost at Nominal Speed
6th St.-4th Ave.		
26. west	6.027	3.717
27. east	15.068	3.717
28. north	11.040	3.717
29. south	5.995	3.717
6th St.-Park		
30. west	5.259	3.717
31. east	4.407	3.717
32. north	4.570	3.717
33. south	7.852	3.717
5th St.-Country Club		
34. west	3.940	3.717
35. east	6.126	3.717
36. north	3.452	3.717
37. south	3.940	3.717
5th St.-Alvernon		
38. west	3.529	3.717
39. east	4.607	3.717
40. north	5.045	3.717
41. south	4.827	3.717
5th St.-Swan		
42. west	4.099	3.717
43. east	3.845	3.717
44. north	6.160	3.717
45. south	4.055	3.717
5th St.-Craycroft		
46. east	4.099	3.717
47. north	4.272	3.717
48. south	5.466	3.717

Table 11--Continued

Section Name (including direction of travel)	Time Cost at Running Speed	Time Cost at Nominal Speed
Council-Stone		
49. west	8.920	7.433
50. east	11.737	7.433
51. north	17.154	3.717
52. south	5.439	3.717
Pennington-Stone		
53. east	19.224	7.433
54. north	15.929	3.717
55. south	9.955	3.717
Broadway-Scott		
56. west	18.583	7.433
57. east	10.519	7.433
Broadway-6th Ave.		
58. west	6.969	7.433
59. east	25.341	7.433
60. north	5.466	3.717
61. south	10.931	3.717
Broadway-4th Ave.		
62. west	6.335	3.717
63. east	9.530	7.433
64. north	5.387	3.717
65. south	9.139	3.717
Broadway-Campbell		
66. west	3.793	3.717
67. east	14.481	3.717
68. north	3.899	3.717
69. south	6.126	3.717
Broadway-Tucson		
70. west	3.608	3.717
71. east	6.445	3.717
72. north	4.407	3.717
73. south	5.777	3.717

Table 11--Continued

Section Name (including direction of travel)	Time Cost at Running Speed	Time Cost at Nominal Speed
Broadway-Country Club		
74. west	3.597	3.717
75. east	7.743	3.717
76. north	3.858	3.717
77. south	4.912	3.717
Broadway-Swan		
78. west	3.806	3.717
79. east	3.845	3.717
80. north	4.114	3.717
81. south	5.091	3.717
Broadway-Craycroft		
82. east	3.431	3.717
83. north	4.145	3.717
84. south	3.717	3.717
22nd St.-Tucson		
85. west	4.272	3.717
86. east	5.284	3.717
87. south	4.055	3.717
22nd St.-Swan		
88. west	3.038	3.717
89. east	3.328	3.717
90. south	4.055	3.717

TABLE 12. CONGESTION COST INDEXES

Section Name (including direction of travel)	Roadway Costs at Running Speed (cents/veh.-mile)	Roadway Costs at Nominal Speed (cents/veh.-mile)	Congestion Cost Index
Speedway-Stone			
1. west	9.316	7.999	1.16
2. east	15.908	8.007	1.99
3. north	9.518	7.999	1.19
4. south	11.045	7.999	1.38
Speedway-6th Ave.			
5. west	9.995	7.999	1.25
6. east	13.424	8.044	1.67
7. north	10.738	7.999	1.34
8. south	9.346	8.007	1.17
Speedway-Country Club			
9. west	10.308	7.999	1.29
10. east	11.831	7.999	1.48
11. north	9.203	7.999	1.15
12. south	11.012	8.007	1.38
Speedway-Jones			
13. west	9.139	7.999	1.14
14. east	10.769	7.999	1.35
Speedway-Craycroft			
15. east	8.959	7.999	1.12
16. north	10.357	7.999	1.29
17. south	8.255	8.007	1.03
3rd St.-Stone			
18. west	10.013	8.462	1.18
19. east	9.615	8.469	1.14
20. north	10.563	7.999	1.32
21. south	10.181	7.999	1.27
3rd St.-4th Ave.			
22. west	11.141	8.462	1.32
23. east	8.686	8.462	1.03
24. north	10.908	8.007	1.36
25. south	8.369	7.999	1.05

Table 12--Continued

Section Name (including direction of travel)	Roadway Costs at Running Speed (cents/veh.-mile)	Roadway Costs at Nominal Speed (cents/veh.-mile)	Congestion Cost Index
6th St.-4th Ave.			
26. west	11.009	7.999	1.38
27. east	22.397	8.007	2.80
28. north	17.741	7.999	2.22
29. south	11.939	7.999	1.49
6th St.-Park			
30. west	10.487	7.999	1.31
31. east	9.062	8.007	1.13
32. north	9.718	8.007	1.21
33. south	14.078	7.999	1.76
5th St.-Country Club			
34. west	8.356	7.999	1.04
35. east	11.442	8.007	1.43
36. north	8.126	7.999	1.02
37. south	8.509	7.999	1.06
5th St.-Alvernon			
38. west	8.045	7.999	1.01
39. east	9.226	7.999	1.15
40. north	9.797	7.999	1.22
41. south	9.509	8.007	1.19
5th St.-Swan			
42. west	8.686	7.999	1.09
43. east	8.359	7.999	1.05
44. north	11.182	7.999	1.40
45. south	8.454	7.999	1.06
5th St.-Craycroft			
46. east	8.618	8.007	1.08
47. north	8.539	7.999	1.07
48. south	10.023	8.007	1.25

Table 12--Continued

Section Name (including direction of travel)	Roadway Costs at Running Speed (cents/veh.-mile)	Roadway Costs at Nominal Speed (cents/veh.-mile)	Congestion Cost Index
Council-Stone			
49. west	22.855	11.375	2.01
50. east	17.791	11.387	1.56
51. north	23.755	7.999	2.97
52. south	10.502	7.999	1.31
Pennington-Stone			
53. east	27.221	11.387	2.39
54. north	23.664	7.999	2.96
55. south	17.205	7.999	2.15
Broadway-Scott			
56. west	24.710	11.375	2.17
57. east	18.033	11.387	1.58
Broadway-6th Ave.			
58. west	13.516	11.375	1.19
59. east	31.799	11.387	2.79
60. north	11.153	7.999	1.39
61. south	17.070	8.007	2.13
Broadway-4th Ave.			
62. west	12.878	7.999	1.61
63. east	15.875	11.387	1.39
64. north	10.604	7.999	1.33
65. south	14.744	8.007	1.84
Broadway-Campbell			
66. west	11.104	7.999	1.39
67. east	20.370	8.007	2.54
68. north	8.366	7.999	1.05
69. south	11.988	7.999	1.50
Broadway-Tucson			
70. west	8.431	7.999	1.05
71. east	14.269	8.007	1.78
72. north	9.073	7.999	1.13
73. south	10.881	7.999	1.36

Table 12--Continued

Section Name (including direction of travel)	Roadway Costs at Running Speed (cents/veh.-mile)	Roadway Costs at Nominal Speed (cents/veh.-mile)	Congestion Cost Index
Broadway-Country Club			
74. west	8.057	7.999	1.01
75. east	13.348	8.007	1.67
76. north	8.386	7.999	1.05
77. south	9.759	7.999	1.22
Broadway-Swan			
78. west	8.318	7.999	1.04
79. east	8.461	7.999	1.06
80. north	8.608	7.999	1.08
81. south	9.886	8.007	1.23
Broadway-Craycroft			
82. east	8.061	7.999	1.01
83. north	8.479	7.999	1.06
84. south	7.944	7.999	0.99
22nd St.-Tucson			
85. west	8.754	7.999	1.09
86. east	9.907	7.999	1.24
87. south	8.658	7.999	1.08
22nd St.-Swan			
88. west	7.449	7.999	0.93
89. east	7.999	8.007	1.00
90. south	8.538	7.999	1.07

Chapter V

A COMPARISON OF PRIORITY SCHEDULES

No data was available to employ the freedom-of-movement concept of congestion indexes. However, TATS had sufficient data to allow the calculations of Hall and George's (1959) "vehicle minutes of delay" indicator (operational-characteristics concept) and Rothrock's "volume to capacity" index (volume to capacity concept).

Vehicle Minutes of Delay

These calculations were made according to the formula:

VMD = PHV(TT - ST), where

VMD = vehicle minutes of delay (veh.-min./hour-mile)

PHV = peak hourly volume (veh./hour)

TT = total rate of travel (min./mile)

ST = standard rate of travel (min./mile)

The standard rates of travel are shown below and were determined by converting nominal speed to miles per minute and taking its reciprocal:

Nominal Speed	Standard Rate of Travel
30	2.0
25	2.4
15	4.0

The values for total rates of travel have already been listed in Table 5. The peak hourly volumes are shown with delay rates (TT - ST) in Table 13 on pages 78, 79, 80 and 81; the vehicle minutes of delay for each roadway section are also shown.

Volume to Capacity Index

These calculations were made according to the formula:

$$VCI = \frac{PHV}{PHPC}, \text{ where}$$

VCI = volume to capacity index

PHPC = peak hour practical capacity (veh./hr.)

Values for PHPC were determined by TATS according to the Highway Capacity Manual "Design Capacity Charts for Signalized Street and Highway Intersections" and Highway Research Board Circular 376. The Highway Research Board (1950) defined the practical capacity of an intersection approach as "the maximum volume that can enter the intersection from that approach during 1 hour with most of the drivers being able to clear the intersection without waiting for more than one complete signal cycle."

The peak hourly practical capacity and volume to capacity indexes for each roadway section are listed in Table 14 on pages 82, 83, 84 and 85.

Priority Schedules

In priority schedules of improvement, the most congested roadway section is listed first, the second most congested section is listed second, etc. Priority schedules were prepared according to the results of the three congestion indexes of this thesis. Only those sections which were congested were included in the schedules; a value of 1.00 or greater indicated congestion for the congestion cost index

TABLE 13. VEHICLE MINUTES OF DELAY

Section Name (including direction of travel)	Peak Hourly Volume	Delay (min./mi.)	Vehicle Minutes of Delay per hour-mile
Speedway-Stone			
1. west	611	0.44	269
2. east	532	3.31	1761
3. north	1102	0.55	606
4. south	605	1.07	647
Speedway-6th Ave.			
5. west	697	0.88	613
6. east	723	2.29	1656
7. north	670	1.17	784
8. south	266	0.50	133
Speedway-Country Club			
9. west	948	0.63	597
10. east	1453	1.55	2252
11. north	826	0.43	355
12. south	434	1.31	569
Speedway-Jones			
13. west	846	0.32	271
14. east	1251	0.83	1038
Speedway-Craycroft			
15. east	740	0.22	163
16. north	407	1.09	444
17. south	209	0.19	40
3rd St.-Stone			
18. west	185	0.13	24
19. east	168	0.26	44
20. north	1121	1.76	1973
21. south	581	0.85	494
3rd St.-4th Ave.			
22. west	208	0.79	164
23. east	326	0.00	0
24. north	524	0.76	398
25. south	221	0.06	13

Table 13--Continued

Section Name (including direction of travel)	Peak Hourly Volume	Delay (min./mi.)	Vehicle Minutes of Delay per hour-mile
6th St.-4th Ave.			
26. west	399	1.24	495
27. east	750	6.10	4575
28. north	495	3.94	1950
29. south	396	1.22	483
6th St.-Park			
30. west	565	0.83	469
31. east	785	0.37	290
32. north	537	0.45	242
33. south	500	2.22	1110
5th St.-Country Club			
34. west	402	0.45	181
35. east	751	1.29	969
36. north	640	0.00	0
37. south	535	0.12	64
5th-Alvernon			
38. west	329	0.00	0
39. east	645	1.41	909
40. north	597	0.71	424
41. south	493	0.59	291
5th St.-Swan			
42. west	283	0.53	150
43. east	431	0.17	73
44. north	542	1.31	710
45. south	460	0.18	83
5th St.-Craycroft			
46. east	304	0.50	152
47. north	489	0.29	142
48. south	408	0.94	384

Table 13--Continued

Section Name (including direction of travel)	Peak Hourly Volume	Delay (min./mi.)	Vehicle Minutes of Delay per hour-mile
Council-Stone			
49. west	48	8.25	396
50. east	383	6.55	2509
51. north	636	6.21	3950
52. south	475	0.88	418
Pennington-Stone			
53. east	692	6.16	4263
54. north	453	6.33	2867
55. south	526	4.00	2104
Broadway-Scott			
56. west	367	5.09	1868
57. east	457	1.66	759
Broadway-6th Ave.			
58. west	425	0.00	0
59. east	648	9.63	6240
60. north	381	0.95	362
61. south	404	3.50	1414
Broadway-4th Ave.			
62. west	464	1.40	650
63. east	915	1.12	1025
64. north	550	0.89	490
65. south	349	4.52	1577
Broadway-Campbell			
66. west	804	0.04	32
67. east	1300	5.79	7527
68. north	497	0.09	45
69. south	441	2.86	1261
Broadway-Tucson			
70. west	825	0.00	0
71. east	1561	1.46	2279
72. north	433	0.37	160
73. south	384	1.10	422

Table 13--Continued

Section Name (including direction of travel)	Peak Hourly Volume	Delay (min./mi.)	Vehicle Minutes of Delay per hour-mile
Broadway-Country Club			
74. west	837	0.00	0
75. east	1398	2.16	3020
76. north	491	0.07	34
77. south	601	0.64	385
Broadway-Swan			
78. west	776	0.10	78
79. east	1308	0.14	183
80. north	561	0.21	118
81. south	476	0.73	347
Broadway-Craycroft			
82. east	1208	0.00	0
83. north	647	0.23	149
84. south	442	0.00	0
22nd St.-Tucson			
85. west	787	0.29	228
86. east	1185	0.84	995
87. south	345	0.18	62
22nd St.-Swan			
88. west	779	0.00	0
89. east	940	0.00	0
90. south	366	0.18	66

TABLE 14. VOLUME TO CAPACITY INDEXES

Section Name (including direction of travel)	Peak Hourly Volume	Practical Capacity	Volume to Capacity Index
Speedway-Stone			
1. west	611	674	0.91
2. east	532	564	0.94
3. north	1102	885	1.25
4. south	605	755	0.80
Speedway-6th Ave.			
5. west	697	973	0.72
6. east	723	1040	0.69
7. north	670	435	1.54
8. south	266	410	0.65
Speedway-Country Club			
9. west	948	976	0.97
10. east	1453	956	1.52
11. north	826	520	1.59
12. south	434	648	0.67
Speedway-Jones			
13. west	846	1510	0.56
14. east	1251	1515	0.83
Speedway-Craycroft			
15. east	740	1146	0.65
16. north	407	267	1.53
17. south	209	262	0.80
3rd St.-Stone			
18. west	185	278	0.67
19. east	168	290	0.58
20. north	1121	931	1.21
21. south	581	901	0.59
3rd St.-4th Ave.			
22. west	208	314	0.66
23. east	326	375	0.87
24. north	524	846	0.75
25. south	221	809	0.27

Table 14--Continued

Section Name (including direction of travel)	Peak Hourly Volume	Practical Capacity	Volume to Capacity Index
6th St.-4th Ave.			
26. west	399	568	0.70
27. east	750	628	1.19
28. north	495	532	0.93
29. south	396	532	0.74
6th St.-Park			
30. west	565	616	0.92
31. east	785	770	1.02
32. north	537	633	0.85
33. south	500	465	1.08
5th St.-Country Club			
34. west	402	1026	0.39
35. east	751	810	0.93
36. north	640	848	0.75
37. south	535	450	1.19
5th-Alvernon			
38. west	329	218	1.51
39. east	645	275	2.34
40. north	597	331	1.81
41. south	493	350	1.41
5th St.-Swan			
42. west	283	238	1.19
43. east	431	275	1.57
44. north	542	369	1.48
45. south	460	425	1.08
5th St.-Craycroft			
46. east	304	366	0.83
47. north	489	313	1.56
48. south	408	404	1.01

Table 14--Continued

Section Name (including direction of travel)	Peak Hourly Volume	Practical Capacity	Volume to Capacity Index
Council-Stone			
49. west	48	97	0.49
50. east	383	242	1.55
51. north	636	454	1.52
52. south	475	421	1.22
Pennington-Stone			
53. east	692	572	1.21
54. north	453	508	0.89
55. south	526	354	1.49
Broadway-Scott			
56. west	367	335	1.10
57. east	457	478	0.96
Broadway-6th Ave.			
58. west	425	313	1.36
59. east	648	367	1.78
60. north	381	302	1.27
61. south	404	300	1.35
Broadway-4th Ave.			
62. west	464	1110	0.42
63. east	915	626	1.46
64. north	550	693	0.79
65. south	349	443	0.79
Broadway-Campbell			
66. west	804	1228	0.66
67. east	1300	1108	1.17
68. north	497	364	1.10
69. south	441	450	1.21
Broadway-Tucson			
70. west	825	1395	0.59
71. east	1561	1495	1.05
72. north	433	286	1.51
73. south	384	433	0.89

Table 14--Continued

Section Name (including direction of travel)	Peak Hourly Volume	Practical Capacity	Volume to Capacity Index
Broadway-Country Club			
74. west	837	995	0.84
75. east	1398	1089	1.19
76. north	491	727	0.68
77. south	601	622	0.97
Broadway-Swan			
78. west	776	1572	0.49
79. east	1308	1614	0.81
80. north	561	1376	0.41
81. south	476	1330	0.36
Broadway-Craycroft			
82. east	1208	1592	0.76
83. north	647	1248	0.52
84. south	442	1240	0.36
22nd St.-Tucson			
85. west	787	956	0.82
86. east	1185	138	1.04
87. south	345	460	0.75
22nd St.-Swan			
88. west	779	659	1.18
89. east	940	867	1.08
90. south	366	200	1.83

and the volume to capacity index, and a value greater than zero indicated congestion for the vehicle minutes of delay index. The priority schedules are shown in Table 15 on pages 89, 90 and 91; the numbers listed with the roadway sections in the previous tables are used in Table 15 for section identification.

Some incompatible results of the priority schedules are:

1. Eighty-eight sections are congested according to the congestion cost index, 80 are congested according to the vehicle minutes of delay index, and 41 are congested according to the volume to capacity index.
2. The priority schedules are not the same.
3. Council-Stone north, the most congested roadway section according to the congestion cost index, is ranked fifth according to the vehicle minutes of delay index and twelfth according to the volume to capacity index.
4. Broadway-Campbell east, the most congested roadway section according to the vehicle minutes of delay index, is ranked fifth according to the congestion cost index and thirty-second according to the volume to capacity index.
5. 5th-Alvernon east, the most congested roadway section according to the volume to capacity index, is ranked fifty-seventh according to the congestion cost index and twenty-fifth according to the vehicle minutes of delay index.

The 15 worst sections according to each index are presented by name in Table 16 on page 92. Regarding this table, 11 of the roadway sections ranked by the congestion cost index are common to the vehicle minutes of delay index, and only three are common to the volume to capacity index. Of the 15 roadway sections ranked by the vehicle minutes of delay index, only 5 are common to the volume to capacity index. Thus, the priority schedules according to the first two indexes are somewhat related, while the priority schedule of the volume to capacity index bears little relation to the others.

Conclusions

Based upon the results of this thesis regarding travel during the evening peak hour on 90 selected roadway sections of Tucson in 1960, the following conclusions are reached:

1. Priority schedules of improvement determined by a congestion cost index, a vehicle minutes of delay index, and a volume to capacity index bear almost no resemblance to each other.
2. Excess travel time is not directly related to excess (greater than practical capacity) traffic volume. This conclusion is based upon the unrelated orders of the vehicle minutes of delay and volume to capacity schedules.

3. Vehicle delay exists on roadway sections even when the traffic volume is less than the practical capacity.
   The vehicle minutes of delay index indicated 49 more congested roadway sections than the volume to capacity index.
4. The variation in the congestion cost schedule and the vehicle minutes of delay schedule is due to operating costs and accident costs.
   Accident and operating costs varied from 12 to 32 percent of the excess roadway costs for 13 of the 15 sections listed in Table 16 under the congestion cost index (note the dominance of time costs). For two of these sections, Council-Stone WB and Broadway-Tucson EB, accident costs amounted to 83 and 42 percent respectively.
5. The volume to capacity index does not fully account for vehicle delay, and the vehicle minutes of delay index does not account for excess operating costs and accident costs.
6. The cost of driving a passenger car varies from eight to twenty-seven cents per mile.

TABLE 15. PRIORITY SCHEDULES

Congestion Cost Index	Vehicle Minutes of Delay	Volume to Capacity Index
roadway section # 51	# 67	# 39
54	59	90
27	27	40
59	53	59
67	51	11
53	75	43
28	54	47
56	50	50
55	71	7
61	10	16
49	55	10
2	20	51
65	28	38
71	56	72
33	2	55
6	6	44
75	65	63
62	61	41
57	69	58
50	33	61
69	14	60
29	63	3
10	86	52
35	35	20
44	39	53
60	7	69
63	57	27
66	44	37
4	62	42
26	4	75
12	5	88
24	3	67
73	9	56
14	12	68
7	26	33

Table 15--Continued

Congestion Cost Index	Vehicle Minutes of Delay	Volume to Capacity Index
roadway section # 64	# 21	# 45
20	64	89
22	29	71
52	30	86
30	16	31
16	40	48
9	73	
21	52	
48	24	
5	49	
86	77	
81	48	
40	60	
77	11	
32	81	
3	41	
58	31	
41	13	
18	1	
8	32	
1	85	
39	79	
11	34	
13	22	
19	15	
72	72	
31	46	
15	42	
85	83	
42	47	
87	8	
46	80	
80	45	
47	78	
90	43	

Table 15--Continued

Congestion Cost Index	Vehicle Minutes of Delay	Volume to Capacity Index
roadway section # 37	# 90	
83	37	
79	87	
45	68	
70	19	
76	17	
25	76	
68	66	
43	18	
34	25	
78		
17		
23		
36		
82		
74		
38		
89		

TABLE 16. ROADWAY SECTIONS OF HIGHEST PRIORITY

Rank	Congestion Cost Index	Vehicle Minutes of Delay	Volume to Capacity Index
1	Council-Stone NB[1]	Broadway-Campbell EB	5th Ave.-Alvernon EB
2	Pennington-Stone NB	Broadway-6th Ave. EB	22nd St.-Swan SB
3	6th St.-4th Ave. EB	6th St.-4th Ave. EB	5th Ave.-Alvernon NB
4	Broadway-6th Ave. EB	Pennington-Stone EB	Broadway-6th Ave. EB
5	Broadway-Campbell EB	Council-Stone NB	Speedway-C. Club NB
6	Pennington-Stone EB	Broadway- C. Club EB	5th Ave.-Swan EB
7	6th St.-4th Ave. NB	Pennington-Stone NB	5th Ave.-Craycroft NB
8	Broadway-Scott WB	Council-Stone EB	Council-Stone EB
9	Pennington-Stone SB	Broadway-Tucson EB	Speedway-6th Ave. NB
10	Broadway-6th Ave. SB	Speedway-C. Club EB	Speedway-Craycroft NB
11	Council-Stone WB	Pennington-Stone SB	Speedway-C. Club EB
12	Speedway-Stone EB	3rd St.-Stone NB	Council-Stone NB
13	Broadway-4th Ave. SB	6th St.-4th Ave. NB	5th Ave.-Alvernon WB
14	Broadway-Tucson EB	Broadway-Scott WB	Broadway-Tucson NB
15	6th St.-Park SB	Speedway-Stone EB	Pennington-Stone SB

[1]NB = northbound SB = southbound
EB = eastbound WB = westbound

Recommendations

Based on the conclusions of this thesis, it is recommended that the congestion cost index should be used to develop priority schedules of roadway improvement. An indication of high volumes alone does not, in the opinion of the author, describe congestion or functional obsolescence as well as indications of delay, high operating costs, and high accident rates.

After the roadways in a community have been rated by the congestion cost index, updating would require only the measurement of travel times in the field. Current accident rates, accident costs, and time costs could be obtained easily from the sources mentioned in Chapter IV. To update the ratings by the vehicle minutes of delay index, traffic volumes, in addition to travel times, would be required. To update the ratings by the volume to capacity index, turning movements, percent commercial traffic, and signal cycle division would have to be determined. Though the calculations for the congestion cost index are more extensive than the others, the use of a computer can eliminate this imbalance.

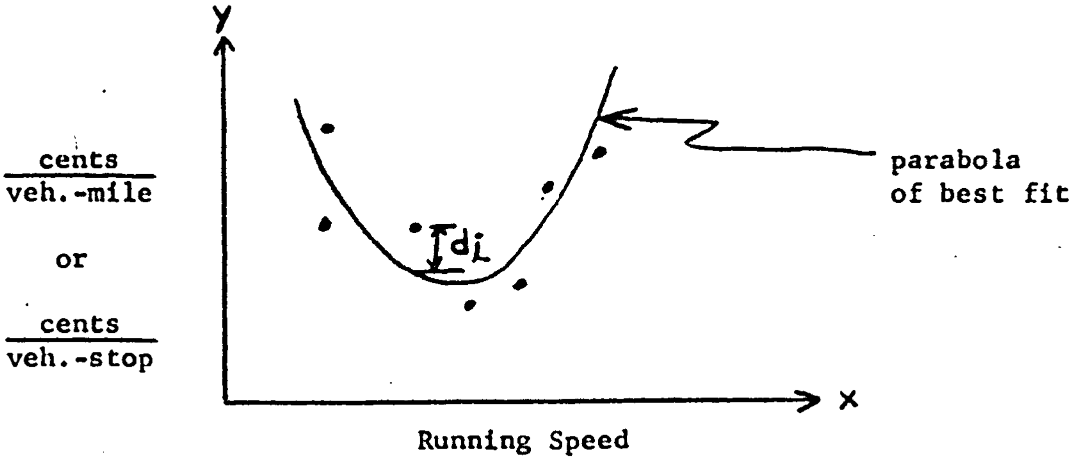
Another reason for recommending the use of the congestion cost index stems from the usual practice of making an economic analysis for roadway improvement. This practice involves studies of return on investment for alternative proposals to correct the functional obsolescence of a roadway. The "return" is the money saved to the motorist as a result of the improvement. By using this index, the present cost to the motorist is found while the obsolenscence is being determined.

Since the cost of travel time is a dominating factor of roadway costs, research, such as that described in Chapter III, should be conducted to evaluate as accurately as possible the unit value of time. Also, the number of stops and idling time should be measured in the field instead of being assumed and calculated as was done in this thesis.

APPENDICES

APPENDIX A

DERIVATION OF McGRAW-HILL OPERATING COST PARABOLAS BY THE METHOD OF LEAST SQUARES



<u>Given</u> General equation: $Y = A + BX + CX^2$

<u>Req'd</u> Coefficients A, B, C

<u>Solution</u>

$$d^2 = \sum_1^N (A + BX + CX^2 - Y)^2$$

Minimize d^2 :

$$\frac{\partial d}{\partial A} = 2 \sum_1^N (A + BX + CX^2 - Y) = 0$$

$$\frac{\partial d}{\partial B} = 2 \sum_1^N X (A + BX + CX^2 - Y) = 0$$

$$\frac{\partial d}{\partial C} = 2 \sum_1^N X^2 (A + BX + CX^2 - Y) = 0$$

Normal equations from above:

$$AN + B\sum_{1}^{N} X + C\sum_{1}^{N} X^2 = \sum_{1}^{N} Y$$

$$A\sum_{1}^{N} X + B\sum_{1}^{N} X^2 + C\sum_{1}^{N} X^3 = \sum_{1}^{N} XY$$

$$A\sum_{1}^{N} X^2 + B\sum_{1}^{N} X^3 + C\sum_{1}^{N} X^4 = \sum_{1}^{N} X^2Y$$

Solve for A, B and C:

Let $d = \sum_{1}^{N} X$ $h = \sum_{1}^{N} XY$

$e = \sum_{1}^{N} X^2$ $k = \sum_{1}^{N} X^4$

$f = \sum_{1}^{N} X^3$ $m = \sum_{1}^{N} X^2Y$

$g = \sum_{1}^{N} Y$

Then $An + Bd + Ce = g$

$Ad + Be + Cf = h$

$Ae + Bf + Ck = m$

$And + Bd^2 + Ced = gd$

$-And - Ben - Cfn = -hn$

(1) $B(d^2 - en) + C(ed - fn) = (gd - hn)$

$Ade + Be^2 + Cfe = he$

$-Ade - Bdf - Cdk = -md$

(2) $B(e^2 - df) + C(fe - dk) = (he - md)$

Combine (1) and (2) and solve for C:

$$C = \frac{(md - he)(d^2 - en) - (hn - gd)(e^2 - df)}{(ed - fn)(e^2 - df) - (fe - dk)(d^2 - en)}$$

Let $S = hn - gd \qquad Q = d^2 - en$

$D = e^2 - df \qquad E = fe - dk$

$P = md - he \qquad R = ed - fn$

Then $C = \frac{PQ - SD}{RD - EQ}$

Find B and A in same manner:

$$B = \frac{P + Ec}{-D}$$

$$A = \frac{(Ce - g) + Bd}{N}$$

These equations for A, B and C were programmed by FORTRAN for use in a computer.

APPENDIX B

COMPUTER PROGRAM

```
#     COMPILE FORTRAN,EXECUTE FORTRAN

C      CONGESTION COST INDEX PROGRAM
C
C      DEFINITION OF SYMBOLS
C           X=RUNNING SPEED
C           Y=CENTS PER VEHICLE MILE OR CENTS PER VEHICLE STOP
C           XSQ=X SQUARED
C           XCU=X CUBED
C           X4TH=X TO THE FOURTH POWER
C           A,B,C=COEFFICIENTS OF LEAST SQUARES PARABOLAS
C           RS=RUNNING SPEED
C           TT=TOTAL RATE OF TRAVEL
C           AL=LENGTH OF SECTION
C           TCVS=STOP AND IDLING COSTS PER VEHICLE STOP
C           NOMSP=NOMINAL SPEED
C           RCVMR=RUNNING COSTS PER VEHICLE MILE AT RUNNING
C           SPEED ON LEVEL TANGENTS
C           RCVMN=RUNNING COSTS PER VEHICLE MILE AT NOMINAL
C           SPEED ON LEVEL TANGENTS
C           SPCMR=STOPPING AND RUNNING COSTS PER VEHICLE MILE
C           AT RUNNING SPEED
C           IGRD=GRADE
C           DGCMR=INCREMENTAL GRADE COST PER VEHICLE MILE AT
C           RUNNING SPEED
C           DGCMN=INCREMENTAL GRADE COST PER VEHICLE MILE AT
C           NOMINAL SPEED
C           OCVMR=OPERATING COSTS PER VEHICLE MILE AT RUNNING
C           SPEED
C           OCVMN=OPERATING COSTS PER VEHICLE MILE AT NOMINAL
C           SPEED
C           ACVMR=ACCIDENT COST PER VEHICLE MILE AT RUNNING
C           EED
C           SPEED
C           AVMRS=ACCIDENTS PER VEHICLE MILE AT RUNNING SPEED
C           ACVMN=ACCIDENT COSTS PER VEHICLE MILE AT NOMINAL
C           SPEED
C           AVMNS=ACCIDENTS PER VEHICLE MILE AT NOMINAL SPEED
C           OACMR=OPERATING AND ACCIDENT COSTS PER VEHICLE
C           MILE AT RUNNING SPEED
C           OACMN=OPERATING AND ACCIDENT COSTS PER VEHICLE
C           MILE AT NOMINAL SPEED
C           TCVMR=TIME COST PER VEHICLE MILE AT RUNNING SPEED
C           TS=TOTAL SPEED
C           TCVMN=TIME COST PER VEHICLE MILE AT NOMINAL SPEED
C           CVMRS=ROADWAY COSTS PER VEHICLE MILE AT RUNNING
```

```
C           SPEED
C           CVMNS=ROADWAY COSTS PER VEHICLE MILE AT NOMINAL
C           SPEED
C           CCI=CONGESTION COST INDEX
C           S,D,P,G,R,E=AS INDICATED IN APPENDIX A
C           SX=SUMMATION OF X
C           RT=RUNNING TIME OF TRAVEL
C           D=IDLING TIME
C
      DIMENSION X(120),Y(120),XSQ(120),XCU(120),X4TH(120),XY
     1(120),XSQY(120),A(120),B(120),C(120),RS(120),TT(120),A
     2L(120),TCVS(120),NOMSP(120),RCVMR(120),RCVMN(120),SRCM
     3R(120),IGRD(120),DGCMR(120),DGCMN(120),OCVMR(120),OCVM
     4N(120),ACVMR(120),AVMRS(120),ACVMN(120),ACMNS(120),OAC
     5MR(120),OACMN(120),TCVMR(120),TS(120),TCVMN(120),CVMRS
     6(120),CVMNS(120),CCI(120)
  201 READ 1,N,IDENT,LAST
    1 FORMAT (3I10)
      READ 2,(X(I),I=1,N)
    2 FORMAT (8F10.3)
      READ 3, (Y(I),I=1,N)
    3 FORMAT (8F10.3)
      AN = N
      I = 0
      S = 0.0
      D = 0.0
      P = 0.0
      G = 0.0
      R = 0.0
      E = 0.0
      SX = 0.0
      SXSQ = 0.0
      SXCU = 0.0
      SX4TH = 0.0
      SY = 0.0
      SXY = 0.0
      SXSQY = 0.0
      DO 10 I=1,N
   10 SX = SX + X(I)
      DO 11 I=1,N
      XSQ(I) = X(I)**2
   11 SXSQ = SXSQ + XSQ(I)
      DO 12 I=1,N
      XCU(I) = X(I)**3
   12 SXCU = SXCU + XCU(I)
      DO 13 I=1,N
      X4TH(I) = X(I)**4
   13 SX4TH = SX4TH + X4TH(I)
      DO 14 I=1,N
   14 SY = SY + Y(I)
      DO 15 I=1,N
      XY(I) = X(I)*Y(I)
```

```
 15 SXY = SXY + XY(I)
    DO 16 I=1,N
    XSQY(I) = XSQ(I)*Y(I)
 16 SXSQY = SXSQY + XSQY(I)
    S =(AN*SXY) - (SY*SX)
    D = (SXSQ)*(SXSQ) - (SX) * (SXCU)
    P = (SX)*(SXSQY)-(SXSQ)*(SXY)
    Q = (SX)*(SX) - (SXSQ)*(AN)
    E = (SXSQ)*(SXCU)-(SX)*(SX4TH)
    R = (SX)*(SXSQ)-(AN)*(SXCU)
    C(IDENT) = (((S*D)-(P*Q))/((Q*E)-(R*D)))
    B(IDENT)=((-(E*C(IDENT))-P)/D)
    A(IDENT)=((SY-(C(IDENT)*SXSQ)-(B(IDENT)*SX))/AN)
    PRINT 100,IDENT,A(IDENT),B(IDENT),C(IDENT)
100 FORMAT (2X,9H IDENT = ,I3,5X,5H A = ,F10.4,5X,5H B = ,F10.4,5X,
   1C = ,F10.6)
    IF(LAST) 200,201,200
200 READ4,NN,LAST1
  4 FORMAT(2I10)
    READ500,(TT(I),I=1,NN)
500 FORMAT(8F10.3)
    READ501,(AL(I),I = 1,NN)
501 FORMAT (8F10.3)
    READ502,(NOMSP(I),I=1,NN)
502 FORMAT(8I10)
    READ503,(IGRD(I),I=1,NN)
503 FORMAT(8I10)
    READ504,(AVMRS(I),I=1,NN)
504 FORMAT(8F10.0)
    READ505,(AVMNS(I),I=1,3)
505 FORMAT(3F10.0)
    READ506,(TS(I),I=1,NN)
506 FORMAT(8F10.0)
    DO 109 I = 1,NN
    RT=TT(I)/(0.132*TT(I)+0.782)
    D=(TT(I)*AL(I))-(RT*AL(I))
    RS(I)=60.0/RT
    IDENT=NOMSP(I)
    RCVMR(I)=C(IDENT)*RS(I)**2+B(IDENT)*RS(I)+A(IDENT)
    AID=IDENT
    RCVMN(I)=C(IDENT)*AID**2+B(IDENT)*AID+A(IDENT)
    CVMIN=0.280*D
    IDENT=50
    CVS=C(IDENT)*RS(I)**2 B(IDENT)*RS(I)+A(IDENT)
    TCVS(I)=CVS+CVMIN
    SRCMR(I)=TCVS(I)+RCVMR(I)
    IDENT=IGRD(I)
    GCVMR=C(IDENT)*RS(I)**2+B(IDENT)*RS(I)+A(IDENT)
    IDENT=100
    GCMRO=C(IDENT)*RS(I)**2+B(IDENT)*RS(I)+A(IDENT)
    DGCMR(I)=GCVMR-GCMRO
    IDENT=IGRD(I)
```

```
      AID=NOMSP(I)
      GCVMN=C(IDENT)*AID**2+B(IDENT)*AID+A(IDENT)
      IDENT=100
      GCMNO=C(IDENT)*AID**2+B(IDENT)*AID+A(IDENT)
      DGCMN(I)=GCVMN-GCMNO
      OCVMR(I)=SRCMR(I)+DGCMR(I)
      OCVMN(I)=RCVMN(I)+DGCMN(I)
      ACVMR(I)=AVMRS(I)*116000.0
      NS=NOMSP(I)
      IF(NS-15)20,20,21
   20 ACVMN(I)=AVMNS(1)*116000.0
      GO TO 24
   21 IF(NS-30)22,23,23
   22 ACVMN(I)=AVMNS(2)*116000.0
      GO TO 24
   23 ACVMN(I)=AVMNS(3)*116000.0
   24 OACMR(I)=OCVMR(I)+ACVMR(I)
      OACMN(I)=OCVMN(I)+ACVMN(I)
      TCVMR(I)=111.5/TS(I)
      ANMSP=NOMSP(I)
      TCVMN(I)=111.5/ANMSP
      CVMRS(I)=OACMR(I)+TCVMR(I)
      CVMNS(I)=OACMN(I)+TCVMN(I)
  109 CCI(I)=CVMRS(I)/CVMNS(I)
      PRINT 300
  300 FORMAT(1X,10H APPROACH ,5X,15H RUNNING SPEED ,5X,15H N
     1OMINAL SPEED,5X6H TCVS ,5X7H RCVMR ,5X7H RCVMN ,5X7H S
     2RCMR )
      PRINT301,(I,RS(I),NOMSP(I),TCVS(I),RCVMR(I),RCVMN(I),S
     1RCMR(I),I=1,NN )
  301 FORMAT(4X,I3,14X,F5.1,13X,I5,5X,4X,F8.4,4X,F8.4,4X,F8.
     14,4X,F8.4)
      PRINT302
  302 FORMAT(1X,10H APPROACH ,5X,7H DGCMR ,5X,7H OCVMR ,5X,7
     1H DGCMN ,5X,7H OCVMN ,5X,7H ACVMR ,5X,7H OACMR ,5X,7H
     2ACVMN ,5X,7H OACMN )
      PRINT303,(I,DGCMR(I),OCVMR(I),DGCMN(I),OCVMN(I),ACVMR(
     1I),OACMR(I),ACVMN(I),OACMN(I),I=1,NN)
  303 FORMAT(4X,I3,14X,F7.4,4X,F7.4,5X,F7.4,5X,F7.4,5X,F7.4,
     15X,F7.4,5X,F7.4,5X,F7.4)
      PRINT304
  304 FORMAT(1X,10H APPROACH ,5X,7H TCVMR ,5X,7H TCVMN ,5X,7
     1H CVMRS ,5X,7H CVMNS ,5X,5H CCI )
      PRINT305,(I,TCVMR(I),TCVMN(I),CVMRS(I),CVMNS(I),CCI(I)
     1,I=1,NN)
  305 FORMAT(4X,I3,14X,F7.4,5X,F7.4,5X,F7.4,5X,F7.4,2X,F10.6
     1)
      IF(LAST 1) 400,200,400
  400 STOP
      END
```

APPENDIX C

A SAMPLE CALCULATION OF THE CONGESTION COST INDEX

Given a particular roadway section

length = 1.00 miles

nominal speed = 30 mph

total travel time = 3.88 min.

annual accident rate = 50.0 per 10,000,000 veh.-miles

composite grade = 1%

Req'd CCI

Solution

1. TT = 3.88 min./1 mile = 3.88 min./mile

$$RT = \frac{3.88}{0.132(3.88) + 0.782} = 3.00 \text{ mile/min.}$$

2. $$RS = \frac{60 \text{ min./hr.}}{3.00} = 20 \text{ mph}$$

Operating Costs

3. CVS = 0.314¢ (Table 4, top page 39)
4. D = 1.00(3.88-3.00) = 0.880 sec.
5. CVMIN = 0.880 (0.280) = 0.246¢
6. RCVMR = 4.301¢ (Table 4, p. 37)
7. RCVMN = 3.709¢ (Table 4, p. 37)
8. GCVMR = 3.733¢ (Table 4, p. 38)
9. GCMRO = 3.725¢ (Table 4, p. 38)
10. DGCMR = 3.733 - 3.725 = 0.008¢

11. GCVMN = 3.717¢ (Table 4, p. 38)

12. GCMNO = 3.709¢ (Table 4, p. 38)

13. DGCMN = 3.717 - 3.709 = 0.008¢

14. OCVMR = 0.314 + 0.070 + 4.301 + 0.008 = 4.693¢

15. OCVMN = 3.725 + 0.008 = 3.733¢

Accident Costs

16. ACVMR = (0.00000500)116,000 = 0.580¢

17. AVMNS = 0.00000496 (Table 7)

ACVMN = (0.00000496)116,000 = 0.464¢

Time Costs

18. $TS = \frac{60 \text{ min./hr.}}{3.88 \text{ min./mile}} = 15.47$ mph

$TCVMR = \frac{111.50}{15.47} = 7.207$¢

19. $TCVMN = \frac{111.50}{30} = 3.717$¢

Roadway Costs

20. CVMRS = 4.693 + 0.580 + 7.207 = 12.483¢

21. CVMNS = 3.733 + 0.464 + 3.717 = 7.914¢

Congestion Cost Index

22. $CCI = \frac{12.483}{7.914} = 1.58$

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