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HURRICANE

EVACUATION STUDY

Prepared for

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EXECUTIVE SUMMARY

This report evaluates the ability of the existing highway system to accommodate the evacuation of people from the Texas Gulf Coast barrier islands prior to landfall of a hurricane. Unfortunately, the state of the art in predicting characteristics of storms necessary to evaluate the transportation system capacity is not sufficiently definitive to make categorical statements concerning hurricane evacuation. Nevertheless, there is sufficient evidence to indicate that an evacuation problem may exist on all the Texas barrier islands because roads may flood before people are aware of a potential storm. The probability of occurrence of this problem, however, is unknown.

The available data base is sufficiently definitive to provide a reasonable estimate of the number of permanent residents and the maximum number of vehicles that permanent residents have available for evacuation. It is also possible to estimate the minimum time it would take to evacuate those permanent residents and their vehicles. This information is summarized in Table ES-1.

The study did not include consideration of tourists because no data existed to indicate when they might leave, or whether they might come during the threat of a hurricane. It was, therefore, assumed that tourists would leave in advance of the critical time period. If tourists need to be evacuated, evacuation times would increase.

The study indicated that winds of 50 mph and gusting to 75 mph can exist 10 to 20 hours prior to landfall of a hurricane. Since, winds of this magnitude can overturn trucks, motor homes and vehicles with trailers, consideration should be given to prohibiting these vehicles on the highways upon issuance of a hurricane warning. This would undoubtedly require special legislation.

Further data and study are needed in several areas. As a result of subsidence, precise elevations along IH-45 are unknown. The study shows that evacuation may be possible if the elevation at which the roadway was constructed still exists. The barrier islands, other than Galvestion Island, all have critical roadway elevations in the range of four feet. Better data are needed to determine when, with what probability, and with what types of storm tides might reach 4 feet.

If 4-foot tides occur with high probability 18 to 36 or more hours prior to a storm, as suggested by the National Weather Service, total evacuation of the barrier islands is not possible, given existing roadway conditions storms and forecasting techniques. The resulting alternatives are: 1) improve storm forecasting procedures; 2) change the roadway elevation; and 3) protect people on the island during the storms rather than attempt evacuation. Each of these alternatives warrants further consideration.

Table ES-1: Evacuation Demand and Capacity

Location	Number of Permanent Residents	Maximum Number of Vehicles	Roadway Capacity (Vehicles per hour)	Minimum Evacuation Time (Hours)
Bolivar Peninsula	3,100	1,798	850	2.1
Galveston Island	68,998	31,459	2,500	12.6
Mustang Island	1,276	933	300	3.2
South Padre Island	589	431	1,000	0.5

Note: Includes only permanent residents.
Assumes everyone evacuates.

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I. INTRODUCTION

The Texas Gulf Coast is subject to a diversity of natural hazards. This study is only concerned with one of those hazards, hurricanes. The study is further limited primarily to consideration of the barrier islands along the Texas Gulf Coast. The scope of analysis is limited to a consideration of the capacity of the existing highway system to accommodate the evacuation of barrier island residents.

The study is concerned with both hurricanes and hurricane evacuation. These storms produce striking changes in the sea; huge waves and storm tides are generated. Hurricanes also trigger heavy rainfall, create high-velocity winds, and spawn tornadoes. These conditions make staying on a barrier island during landfall of a hurricane dangerous. They also make evacuation difficult, and in some cases, impossible.

This study has two objectives concerning evacuation of the Texas Gulf Coast barrier islands.

1) To ascertain if total evacuation is possible, given present populations and possible warning times, and if possible, how long it would take.

2) To determine what actions can improve the ability to evacuate barrier island residents.

An extensive search of the literature relative to hurricanes and hurricane evacuation was made. Little information specifically about hurricane evacuation capacity was found. Any attempts that were made utilized many assumptions, some of questionable validity, in order to estimate demand/capacity relationships. The literature did contain information concerning response rates, but response varied from 30 to nearly 100 percent. This report will hopefully extend the state of the art in evaluating demand versus capacity.

During the early stages of the study, an attempt was made to develop a model of the demand/capacity relationship. The thought was to break the problem into discrete components, such as environmental factors, physical factors, and demographic factors. As work progressed, it became clear that the process could not be easily broken into discrete components because many factors were interrelated. This discrete component idea was subsequently dropped; however, the process is sufficiently modular that different components can be replaced as the state-of-the-art improves.

Instead of a model showing all the interactions, the analysis process has been divided into two parts. A procedure will be developed to estimate the demand in total vehicles that could reasonably be expected to evacuate during an approaching hurricane. Also, a procedure will be developed to estimate the vehicle capacity of a street system under the environmental conditions that precede landfall of a hurricane.

Finally, the analysis methodology will be applied to the barrier islands along the Texas Gulf Coast that have significant populations. These areas would include (from North to South) Bolivar Peninsula, Galvestion Island, Mustang Island, and Padre Island.

II. DEMAND RELATIONSHIPS

The vehicular demand for evacuation during a hurricane can be estimated in a three-step process. First, it is necessary to know how many people reside in the area under evaluation. Second, an estimate of how many vehicles and what types of vehicles will be used in the evacuation. Third, it is necessary to estimate the percentage of the residents that will leave. These factors are called demographic factors, vehicle factors, and response factors, respectively.

Although a fourth parameter, when will they leave, would be desirable, the lack of data makes an alternative approach necessary. The approach to be used is--given available capacity, when must evacuation begin to be sure that an opportunity exists for everyone to evacuate. For the purpose of this study, two levels of demand will be analyzed. One level will be everyone residing in the area; the second will be everyone likely to evacuate.

Demographic Factors

The starting place for population estimates is the 1970 Census of Population. Where reliable data of a more current nature are available, they are used. The census data will also be used for estimating the number of automobiles available for evacuation.

Although the summer population in coastal areas increases, there is no evidence to indicate that tourists stay during the threat of a hurricane. In fact, the threat of a hurricane appears to have an adverse effect on the tourist business. Pending evidence to the contrary, no consideration will be given to tourist populations, although a fast moving storm my cut off some low-lying areas with little or no warning.

There is, however, some likelihood of an increase in the number of part-time residents who are interested in protecting their property (e.g., beach houses) or possibly in removing valuables such as boats. Again, there are no data available to quantify these relationships.

Vehicle Factors

Two vehicle factors are of importance in the demand estimate--how many vehicles and what types will be used. The number of vehicles used is determined by how many people will leave and how many people will be in each vehicle. The types of vehicles used will depend on the types available, the number to be used, and the priority for using each type of vehicle, if a surplus of vehicles exists.

There are some potentially conflicting desires in determining how many vehicles will be used. For example, it may be desired to remove all, or as many as possible, of a family's vehicles. This may or may not be possible depending on the number of vehicles and the number of drivers. A conflicting desire may be that a family does not want to separate during evacuation.

Nevertheless, the number of evacuees will be based on the number of available vehicles. This is not unreasonable if we compare the number of licensed drivers with the number of available vehicles on March 31, 1977. The number of licensed drivers in Texas, according to the Department of Public Safety, was 8,159,265 on March 31, 1977 which is the last day of the 1976 motor vehicle registration year, and the most current available data. The number of registered passenger vehicles was 6,534,582 according to the Texas State Department of Highways and Public Transportation, Motor Vehicle Division. Based on previous TTI research (1), approximately 30 percent of all trucks are pickups used primarily as personal use vehicles. There were 2,265,785 trucks of all types registered on March 31, 1977; therefore, approximately 679,736 pickups are used as personal vehicles. Together these two classes of vehicles comprise a total of 7,214,318 vehicles. The vehicle availability will be used as the controlling factor on the total number of vehicles used during an evacuation.

Response Factors

A difficult factor to estimate is what portion of the population will evacuate. There may, however, be an obligation to provide an opportunity for everyone to evacuate. For this reason, one estimate of required evacuation time will be made based on all residents evacuating. A second estimate of evacuation time will be made based on those most likely to leave.

Studies (2-5) of reaction to the threat of a hurricane indicate a wide variation in response. The most significant influence on whether people evacuate or stay is the action of local public officials. This has been shown (5) to be the case in an analysis of response to Carla. When the official position was a firm, uncompromising and unanimous request to evacuate, action followed. The case on Galveston Island during Hurricane Carla was to allow citizens to make the decisions to evacuate or take shelter. Several factors can be attributed to the lack of an order to evacuate. Such a decision would be unpopular. Also, the sea wall gives residents a feeling of security. Finally, the tradition in Galveston has been to fight it out (4).

The evacuation percentage for various coastal communities has been shown (2-5) to vary from 30 percent to 100 percent. Given a firm order to evacuate, at least two-thirds of the population of larger urban areas could reasonably be expected to leave. In smaller coastal communities, it may not be unreasonable (1) to expect nearly 100 percent evacuation.

Generalized Demand

The following procedure is recommended to provide a planning estimate of demand. First, estimate population (either present or future as appropriate to the analysis) using U.S. Census data or other reliable projection. Second, determine the most current per capita vehicle rates for study area (or next largest geographical area for which both registered vehicles and population data are available). The per capita rate is simply total registered autos and pick-ups owned as personal vehicles (use 30 percent of total trucks as an estimate of pickups if necessary) divided by total population for the same area. Third, determine the maximum number of vehicles to be evacuated by multipling the population by the per capita rate. The demand is then reduced by the appropriate response factor (0.30 to 1.00).

III. CAPACITY RELATIONSHIPS

The ability to accommodate vehicular traffic is a primary consideration in the hurricane evacuation problem. Highway capacity is a measure of the effectiveness of various highways in accommodating traffic. Traffic engineers are familiar with methods of computing capacity under normal conditions. This study will provide additional factors to adjust for environmental conditions experienced prior to the landfall of hurricanes. These factors are necessary because traffic engineers generally ignore the effects of rain, wind and accidents on capacity, since they occur relatively infrequently. During a hurricane evacuation, they can be expected with reasonable certainty. In addition, simplified techniques for determining capacity will be developed as a planning tool for those not familiar with techniques for determining capacity.

Definition

Capacity is the maximum number of vehicles which has a reasonable expectation of passing over a given section of a lane or roadway during a given time period under prevailing roadway, traffic, and ambient conditions. In expressing capacity, it is essential to state the *prevailing roadway, traffic and ambient conditions* under which the capacity is applicable.

The number of vehicles passing a given point on a roadway during periods of heavy demand will be governed by one of the following:

1. The demand being placed upon the section of roadway by vehicles desiring to use it at the particular time, or
2. The capacity of the roadway at:

   (a) The point of observation

(b) A point upstream; or

(c) A point downstream.

There are two points to be made relative to hurricane evacuation. First, if the demand is less than the capacity, as in Item 1 above, a portion of the possible capacity over a period of time is lost and cannot be used. An example will illustrate the point. If the capacity of a section of roadway is 1,000 vehicles per hour, the capacity is 10,000 vehicles for a 10-hour period. However, if only 500 vehicles use the roadway in the first hour, the capacity in the remaining nine hours is still 9,000 vehicles. After the first hour, the maximum possible utilization is only 9,500 vehicles for the 10-hour period. The 500 vehicle capacity not used in the first hour is lost.

The second point is that the capacity of an evacuation route is the capacity of that section of roadway with the least capacity. For example, if an upstream section of roadway has a capacity of 500 vehicles per hour, a downstream section having a capacity of 1,000 vehicles is of little significance. The previous statement is conditional upon the fact that if an incident (e.g., traffic accident) occurs on the section with the higher capacity, the effect of the incident may be lessened or eliminated by the effect of excess capacity.

Prevailing Conditions

The capacity of a section of roadway depends on a number of traffic conditions. Composition of traffic, roadway alignment, and number and width of lanes are a few of those conditions which may be referred to collectively as the *prevailing conditions*.

The prevailing conditions may be divided into three general groups: (1) those that are established by the physical features of the roadway; (2) those dependent on the nature of traffic on the roadway; and (3) those dependent on the environmental situation. Those in the first group, none of which can be changed unless some construction or reconstruction takes place, are referred to as *prevailing roadway conditions*. Those in the second group, any of which can be changed from hour to hour, are referred to as *prevailing traffic conditions*.

The third type of prevailing conditions are usually ignored because they occur during limited periods. This group of prevailing conditions is called the *ambient conditions*. They are, however, a very important consideration in hurricane evacuation since they are very likely to occur and reduce capacity. These conditions primarily relate to weather and include rain, wind, and high tides. Ambient factors are developed in Appendix A, and are herein summarized. Rain is shown to reduce capacity by a factor 0.84. Wind is shown to be a potenially serious problem for trucks, motor homes, and vehicles with trailers. Prohibition of these vehicles during a hurricane warning, which would require special legislation, is suggested as the appropriate remedy. Tides are considered to reduce capacity to zero once a lane is half covered with water.

One note concerning number of lanes available for evacuation is appropriate. First, it is considered necessary by Civil Defense officials that one lane be maintained for emergency and other authorized vehicles to enter the evacuation area. If this assumption is accepted, it would be difficult to use lanes other than those for traffic flow in the normal direction for evacuation. The reason for this conclusion is that special traffic control such as traffic cones and/or police officers would be necessary to designate which lanes could or could not be used.

For this study only normal traffic lanes were considered for evacuation.

This is not to say, however, that if a traffic accident occurred, that reverse flow lanes would not be used for a short distance to bypass an accident.

Generalized Capacity

Generalized capacity figures are developed in Appendix A for several types of highways--freeways and expressways, urban streets, 2-lane rural highways and multilane rural highways. The various capacities are shown in Table III-1. Appendix A can also be used to determine the capacity of a specific roadway.

Table III-1: Generalized Capacities

Type of Facility	Capacity Vehicles per Lane per hour
Freeways and Expressways	1150
Urban Streets	500
Two-lane rural highways	850
Multilane rural highways	1150

Note: Capacities include ambient condition adjustment for hurricanes, and an adjustment for poor roadway conditions (See Appendix A).

Evacuation Time

The minimum time required for evacuation is the total number of vehicles divided by the total capacity at the critical point in the roadway network. The critical point is that which has the lowest product of number of lanes in direction of evacuation times the appropriate capacity in Table III-1.

IV. EVALUATION OF TEXAS BARRIER ISLANDS

A demand and capacity estimate is made for each of four Texas Barrier Islands with significant populations. The four islands to be evaluated are Bolivar Peninsula, Galveston Island, Mustang Island, and South Padre Island.

Bolivar Peninsula

Bolivar Peninsula includes the communities of Port Bolivar, Crystal Beach, Caplen and High Island. The most direct access to the mainland is via State Highway 124 (SH-124) at High Island.

Population

The 1970 U.S. Census (6) gives the population of the above mentioned communities as 2424. A more recent study (7) estimates the 1978 population to be 3100 and this figure will be used as the basis for projecting vehicles available for evacuation.

Vehicles Available

The 1970 U.S. Census (6) indicates more than 1124 autos on the peninsula. The exact number is not known since the Census Bureau uses only one category for those having three or more autos. This per capita auto availability of 0.464 agrees well with the 1970 statewide per capita rate of 0.455 (See Appendix E). Since the 1976 statewide per capita rate increased to 0.523, and since the statewide per capita pickup truck rate for those used as personal vehicles was

0.054, a per capita vehicle availability rate 0.58 will be used to estimate vehicles available. This translates into 1798 vehicles for evacuation.

Capacity

The elevations along SH-87 are generally less than five feet. The highway is subject to flooding for a distance of about 20 miles under less than hurricane conditions. According to the National Hurricane Center, the onset of tides two to four feet above normal can frequently occur along the Texas Coast 36 hours before landfall with a large, slow-moving hurricane and 18-24 hours before landfall for a large, faster moving hurricane.

Residents of Port Bolivar, Crystal Beach, Gilchrist and Caplen, must take action before the issuance of a hurricane warning. These residents must follow storms carefully and be prepared to evacuate almost instantaneously. Using a 2-lane rural capacity of 850 vehicles per hour, evacuation would require 2.1 hours. It is possible that many residents could be stranded due to a rapid tide buildup.

Galveston Island

Access to Galveston Island includes the Interstate Highway 45 (IH-45) causeway bridge, the ferry to Bolivar and the county owned bridge at San Luis Pass. Pelican Island, which is connected to Galveston Island by bridge, is also part of the study area. It should be noted that the city limits of the City of Galveston changed significantly during the 1970's due to annexation. All future references to Galveston Island are without regard to city limits and include Pelican Island.

Population

The 1970 Census (6) placed the Galveston Island population at 62,897. The estimated population increase for the Galveston SMSA through July 1, 1976 is 9.7 percent. Using this percentage yields a population estimate of 68,998 which will be used to project the number of vehicles available for evacuation.

Vehicles Available

The 1970 U.S. Census (6) indicated somewhat more than 21,910 autos (the census has a single category for households with 3 or more autos, making exact projections impossible) on Galveston Island. This number of vehicles represents a 0.348 per capita auto ownership. The census data for Galveston County indicates a per capita auto rate of 0.404 based on a 1970 census population of 169,812 and more than 68,653 autos.

The Census Bureau estimates the 1976 Galveston County population at 186,300. Galveston County registered autos numbered 91,524, or a per capita rate of 0.491. The number of registered trucks in Galveston County in 1976 was 26,960 and yields a per capita rate of pickups used as personal vehicles of 0.043. This is again based on the 30 percent rate (1) previously mentioned.

For the purpose of this study, the 1976 Galveston County rates based on actual registrations will be factored by the ratio of the 1970 census autos per capita on Galveston Island to the per capita rate for Galveston County. (0.348 divided by 0.404 yields a factor of 0.853). The result is a per capita auto availability of 0.419 and a per capita pickup used as a personal vehicle of 0.037, or a total vehicle availability of 0.456 for Galveston Island. Total vehicles for evacuation therefore, is estimated as 68,988 times 0.456, or 31,459.

Capacity

There are three means of roadway access to and from Galveston Island: 1) The IH-45 causeway, 2) the San Luis Pass (Toll) Bridge, and 3) the ferry to Bolivar. Because of the low elevation of roadways, the long distances required, and the exposed nature of the highways along the coast, the IH-45 causeway is the most viable means of evacuation for Galveston Island. The other two routes will not be considered as evacuation routes.

The critical point for evacuation capacity is the intersection of 61st and Broadway that feeds onto the causeway. Virtually all traffic leaving the island has to use one of these five lanes. Using the previously developed 500 vehicles per lane per hour yields an hourly capacity of 2,500 vehicles.

Time Required

In order to evacuated 31,459 vehicles at 2,500 vehicles per hour would require a minimum of 12.6 hours assuming 2,500 vehicles were continuously available during the 12.6 hours. However, if only 38 percent of the population evacuates as indicated in a recent study (5), only 4.8 hours would be required for evacuation.

Time Available

The available evacuation time is partially determined by when the evacuation route will become flooded. This can occur either due to rainfall or due to storm surge (tides). As indicated previously, prediction of rainfall is difficult. No prediction of rainfall closure will be made, however, *it is quite* *possible that roadways will be impassable due to rainfall before they are flooded due to storm surge.*

The lowest *construction* elevation of IH-45 from 59th street to SH-6 is 7.8 feet. However, *subsidence may have reduced some elvations to five feet or less.* As indicated earlier, tides of four feet can occur 18 to 36 hours before landfall of a hurricane.

The National Weather Service's goal is to issue a hurricane WARNING 18-24 hours before landfall. If a minimum elevation of 7.8 feet exists, the necessary evacuation time is possible as shown in the surge profiles in Appendix C. However, if the minimum elevation is 4 feet or less, evacuation *may be possible*. It would also be equally *likely not to be possible*, regardless of the number desiring to leave.

Mustang Island

The principal population center on Mustang Island is Port Aransas. There are two means of access to Port Aransas. The first, via Park Road 53 and the Kennedy Causeway is 22 miles of mostly two-lane highway subject to blowing sand and flooding due to the low elevation (five feet or less) and close proximity to the Gulf. The second access, Via SH-361, is 6 miles of equally poor conditions and a short ferry ride. The second alternative appears to offer less exposure and should be open as long as the causeway alternative because the ferry operates until 4-foot tides and/or hurricane force winds arrive.

Population

The 1970 census placed the Port Aransas population at 1218. The estimated population increase for the Corpus Christi SMSA through July 1, 1976 was 4.8

percent. Using this percentage yields a population estimate of 1276 which will be used to project vehicles available for evacuation.

Vehicles Available

The 1970 U.S. Census (6) indicated somewhat more than 652 autos available in Port Aransas. This is a per capita auto availability of 0.535. The 1970 per capita rate for Nueces County based on census data is 94,208 autos divided by 237,544 persons, or 0.396.

The 1976 registered auto count was 125,481 and the population estimate was 247,600. The per capita auto rate was therefore 0.507 for Nueces County. The number of registered trucks was 35,305. This results in a 0.043 per capita pickups used as personal vehicles based on the 30 percent factor (1) explained earlier.

Again, for the purposes of the study, the Port Aransas per capita vehicle rate will be estimated based on actual 1976 Nueces County registrations. The Nueces County rate will be factored by the ratio of the 1970 census autos per capita for Port Aransas divided by the 1970 census autos per capita for Nueces County (0.532 divided by 0.396 yields a factor 1.36). The result is a per capita auto availability of 0.690 and a per capita pickup used as a personal vehicle availability of 0.041, or a total vehicle availability of 0.731 for Port Aransas. Total vehicles available for evacuation is, therefore, estimated as 1276 times 0.731, or 933.

Capacity

The ferries from Port Aransas to Aransas Pass have 3 slips at each end and a maximum capacity of six ferries making a round trip every ten minutes. A ferry's capacity averages 9 cars, yielding a capacity of 9 cars times six ferries times six trips per hour, or a total 324 cars per hour. For planning purposes, a capacity of 300 vehicles per hour will be used.

Time Required

To evacuate 933 vehicles at 300 vehicles per hour would require 3.2 hours. Based on survey responses (2), it is assumed that all residents will desire to evacuate.

Time Available

As previous stated, 4 foot tides can occur 18 to 36 hours prior to landfall of a hurricane. Under these circumstances, evacuation would have to begin prior to issuance of a hurricane warning. This would require action as soon as a tide buildup become apparent and would result in evacuation in many causes when landfall in the area did not become a reality. Again it is obvious that being trapped on the island is a definite possibility and appropriate plans should be made in advance.

South Padre Island

South Padre Island is the southmost barrier island along the Texas Gulf Coast. Access is provided by the Queen Isabella Causeway, a modern 4-lane divided facility. The majority of the island roadway system is two lane, except in the area approaching the causeway.

Population

The 1970 census included South Padre Island as a portion of a larger census tract including Port Isabel and Bayview. However, in September 1977 a special census was conducted by the U.S. Census Bureau for the island and indicated a population of 589 permanent residents.

Vehicles Available

For estimating purposes, the number of vehicles available will be assumed to be the same as for Port Aransas, or 0.731 per capita. An assumption is necessary since the 1970 census data can not be broken down for South Padre Island. This translates into 431 vehicles available for evacuation.

Capacity

The critical point in the system is the intersection of Park Road 100 and the causeway. However, it is questionable whether the 2-lane road system on the rest of the island can provide enough vehicles to reach the capacity of the bridge approaches. The distribution of the residents on the island is also not known. It will, therefore, be assumed that effectively the two lanes operate under urban flow conditions with an effective capacity of 500 vehicles per lane per hour, or 1000 vehicles per hour.

Time Required

The time required to evacuate 431 vehicles at 1000 vehicles per hour is about 26 minutes. Since the Town of South Padre Island has an ordinance (8) providing for mandatory evacuation, there is no reason to presume less than 100 percent evacuation.

Time Available

The approach to Queen Isabella causeway has a low point of 4 feet. As previously stated, tides of four feet can exist 18 to 36 hours before landfall. This may require action prior to issuance of an hurricane warning if evacuatuion is to be assured, otherwise it is very possible that residents would be stranded.

V. SUMMARY AND CONCLUSIONS

The report has evaluated, given present conditions, the first objective of the study--Is total evacuation of the four barrier islands possible? The answer to the question is: total evacuation may not be possible on any of the islands for some storms; it may not be possible during the time frame of a hurricane warning, nor during the time frame of a hurricane watch.

The second objective of the study was to determine what actions can improve the ability of residents to evacuate. An alternative is to improve forecasting procedures in those areas most critical to evacuation. For the Texas Gulf Coast barrier islands, the time of occurrence of four-tides, the probability of occurrence of four-foot tides and the severity of storms that can follow 18 to 36 hours behind a four-foot tide is information necessary for evaluation.

Another possible answer is to raise the elevation of the roadway. For this to be effective on a barrier island, the technique used on Galveston following the 1900 hurricane would be required. The technique was construction of a seawall and a literal raising of the island. It is not known whether this could be done today, given the present state of environmental awareness, nor if it is financially feasible.

If, after refining the analysis with better hurricane forecasting data, and if increasing roadway elevation is not possible, the remaining alternative is to protect residents at or near their homes. This would require structures of sufficient height and strength to weather a major hurricane, and the capacity to house the appropriate number of people.

It is necessary to look at Galveston as a special case. A large number of people live behind a seawall on a raised island. Because the seawall is not higher than some potential storm surges (tides) and because the seawall does not ring the island, evacuation is still a necessary consideration. In the case of Galveston, evacuation is contingent upon determination of the effect of subsidence on IH-45. If necessary, it may be possible to raise some roads, thereby providing a means of escape.

The study indicated that winds of about 50 mph and gusting to 75 mph can exist 10 to 20 hours before landfall of a hurricane. Since winds of the magnitude can overturn trucks, motor homes, and vehicles with trailers, consideration should be given to prohibiting these vehicles on the highways upon issuance of a hurricane warning. This would undoubtedly require special legislation.

One additional area that requires further study is tourists. This study assumed they would leave before the critical evacuation time period. The first question to be answered is how long will they stay? If they stay past the time critical to evacuation, then it is necessary to estimate their numbers.

APPENDIX A-CAPACITY

Capacity Under Interrupted and Uninterrupted Flow

This appendix is intended to serve two purposes. First, it documents the procedure used to arrive at the capacity figures used in Chapter III. Second, this appendix will provide the basic tools to further refine the capacity figures for specific locations if so desired. The analysis uses two different techniques, one for uninterrupted flow (9) and another for interrupted flow (10,11).

Uninterrupted Flow

Although few highways actually operate under the "ideal" conditions associated with uninterrupted flow, modern freeways, expressways, and rural highways may approach the "ideal" conditions required for uninterrupted flow conditions. Where there is at least two lanes for the exclusive movement of traffic in one direction, the capacity of a multilane highway under *ideal* conditions is considered to be 2000 *passenger* vehicles per lane per hour. The capacity of a two-lane, two-way roadway under *ideal* conditions is 2000 *passenger* vehicles per hour, *total of both directions.*

Interrupted Flow

Interrupted flow is generally associated with urban highways. Unlike uninterrupted flow, few broad criteria can be described for interrupted flow. It is not feasible to define capacities under ideal conditions, because too many variables are involved. Interrupted flow requires a detailed study of the elements producing the interruptions.

Generally speaking, a line of vehicles stopped by an interruption such as a traffic signal, will only rarely move away from an interruption at *rate* greater than 1750 passenger cars per lane per hour, during those periods when the interruption (e.g., red signal) is not in effect. *It is essential to note that these values are* rates, *not volumes.* For traffic signals, the values must be multiplied by the percent of total time the signal is green for the lane under consideration.

Factors Affecting Capacity

It is seldom that all roadway and traffic conditions that affect capacity are ideal. Therefore, adjustment factors must be applied to determine capacity for most highways. Factors affecting capacity can be classified in three categories--roadway factors, traffic factors, and ambient factors, although in some cases they are interrelated.

Roadway Factors

Restrictive physical features in a roadway that reduce the capacity and level of service generally are called "roadway factors" and include lane width, lateral clearance to roadside obstacles, grades, shoulders, auxiliary lanes, and surface conditions.

(1) Lane Width. Twelve-foot wide lanes are considered to represent an "ideal" lane width. Lane widths less than 12-ft. reduce roadway capacity. Narrow lanes adversely affect the ability to pass on two-lane highways. On multilane roadways, vehicle enroachment on adjacent lanes increases as the travel lanes narrow. Lane width reduction factors for lanes as narrow as 9 ft. have been established

as a percentage factor of the 12-ft. lane width considered ideal (100 percent). These factors are applicable for uninterrupted flow conditons.

(2) Lateral Clearance. Obstructions adjacent to the roadway (such as retaining walls, bridge abutments, sign posts, parked cars, etc.) located closer than 6 ft. from the edge of the travel lane reduce its effective width, and therefore, reduce capacity. Even one restriction will reduce the capacity of the entire section. Factors have been developed for application on uninterrupted flow conditions for obstructions closer than 6 ft.

(3) Grades. Grades affect capacity in several ways. On two-lane facilities, passing sight distance may be restricted and if the percentage of trucks in the traffic stream is appreciable, the capacity or service volume is considerably reduced, particularly when grades are long. To take into effect the reduction due to grades, degrading factors have been established for uninterrupted flow conditions. The factors are applied by considering the percentage of trucks, the general type of terrain (level, rolling, or mountainous) and on two-lane highways, considering the percentage of passing sight distance less than 1500 ft. along the highway section.

(4) Shoulders. To prevent short-duration lane blockage, shoulders are essential since one stalled vehicle can effectively block a travel lane. Shoulders, in addition to providing refuge for disabled vehicles, in some cases increase the effective width of the travel lanes. For lanes less than 12 ft. wide, surfaced shoulders 4 ft. wide or more increase the effective width of the adjacent travel lane by 1 ft.

(5) Auxiliary Lanes. Speed change, weaving, turn-bays, and climbing lanes improve the quality of service on the through lanes. Although not specifically quantified in capacity analysis, the presence of these lanes can improve capacity.

(6) Surface Conditions. Adjustment factors are not available to reflect the effect of surface conditions at particular levels of service. However, it may be assumed that where surface conditions are very poor, operating speeds are somewhat lowered for any given volume as compared to those attained where the surface is good.

Traffic Factors

Capacity and level of service on two geometrically similar highways may be appreciably different due to the composition and behavior of the traffic stream. Factors which take these considerations into account are called "traffic factors" and include trucks, buses, and traffic interruptions in particular.

(1) Trucks. Trucks and buses reduce the capacity of a highway in terms of the total vehicles carried per hour. Each truck displaces several passenger cars in the traffic stream. Also, trucks exhibit unique operating characteristics and slow the traffic stream on grades or due to passing sight distance problems, particularly on two-lane highways. Correction factors are based on truck volume percentages within the traffic stream for both uninterrupted and interrupted flow level of service analysis.

(2) Right and Left Turns. Right and left turning vehicles produce an adverse effect on capacity. Generally, turning factors become more important in interrupted flow analysis. The inclusion of turn=bays and separate signal phasing helps to reduce the turn conflicts.

Adjustment factors for left and right turns to and from both one-way and two-way streets have been established for interrupted flow level of service analysis.

Ambient Factors

Ambient conditions as previously stated are generally ignored in traffic capacity due to their infrequent occurrence. In Houston wet conditions (rainfall greater than 0.01") occur about 53 times a year during morning and evening peak periods. However, the likelihood of bad weather during a hurricane evacuation is high, and it is necessary to adjust capacity for rain, wind and high tides.

The development of factors for ambient conditions is difficult because, unfortunately, available data is often limited or widely variable. Nevertheless, what, hopefully, are conservative factors will be developed for hurricane evacuation analysis.

Rain. During the hurricane evacuation time frame (6-18 hours before arrival of the center), hourly rainfall varies from zero to .20 inches. The rainfall rate, however, is likely to be two to four times the total observed rainfall as the most intense part of a squall lasts only 10 to 15 minutes.

Studies (6) of rainfall records and extensive traffic flow data on the Gulf Freeway in Houston were used to define the effect of rain on capacity. Rain was found to reduce freeway capacity to between 81 and 86 percent of dry weather capacity with 95 percent confidence. These studies included hourly rainfalls that varied from as little as 0.01" to more than 1.0".

It, therefore, appears reasonable to reduce capacity because of rainfall, to 84 percent of dry weather capacity for hurricane evacuation purposes.

Although the data is for uninterrupted flow conditions, it will also be used as the best estimate of the effect on interrupted flow.

Rain has been shown (13) to increase accident rates, however, as shown in Appendix D, the overall effect of accidents in general is very small. For the purpose of this study, the effect of accidents in general will not be considered.

Wind. The problem associated with wind is the increased potential of an accident due to high winds, especially gusting winds. With the inception of the interstate highway system came the concern for vehicle handling under high-speed driving conditions, where the normal disturbance of the vehicle arises from aerodynamic inputs. Considerable work (14-16) has been done in the U.S., Germany and Japan in the area of modeling vehicle performance under crosswind gusts.

In reality, a constant crosswind will not occur. Due to natural gusts and obstacles in the vicinity of the road (e.g. bridges and other vehicles) both velocity and direction of the wind acting on the vehicle are changing with time and distance. The driver must, therefore, compensate for directional deviations of his vehicle. Beyond a limit that is difficult to calcuate, these tedious directional adjustments will become a risk for driver and vehicle.

Desirably we would like to know at what wind speed or gust condition various vehicles become unstable. Although the state of the art does not appear to be able to give us a direct answer, it does give an indication of what causes the problem. Futhermore, empirical evidence also gives an estimate of when a problem does occur.

Winds that ranged from 0 to 47 mph and gusting to 75 mph (based on 1.6 gust factor) caused a serious accident problem for trucks and motor homes on I-8 mountain bridge (17). Since winds of this magnitude can exist 10 to 20 hours before the arrival of the eye (see Appendix B), prohibition of trucks, motor homes, and vehicles with trailers should be considered upon issuance of a hurricane warning. This would undoubtedly require special legislation. The reason for considering such drastic action is that it is difficult to remove a large vehicle from the roadway. It should also be noted that the Governor of Texas authorized the movement of mobile homes without permits during Hurricane Anita in 1977. The appropriate action would have been to cancel any existing permits effective upon issuance of a hurricane warning.

Since it is not possible to estimate the effects of wind on large vehicles at this time, the analysis must presume appropriate action to eliminate the accidents and associated capacity reduction caused by such vehicles. The most effective measure would be the prohibition previously stated.

Tide. Rising tides perhaps have greatest effect on capacity. Once the roadway is flooded, the capacity is reduced to zero. For the purposes of analysis, it will be assumed that once half a lane width of pavement is covered, the lane no longer has any capacity. What additional capacity does exist will be required to clear vehicles already on the highway, but no additional vehicles should be allowed to begin evacuation.

The prediction of tides is difficult. The National Weather Service has developed two computer models to predict tides *along the open coast.* Nineteen computer runs using the Splash II model were made along tracks as shown in Appendix C. The differences in tide heights are primarily the result of differences in water depth offshore.

Due to the limitations of the model, it is necessary to use the data with *caution.* The data are certainly reasonable for roads along the islands. It will also be used as an *approximation* of what may happen in the bays and on the mainland immediately in from the bays. *However, tides can rise faster in the bays due to the confined nature of the basins.*

Uninterrupted Flow Capacity Calculations

For planning purposes, we need to determine the maximum volume that may be accommodated. This maximum volume is computed by making a number of adjustments or corrections to the ideal capacity for various factors influencing capacity. The general expression for including these factors is as follows:

Capacity = (Ideal Capacity) x
(Roadway Factors) x (Traffic Factors) x (Ambient Factors).

When we quantify the function, the relationship becomes:

$$C = 2000 \text{ vph/lane} \times N \times W \times T \times A.$$

where:

N = Number of lanes in one direction.

W = A fractional multiplier to account for the reduction effects of lane width and lateral clearance of obstructions.

T = A fractional multiplier to account for the effects of the number of trucks and the type of terrain.

A = A fractional multiplier to account for ambient conditions.

Computational Procedures for Two-Lane Highways

The general relationship developed above is applicable to two-lane highways, except for the application of N, the number of lanes. For two-lane highways, N = 1, because they are only able to accomodate a total of 2000 vph in both directions. If vehicles have complete freedom to pass (opposing volume approaches 0) the capacity in one direction approaches 2000 vph.
Thus, the relationship is:

$$\text{Capacity} = 2000 \text{ vph} \times W \times T \times A$$

Roadway Factors. For two-lane highways, roadway factors consist of lane widths and lateral clearances, sight distance restrictions, and average highway speed. Adjustment factors for the combined effect of lane width and lateral clearances are give in Table A-1.

Traffic Factor. The adjustment factors for the effect of trucks on capacity are found in Table A-2.

Ambient Factor. The adjustment factor for the effect of rain is 0.84.

Computational Procedures for Multilane Highways and Freeways

The main difference in dealing with multilane highways and freeways compared to two-lane highways is that capacity is based on the number of lanes, whether or not the facility is divided or undivided and whether access is controlled. The general capacity relationship developed earlier applies:

$$\text{Capacity} = 2000 \times N \times W \times T \times A$$

Roadway Factors. Lane width and lateral clearance effects are combined into one adjustment factor given in Tables A-3 and A-4. Table A-3 applies to divided highways and freeways.

Traffic Factors. The adjustment factors for trucks related to type of terrain are given in Table A-5 and Table A-6. These factors apply to freeways as well as multilane highways. Either table may be used.

Ambient Factor. The adjustment factor for the effect of rain is 0.84.

Generalized Capacity

For planning purposes, a single generalized capacity for uninterrupted flow would be useful. Several assumptions will be made concerning prevailing conditions such that a generalized capacity can be computed. The assumed

Table A-1: Combined Effect of Lane Width and Restricted Lateral Clearance On Capacity of Two-Lane Highways with Uninterrupted Flow.

Distance From Traffic Lane Edge To Obstruction (FT)	Adjustment Factor *W* For Lateral Clearance & Lane Width							
	Obstruction on One Side Only				Obstructions on Both Sides			
	12-FT Lanes	11-FT Lanes	10-FT Lanes	9-FT Lanes	12-FT Lanes	11-FT Lanes	10-FT Lanes	9-FT Lanes
6	1.00	0.88	0.81	0.76	1.00	0.88	0.81	0.76
4	0.97	0.85	0.79	0.74	0.94	0.83	0.76	0.71
2	0.93	0.81	0.75	0.70	0.85	0.75	0.69	0.65
0	0.88	0.77	0.71	0.66	0.76	0.67	0.62	0.58

Source: Reference (9)

Table A-2: Average Generalized Adjustment Factors for Trucks on Two-Lane Highways, over Extended Section Lengths.

Percentage of Trucks	Truck Adjustment Factor, *T*		
	Level Terrain	Rolling Terrain	Mountainous Terrain
1	0.99	0.96	0.90
2	0.98	0.93	0.82
3	0.97	0.89	0.75
4	0.96	0.86	0.69
5	0.95	0.83	0.65
6	0.94	0.81	0.60
7	0.93	0.78	0.57
8	0.93	0.76	0.53
9	0.92	0.74	0.50
10	0.91	0.71	0.48
12	0.89	0.68	0.43
14	0.88	0.64	0.39
16	0.86	0.61	0.36
18	0.85	0.58	0.34
20	0.83	0.56	0.31

Source: Reference (9)

Table A-3: Combined Effect of Lane Width and Lateral Clearance on Capacity of Undivided Multilane Highways with Uninterrupted Flow

DISTANCE FROM TRAFFIC LANE EDGE TO OBSTRUCTION (FT)	ADJUSTMENT FACTOR, *W*, FOR LATERAL CLEARANCE AND LANE WIDTH							
	OBSTRUCTION ON RIGHT SIDE ONLY, OF ONE-DIRECTION TRAVELED WAY (INCLUDES ALLOWANCE FOR OPPOSING TRAFFIC ON LEFT)				OBSTRUCTIONS ON BOTH SIDES OF ONE-DIRECTION TRAVELED WAY			
	12-FT LANES	11-FT LANES	10-FT LANES	9-FT LANES	12-FT LANES	11-FT LANES	10-FT LANES	9-FT LANES
(*a*) 4-LANE UNDIVIDED HIGHWAY, ONE DIRECTION OF TRAVEL								
6	1.00	0.95	0.89	0.77	N.A.	N.A.	N.A.	N.A.
4	0.98	0.94	0.88	0.76	N.A.	N.A.	N.A.	N.A.
2	0.95	0.92	0.86	0.75	0.94	0.91	0.86	N.A.
0	0.88	0.85	0.80	0.70	0.81	0.79	0.74	0.66
(*b*) 6-LANE UNDIVIDED HIGHWAY, ONE DIRECTION OF TRAVEL								
6	1.00	0.95	0.89	0.77	N.A.	N.A.	N.A.	N.A.
4	0.99	0.94	0.88	0.76	N.A.	N.A.	N.A.	N.A.
2	0.97	0.93	0.86	0.75	0.96	0.92	0.85	N.A.
0	0.94	0.90	0.83	0.72	0.91	0.87	0.81	0.70

Source: Reference (9)

Table A-4: Combined Effect of Lane Width and Restricted Lateral Clearance on Capacity of Divided Multilane Freeways and Multilane Highways with Uninterrupted Flow

DISTANCE FROM TRAFFIC LANE EDGE TO OBSTRUCTION (FT)	ADJUSTMENT FACTOR, *W*, FOR LANE WIDTH AND LATERAL CLEARANCE							
	OBSTRUCTION ON ONE SIDE OF ONE-DIRECTION ROADWAY				OBSTRUCTIONS ON BOTH SIDES OF ONE-DIRECTION ROADWAY			
	12-FT LANES	11-FT LANES	10-FT LANES	9-FT LANES	12-FT LANES	11-FT LANES	10-FT LANES	9-FT LANES
(*a*) 4-LANE DIVIDED FREEWAY, ONE DIRECTION OF TRAVEL								
6	1.00	0.97	0.91	0.81	1.00	0.97	0.91	0.81
4	0.99	0.96	0.90	0.80	0.98	0.95	0.89	0.79
2	0.97	0.94	0.88	0.79	0.94	0.91	0.86	0.76
0	0.90	0.87	0.82	0.73	0.81	0.79	0.74	0.66
(*b*) 6- AND 8-LANE DIVIDED FREEWAY, ONE DIRECTION OF TRAVEL								
6	1.00	0.96	0.89	0.78	1.00	0.96	0.89	0.78
4	0.99	0.95	0.88	0.77	0.98	0.94	0.87	0.77
2	0.97	0.93	0.87	0.76	0.96	0.92	0.85	0.75
0	0.94	0.91	0.85	0.74	0.91	0.87	0.81	0.70

Source: Reference (9)

Table A-5: Average Generalized Passenger Car Equivalents of Trucks and Buses on Freeways and Multi-Lane Highways, Over Extended Section Lengths (Including Upgrades, Downgrades, and Level Subsections).

Adjustment Factors	Equivalent, *E*, For:		
	Level Terrain	Rolling Terrain	Mountainous Terrain
E for trucks	2	4	8
E for trucks	1.6	3	5

Source: Reference (9)

Table A-6: Adjustment Factors for Trucks on Freeways and Multi-Lane Highways, over Extended Section Length.

PERCENTAGE OF TRUCKS	FACTOR, *T*, FOR ALL LEVELS OF SERVICE		
	LEVEL TERRAIN	ROLLING TERRAIN	MOUNTAINOUS TERRAIN
1	0.99	0.97	0.93
2	0.98	0.94	0.88
3	0.97	0.92	0.83
4	0.96	0.89	0.78
5	0.95	0.87	0.74
6	0.94	0.85	0.70
7	0.93	0.83	0.67
8	0.93	0.81	0.64
9	0.92	0.79	0.61
10	0.91	0.77	0.59
12	0.89	0.74	0.54
14	0.88	0.70	0.51
16	0.86	0.68	0.47
18	0.85	0.65	0.44
20	0.83	0.63	0.42

Source: Reference (9)

conditions are a two-lane roadway, ten-foot lanes, obstructions on both sides within 0-feet, and five percent trucks over rolling terrain.

As previously stated:

Capacity = 2000 vph x W x T x A

Thus: Capacity = 2000 vph x .62 x .83 x .84

or 864.5 vehicles per hour. A figure of 850 vehicles per hour on a two-lane rural roadway is suggested for planning purposes.

For multilane highways and freeways, the assumed conditions are a four-lane undivided highway, 10-foot lanes, and 5 percent trucks over rolling terrain.

As previously stated:

Capacity = 2000 vph x N x W x T x A

Thus: Capacity = 2000 x 1.0 x 0.80 x 0.87 x 0.84

or 1169 vehicles per lane per hour. A planning figure of 1150 vehicles per lane per hour is suggested for multilane highways both divided and undivided, even though a divided highway would have a higher capacity. The difference is small and does not warrant special consideration.

Interrupted Flow Computational Procedures for Capacity

Capacity and level-of-service on urban streets where interrupted flow exists are predominantly related to the intersection. The reason, of course, is because time sharing of the area common to both approach roadways significantly reduces the capability of a street to handle traffic flow. Further, the capacity for interrupted flow is built almost entirely around signalized intersections.

The following procedure has been simplified for planning purposes. Those desiring a more rigorous approach should refer to References (10 and 11) which are the basis of the procedure used here or reference (9) which provides an alternative method.

An approximate expression for the number of vehicles that can move into an intersection from one approach movement is:

$$CAP = 1203 \times G \times N/C$$

Where:

G is the amount of green time for a particular evacuation approach movement.

N is the number of approach lanes going in the direction of the evacuation route, and

C is the cycle length.

The expression is derived as follows. The reader can refer to References (10 and 11) for a detailed explanation. The number of vehicles, NV, that can move from one approach movement is:

$$NV = g \times \frac{S}{3600}$$

where S is the saturation capacity flow of the approach in vehicles per hour and g is approximately equal to the actual green, G, in seconds.

The number of vehicles that can enter the intersection per hour from the approach, the capacity CAP, is

$$CAP = NV \times \frac{3600}{C}$$

where C is the cycle length in seconds, or:

$$CAP = \frac{G \times S \times 3600}{3600 \times C}$$

thus: $$CAP = \frac{G \times S}{C}$$

If we add an adjustment for ambient conditions equal to 0.84, then:

$$CAP = 0.84 \frac{G \times S}{C}$$

Table A-7 provides the appropriate saturation flows to solve for capacity. However, Table A-7 is in through car units and it is necessary to adjust for trucks, buses and turning vehicles. Table A-8 provides appropriate adjustment factors.

Table A-7: Saturation Flow Data

Lane Width	9'	10' to 12'
Lane Type	Saturation Flows	Through Car Units/hr.
Through & Through Right	1600	1750
Through Left		1550
Left		1700

Source: Reference (10)

Table A-8: Through Car Unit (T.C.U.) Factors

One truck or bus	=	2.0 passenger cars (p.c.)
One left turn (p.c.)	=	3.0 T.C.U.'s
One right turn (p.c.)	=	1.25 T.C.U.'s
One through (p.c.)	=	1.0 T.C.U.

Source: Reference (10)

To simplify the expression for planning purposes, we will assume a two-lane approach, no special turning lanes, 5 percent trucks, 5 percent left turns, 5 percent right turns, and 10-foot lanes.

The appropriate left lane saturation flow is 1550 T.C.U.'s per hour. Therefore 1550 equals the number of through cars, 0.95V, plus the adjusted number of left-turning cars, 0.05V x 3.00, plus the adjusted number of trucks, 0.05V x 2.00. The number of vehicles, V, is 1292.

Similarly for the right lane, the saturation flow of 1750 equals 0.95V + (0.05V x 2.00) + (0.05V x 1.25). The number of vehicles, V is 1573. Therefore, the average for the two lanes is 1432 vehicles per hour. Substituting in the capacity formula yields:

$$CAP = 0.84 \frac{S}{C} \times 1432$$

or:

$$CAP = 1203 \frac{G}{C}$$

The critical intersection is that intersection having the lowest N, times G, divided by C value. Several additional factors must be considered. Has a special hurricane evacuation timing plan been developed? Will the traffic signal be operated during an evacuation? Will the police override the signal timing or manually direct traffic?

If the signal is turned off, the green time effectively becomes 100 percent. If the signal timing is changed, so is the green time for any approach and possibly the cycle length. However, the green time cannot exceed 100 percent and is less than 100 percent when time is allocated to two or more approaches due to loss time (the yellow interval) when changing from one approach to another.

If we further assume that two two-way streets intersect, there are no special turning phases (e.g. left turn green arrow), a 60-second cycle length, and time is equally apportioned between the two streets, the capacity would be:

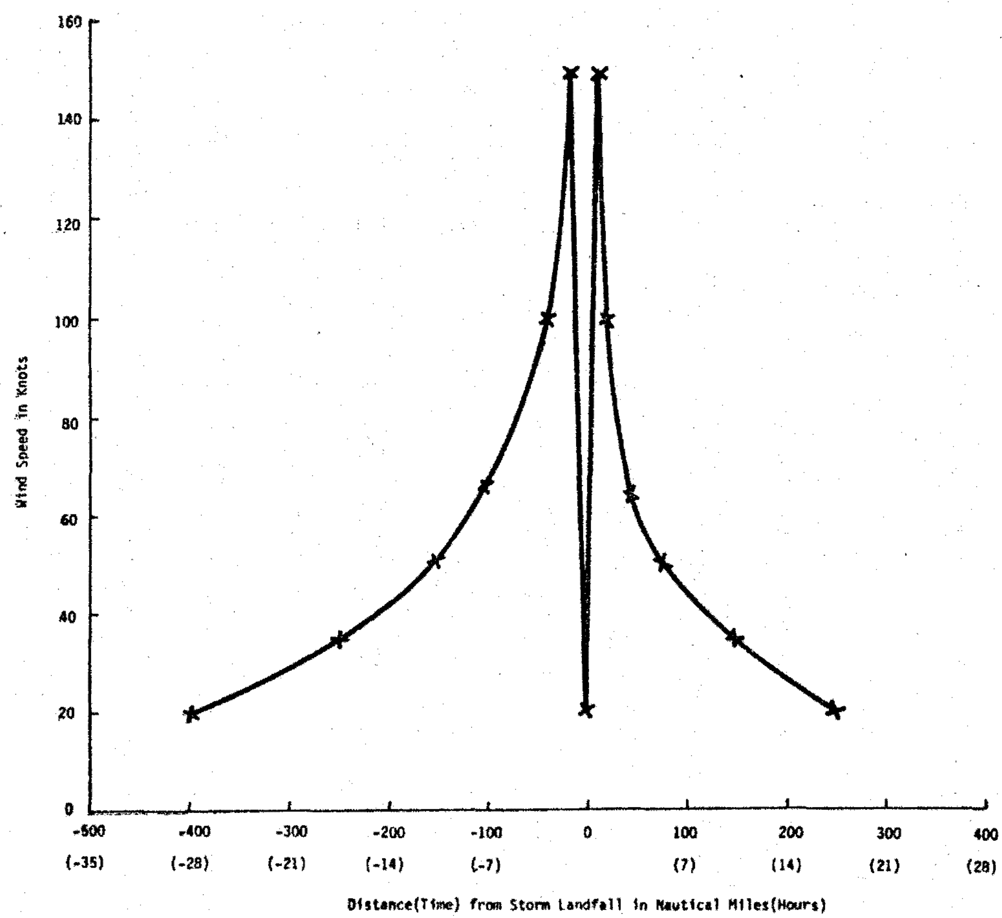
$$CAP = 1203 \times 25 \times N/60$$

or 501.2 vehicles per <u>lane</u> per hour. A figure of 500 vehicles per lane per hour would not be unreasonable in an urban area.

APPENDIX B

Model Hurricane Windfield

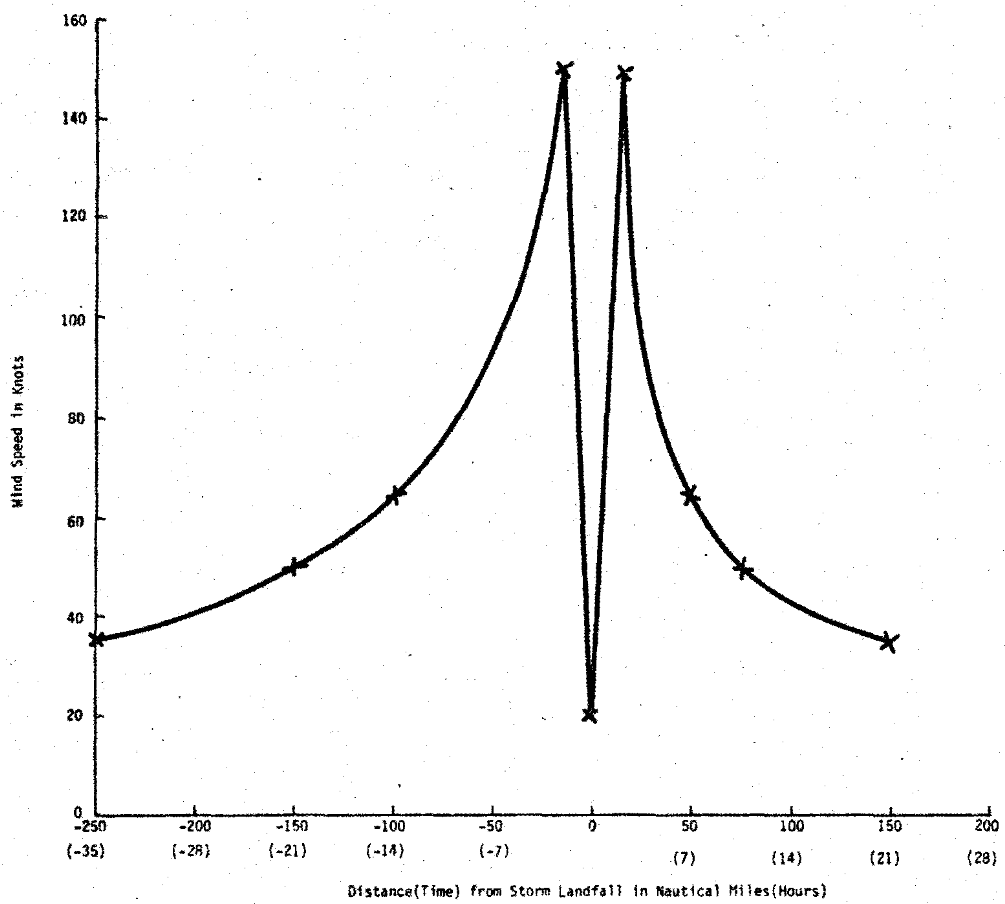
The graph in Figure B-1 is a model of sustained winds in a 910 millibar hurricane with a radius of 30 nautical miles and moving at 14 knots. Actual records of winds of hurricanes show great variation with time and not the smooth increase shown in the model. Most of the wind during a hurricane evacuation is likely to occur in squalls with much higher gusts than indicated on the graph of sustained winds. The 20 knot winds in the eye and on the periphery of hurricanes should NOT be used for planning purposes.



Source: National Hurricane Center

Figure B-1 Model wind profile for 910 millibar hurricane moving at 14 knots and having an eye diameter of 30 nautical miles.

Figure B-2 is the same size storm as Figure B-1, but moving at half the speed. Although the slower storm has the same peak winds, its effect is felt much sooner in time.



Source: National Hurricane Center

Figure B-2 Model wind profile for a 910 millibar hurricane moving at 7 knots and having an eye diameter of 30 nautical miles.

APPENDIX C

Storm Surge Model

The National Hurricane Center uses two computer models--SPLASH I and SPLASH II-- to predict storm surge (hurricane tides). SPLASH I is generally used for hurricanes making landfall, while SPLASH II was designed for hurricanes paralleling the coast. However, only SPLASH II provides the tide versus time output required for this study. Therefore, SPLASH II was used for all hurricane tracks in this study.

Nineteen computer runs were made along 14 tracks as incicated in the maps in Figure C-1. Storms with central pressures of 910 and 950 millibars were simulated. Ten runs moved the hurricane onshore perpendicular to the coastline at 5 different locations indicated as tracks 1 to 5 in Figure C-1. Two different storm intensities where used along each of the five tracks and given the suffix A for 910 millibar storms and the suffix B for 950 millibar storms.

Eight runs (numbered 6-13 in Figure C-1) moved the hurricane paralleling the coast, the point nearest the coastline. Tracks 6 and 7 represent a storm having a 930 millibar central pressure at 10 which increases to 950 millibars at T_{24}. Tracks 8 through 13 have a 940 millibar central pressure at T_0 and a 960 millibar central pressure at T_{24}.

The final track, number 14 on Figure C-1 moves a storm with a central pressure of 940 millibars across Galveston Island from the south. The eye of all 14 storms have a radius of 15 nautical miles. A 950 millibar hurricane is a category 3 hurricane and a 910 millibar hurricane is a category 5 hurricane. Categories 3, 4, and 5 are all considered to be major hurricanes.

The results of the computer simulation is shown for selected location along the Texas Gulf Coast in Figure C-2 through C-5. Several qualifications must be noted. The projections are for a single point along the coast. The computations are valid estimates on the *open coast only*. Broken features (bays, estuaries, intracoastal waterways, etc.) are NOT incorporated in the model.

The onset of tides 2 to 4 feet above normal, which can cut off some evacuation routes, can frequently occur along the Texas Coast 36 hours or more before landfall with large, slow moving hurricanes, and 18-24 hours before landfall with large, faster moving hurricanes.

The purpose of the projections selected is not to pick peak surge values, but to estimate the time versus surge relationship for several storms. Due to the severe limitations of the estimates, they must be used with extreme caution. In all cases, they are only a indication of what might happen, not necessarily what will happen.

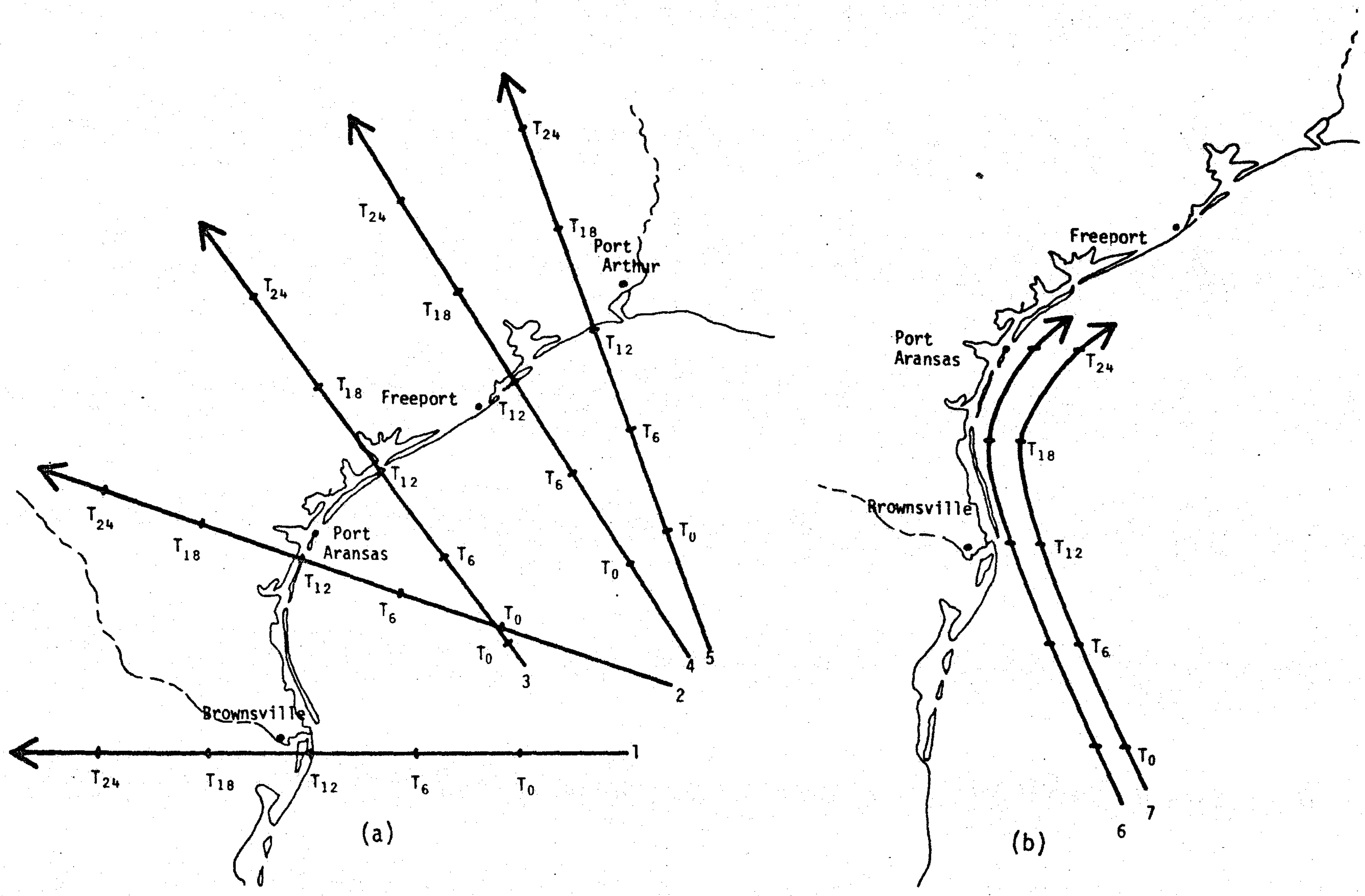


Figure C-1: Storm Surge Model Hurricane Tracks for Texas Coast

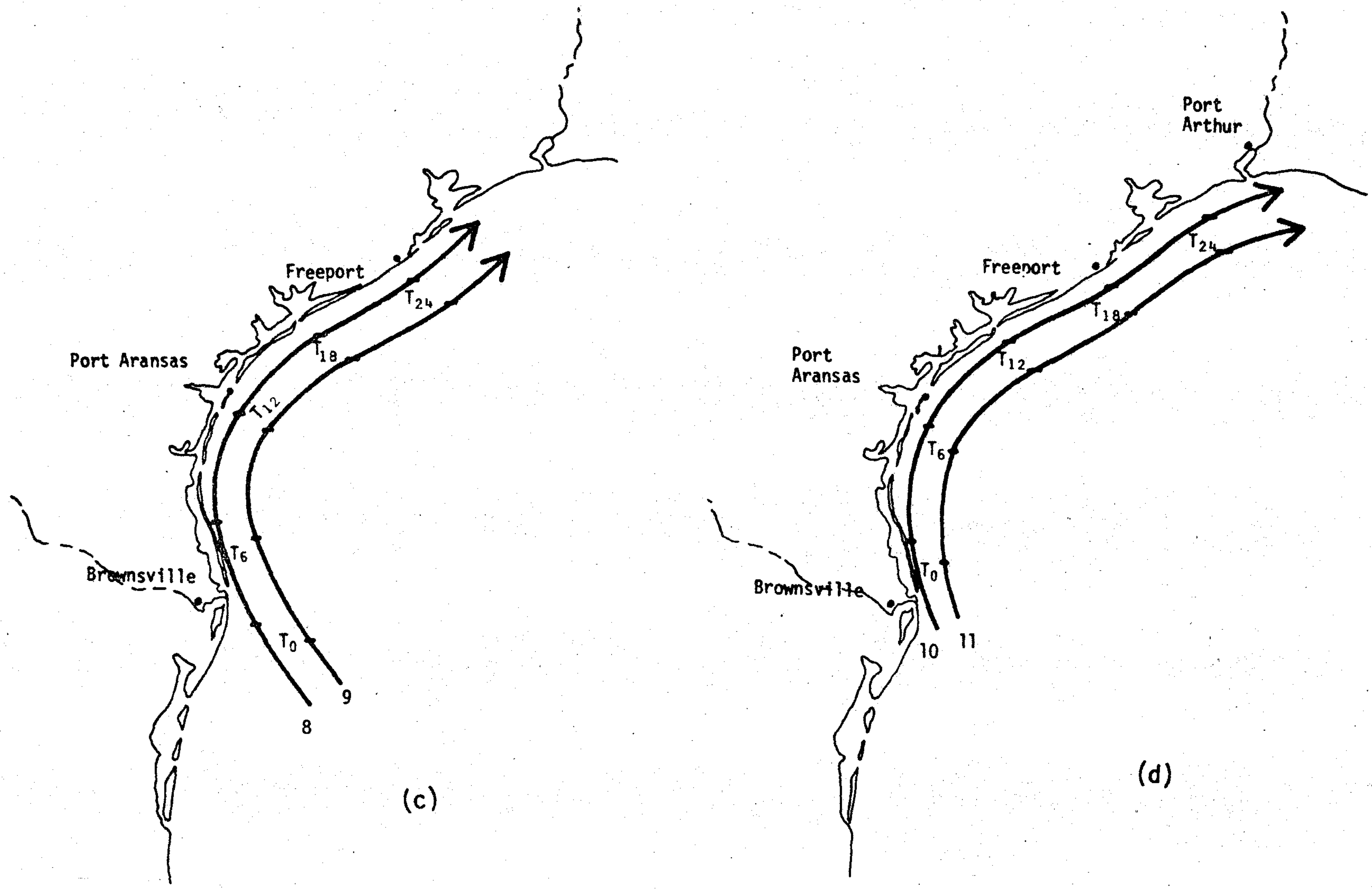


Figure C-1 (continued): Storm Surge Model Hurricane Tracks for Texas Coast

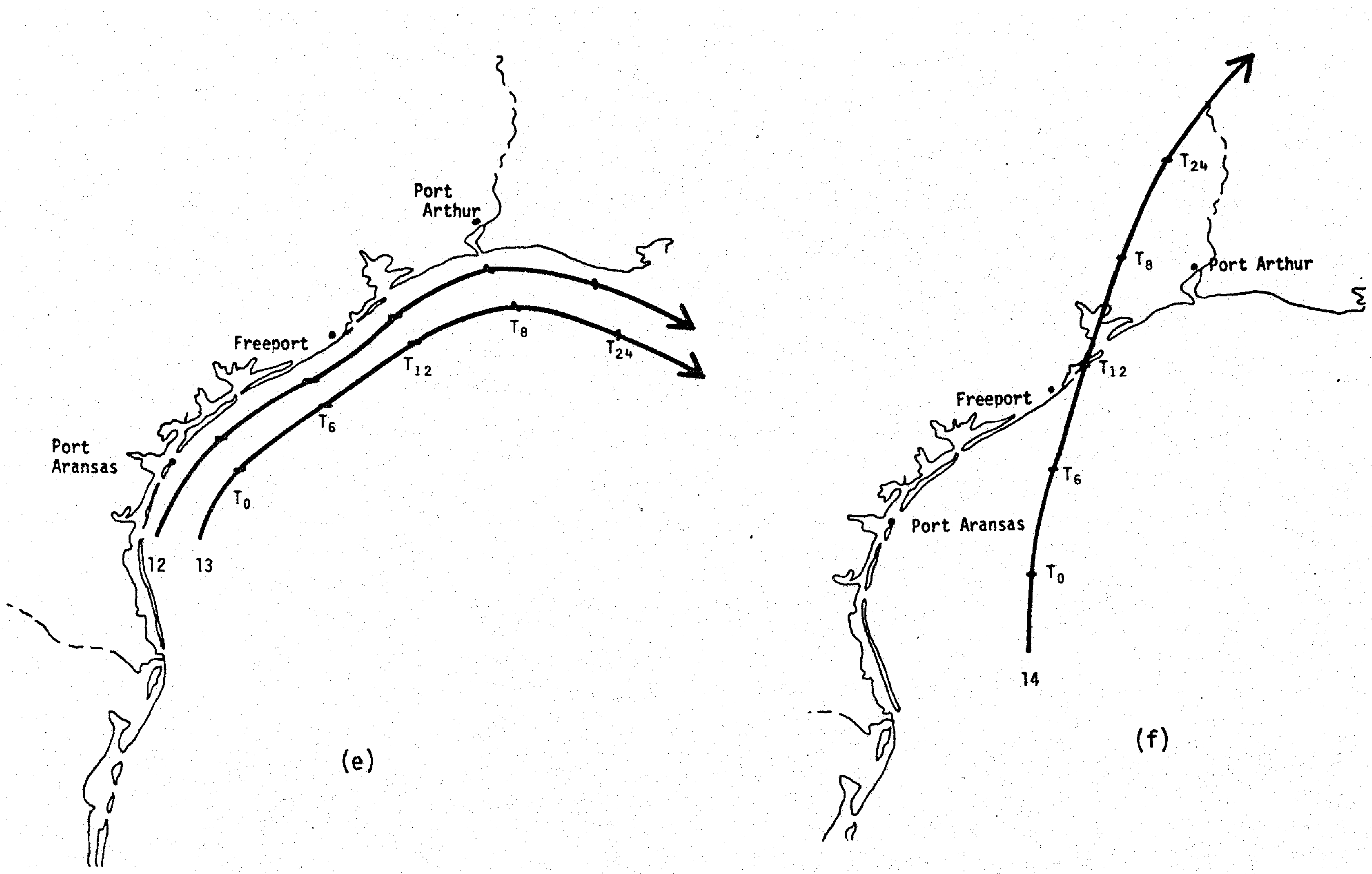
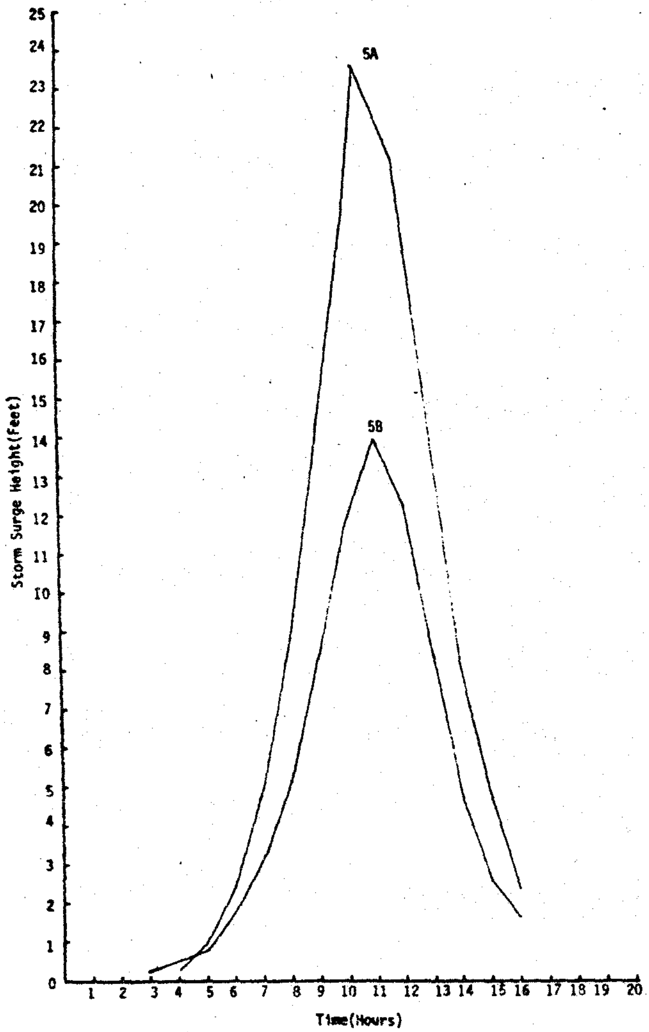
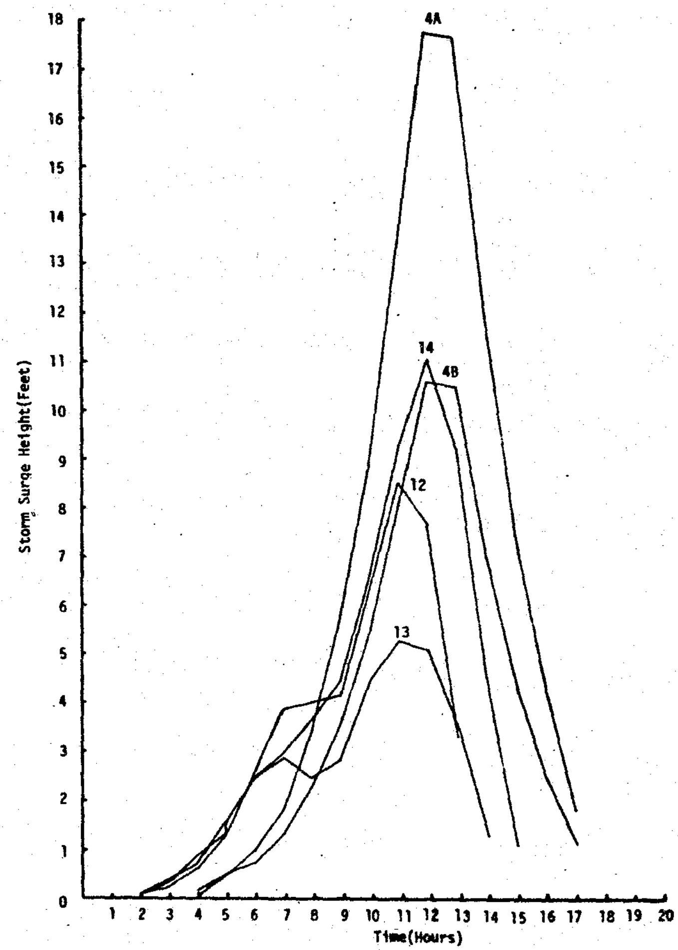


Figure C-1 (continued): Storm Surge Model Hurricane Tracks for Texas Coast



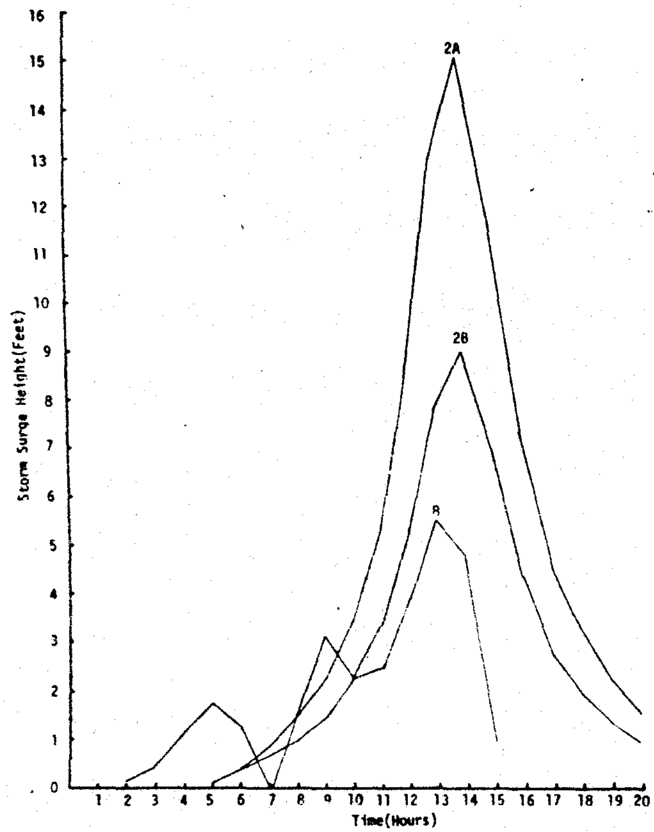
Source: National Hurricane Center

Figure C-2: Potential Storm Surges at Sabine Pass



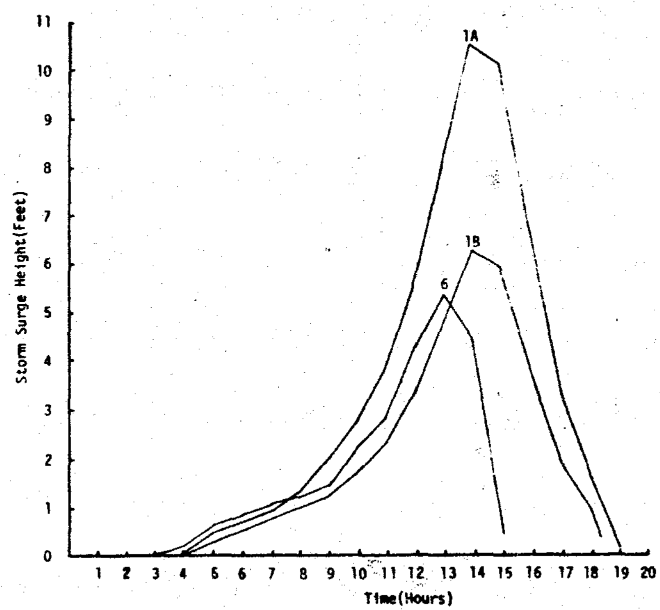
Source: National Hurricane Center

Figure C-3: Potential Storm Surges at Galveston



Source: National Hurricane Center

Figure C-4: Potential Storm Surges at Port Aransas



Source: National Hurricane Center

Figure C-5: Potential Storm Surges at Port Isabel

APPENDIX D

Capacity Reduction Due to Accidents

The following procedure was used to estimate capacity reductions due to accidents. Although there are several inherent problems with the process used, it is the best that can be done with available data.

First, it is assumed that the evacuation route is 10 miles long with 80 percent being rural and 20 percent urban. The capacity of the rural section is assumed to be 6000 vehicles per hour and the urban section is assumed to have a capacity of 5250 vehicles per hour. These capacities both assume 3 lanes and nearly ideal conditions.

The accident rates for Texas highways in 1977 was 57.15 rural and 151.00 urban injury accidents per 100 million vehicle miles. It is assumed that injury accidents are the only ones that are severe enough to cause significant traffic problems. The fact that accident rates in the rain are high is not considered.

The number of rural accidents per hour on the hypothetical roadway system is 6000 vehicles per hour times 8 miles times 57.16 divided by 100 million, or 0.03 accidents per hour. For the urban section, the number of accidents per hour is 5250 times 2 times 151 divided by 100 million, or 0.016 accidents per hour.

Studies on the Gulf Freeway in Houston (17) indicate an accident reduces capacity to 48 percent of normal if one of the three lanes is blocked. Detection takes 1 minute due to the existence of television surveillance on the Gulf Freeway. It is anticipated that detection would also be quick during an evacuation. Location, dispatch and travel to the scene required 11 minutes. Clearing the accident required 4 minutes and investigation required 24½ minutes. It is assumed that investigation would be forgone during evacuation. During the 16 minutes from occurrence to clearance, capacity was reduced 51 percent from 92.7

vehicles/minute to 45.3 vehicles/min.

Given the above data and assumption, the capacity reduction due to accidents on the rural portion is 0.03 accidents/hour times 16 minutes/accidents times 1 hour/60 minutes times 51 percent reduction in capacity, or 0.41 percent. For the urban portion, the capacity reduction is 0.016 times 16 times 51 divided by 60, or 0.22 percent.

To indicate the sensitivity of the result to the assumption, the reduction was recomputed with the accident rate doubled. The result is a doubling of the reduction in capacity to 0.82 percent in the rural section and 0.44 percent in the urban section. It is therefore suggested that accidents of a routine nature be ignored in the analysis.

APPENDIX E

Texas Vehicles Per Capita

Registration Year	Autos	Trucks	Population	Autos Per Capita	Trucks Per Capita	.3x Trucks Per Capita
1970	5,092,881	1,467,205	11,198,655	0.455	0.131	0.039
1976	6,534,582	2,265,787	12,486,900	0.523	0.181	0.054

Source: U.S. Census Burea and State Department of Highways and Public Transportation

REFERENCES

1. A Preliminary Evaluation of the Temporal Stability of Trip Generation Rates. D. L. Christiansen and V. G. Stover, Texas Transportation Institute Research Report 167-6, College Station, Texas, April 1973.

2. Post Anita Survey. Texas Coastal and Marine Council, unpublished, 1977.

3. Reactions to Storm Threat During Hurricane Eloise. G. O. Windham, E. I. Posey, P. J. Ross and B. G. Spencer, Social Science Research Center, Mississippi State University, Report 51, March 1977.

4. Hurricane Carla. September 3-14, 1961, Mattie E. Treadwell, Department of Defense, Office of Civil Defense, Region 5, Denton, Texas, U.S. Government Printing Office, Washington, D.C., no date.

5. Assessment of a Hurricane Awareness Program. L. Christensen and C. E. Ruch, Texas A & M University, College Station, Texas, c. 1977.

6. 1970 Census of Population. U.S. Department of Commerce, Bureau of Census, U. S. Government Printing Office, Washington, D. C., May 1973.

7. Bolivar Peninsula, A Growth Management and Beach Access Study. Texas A & M University School of Landscape Architecture, College Station, Texas, August 1978.

8. Accident Reporting and Clearance Procedures on the Gulf Freeway. Merrell E. Goolsby, Texas Transportation Institute Research Report 139-1, College Station, Texas, September 1969.

9. Highway Capacity Manual. Highway Research Board, Special Report 87, Washington, D. C., 1965.

10. Capacity and Quality of Service of Arterial Street Intersections. David J. Berry, Texas Transportation Institute Research Report 30-1, College Station, Texas, August 1974.

11. A Guide for Designing and Operating Signalized Intersections in Texas. C. J. Messer and D. B. Fambro, Texas Transportation Institute Research Report 203-1, College Station, Texas, August 1975.

12. Effect of Rain on Freeway Capacity. E. R. Jones and M. E. Goolsby, Texas Transportation Institute Research Report 24-23, College Station, Texas, August 1969.

13. An Investigation into the Relationship Between Rainfall and Road Accident Frequencies in Two Cities. Dariush Haghighi Talab, Accident Analysis and Prevention, Volume 5, Pregamon Press, Great Britian, 1973.

14. Theoretical Prediction of the Aerodynamic Derivatives of a Vehicle in Cross Wind Gusts. W. H. Huncho and H. J. Emmelmay SAE Transactions, Vol. 82, paper 730232, 1973.

15. Transient Nature of Wind Gust Effects on an Automobile. F. N. Beauvaes, SAE Transactions, Vol. 76, paper 670608, 1967.

16. Vehicle Performance in Crosswinds. P. J. Milner, Automobile Engineer, August, 1968.

17. The Use of a Screen to Subdue Gale-Force Winds on a Mountain Bridge. E. F. Nordlin and L. Bouryet, Highway Research Board Special Report 107, Washington, D. C., 1970.