An Economic Evaluation of Traffic Movement at Various Speeds

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The purpose of this study was to evaluate economic utility or cost of resources consumed by the highway transportation industry for various speeds of travel in rural and urban areas for passenger cars and commercial vehicles on 2- and 4- lane streets and highways during daytime and nighttime travel. Graphical relationships of economics of vehicle operation, values of time, safety of travel, and their sum, which is defined as the total cost of traffic movement, were drawn for the various conditions. The minimum point on each total cost curve represents that speed at which the cost of traffic movement is minimized.

Results indicated that there was a speed which minimized the cost of traffic movement for each of the various conditions considered. This speed was defined as the optimal speed. In rural areas the optimal speed was 50 mph for passenger cars and 41 mph for commercial vehicles. Optimal speeds in urban areas decreased with an increase in number of stops per mile from 41 to 29 mph for passenger cars and from 36 to 25 mph for commercial vehicles with 1 and 8 stops per mile, respectively.

The most direct application of the results is likely to be in the establishment of statewide or areawide speed limits where the limit is established so that the mean speed of the vehicles coincides with the optimal speed.

•HIGHWAY transportation is a branch of the transportation industry that consumes a large portion of America's resources, both natural and human (28). The expenditure of resources in promoting place and time utilities through highway transportation can be analyzed according to the following elements:

1. Economics of vehicle operation—expenditures incurred directly as a result of the operation of motor vehicles on street and highway systems.
2. Values of time to drivers and passengers—rate of travel has varied personal and business importance in affecting highway transportation.
3. Safety of travel—reduction of accidents has economic implications, such as decreased insurance rates, and personal bearings, such as absence of injury to ohe's self, friend, or relative.
4. Travel comfort and convenience—this service resource affects psychological attitudes of the motor vehicle occupants.

To obtain maximum benefits and services for a given investment of capital, labor, land, managerial ability, and technical innovation, proper distribution of these resources must be made among these various benefits and services (28). Therefore, it is essential that the most efficient allocation of these four resources be developed to

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enable the acquisition of optimal production of benefits and services in the highway transportation industry.

These four resources must be evaluated on a quantitative scale that allows them to be summed together in their proper proportions. This procedure is similar to the numerical system of arithmetic. A convenient method allowing the resources to be evaluated in their combined effect, and also in their proper proportion, is based on the expenditures of these resources per mile of travel, such as cents per mile. Because of the manner in which these various resources were measured, the investigation was reduced to an economic evaluation of traffic movement at various speeds.

The purpose of this study was to evaluate the economic utility or cost of the resources consumed by the highway transportation industry for various speeds of travel in rural and urban areas for passenger cars and commercial vehicles on 2- and 4-lane streets and highways during daytime and nighttime travel. This study was restricted to vehicular movement over level, tangent sections of well-paved streets and highways under free-flowing traffic conditions.

Graphical relationships of these four resource costs and their sum, defined as the total cost of traffic movement, were ascertained from economic studies of vehicular flow in rural and urban traffic areas for various types of motor vehicles. These curves were further refined for both 2- and 4-lane streets and highways and for daytime and nighttime travel conditions.

The speed that the majority of motor vehicles must travel to minimize the cost of traffic movement was obtained from the minimum points on the various total cost curves. The speed that minimizes the cost of traffic movement is defined as the "optimal speed" for the specified traffic area, vehicle type, highway type, and travel condition which the curve represents. These cost curves were representative of motor vehicle travel for roadway, traffic, and environmental conditions that are nearly ideal; that is, vehicular speeds were not limited by various physical and/or environmental factors. Because speeds of the various motor vehicles are not uniform but represent an approximate normal distribution, the optimal speed represents the mean speed of the motor vehicles (29).

Results of this investigation are likely to be useful in the development of statewide or areawide speed-zoning and in completing data that are lacking in the present road-user benefit analyses.

REVIEW OF LITERATURE

Many investigations have been made to evaluate motor vehicle movement costs at various speeds of operation. This review of literature has been confined to summarizing those studies that have attempted to measure traffic movement costs at various speeds in rural and urban areas for passenger cars and commercial vehicles on 2- and 4-lane streets and highways during daytime and nighttime travel conditions.

Operation Cost

Operation costs are defined as those direct road-user costs that are incurred as a result of the operation of motor vehicles. They can be divided into five elements: fuel, oil, tire, maintenance, and depreciation.

Fuel cost is influenced by both unit cost and consumption rate. Usually, fuel cost is approximately 40 to 50 percent of the total operation cost (6). Fuel consumption is dependent on the characteristics of the motor vehicle, speed and type of operation, road conditions, vehicle use, driving conditions, and individual driving practices (27).

"Road User Benefit Analyses for Highway Improvements" (6) disclosed some facts on fuel mileage of average on-the-road passenger cars operating at a constant speed over level, tangent sections of well-paved highways. For these conditions the fuel mileage increased with an increase in speed up to 18 miles per gallon (mpg) at 25 mph and then decreased at an increasing rate with additional increase in speed.

In a recent investigation, Claffey (5) reported fuel consumption rates at various speeds for a pickup and a dump truck, both in an empty and a loaded condition, and a passenger car. Results revealed that at the optimum speed, or the speed at which fuel consumption is at a minimum, fuel consumption of the empty pickup truck was the lowest, followed by the loaded pickup truck, passenger car, empty dump truck, and loaded dump truck.

Fuel consumption is less on 4-lane divided highways than on 2-, 3-, or 4-lane undivided highways. This differential is explained by the fact that passing maneuvers can be made with less change in speed on 4-lane highways than on either 2- or 3-lane highways. The median on a 4-lane divided highway provides a physical separation between opposing traffic, which helps to reduce the magnitude of speed changes and fuel consumption (6).

Fuel-consumption rates described in the preceding paragraphs can be used for restrictive-type vehicular operation (like that encountered along the built-up routes in urban areas), as well as for free-type vehicular operation (like that encountered along the non-built-up routes in rural areas or on fully controlled access routes in urban areas), if the additional fuel necessary for slow downs and stops is included in the total fuel consumption (6). Claffey (5) reported a linear increase in fuel consumption with an increase in speed. It was observed that the empty and loaded pickup truck consumed less fuel per stop for various approach speeds than did the passenger car, while the reverse was true for the empty and loaded dump truck. His investigation also disclosed excess fuel consumption caused by a slow down of 10 mph from various approach speeds. For both the empty and loaded conditions, the pickup and the dump trucks had definite speeds at which excess fuel consumption for a 10 mph slow down was a maximum, while excess fuel consumption for the passenger car increased at an increasing rate with an increase in speed. The four optimal approach speeds were in the 35- to 45-mph range.

In summary, fuel consumption, thus fuel cost, increased with an increase in speed beyond some optimal speed and in size of vehicle and increased with a decrease in number of traffic lanes and in freedom of vehicular operation.

Oil cost is a function of the unit price and the amount consumed. Major factors influencing oil consumption are maintenance practices, vehicle characteristics, condition of the engine and vehicle, speed of operation, vehicle equipment, road condition, weather, and driver characteristics (27).

Lane (18) related that oil mileage increased with increasing speed up to about 800 miles per quart (mpq) at 30 mph. Then, oil mileage decreased with further increases in speed to approximately 200 mpq at 70 mph.

The Washington State Highway Commission (39) observed that oil cost for a private passenger car was 0.185 cents per mile, while oil cost for commercial vehicles ranged from 0.107 cents per mile for a vehicle weighing 4,000 lb to 0.371 cents per mile for a vehicle weighing 60,000 lb.

Research has shown that oil consumption, hence oil cost, increased with an increase in speed beyond some optimal speed and in size of vehicle.

Tire cost is influenced by both initial cost and rate of wear. Rate of wear is dependent on vehicle characteristics, highway features, speed of travel, type of operation, tire maintenance, and driver habits (27).

Evans (8) reported that at 15 mph a passenger car obtained approximately 30 percent more tire mileage than at a speed of 35 mph and about 50 percent less tire mileage at 55 mph than at 35 mph.

From an investigation performed by the Washington State Highway Commission (39), tire cost for a private passenger car was found to be 0.496 cents per mile, while tire cost for commercial vehicles ranged from 0.411 cents per mile for a vehicle weighing 4,000 lb to 2.371 cents per mile for a vehicle weighing 60,000 lb.

Tire wear has been found to be less on 4-lane divided highways than on 2-, 3-, or 4-lane undivided highways. This is explained by the reduction in number of speed changes caused by passing maneuvers on 4-lane highways. The median on a 4-lane divided highway provides a physical separation between opposing traffic that also helps to reduce the magnitude of speed changes and tire wear (6).

Restrictive-type vehicular operation, peculiar to travel on city streets, greatly increases tire wear over that of the free-type vehicular operation found on rural highways and urban freeways. Moyer (25) found that a single stop and start at 35 mph wore away approximately as much rubber as a mile of travel at the same normal speed.

In summary, tire wear, thus tire cost, increased with an increase in speed beyond some optimal speed and in size of vehicle and increased with a decrease in number of lanes and in freedom of vehicular operation.

Maintenance cost, which includes cost of engine, chassis, body servicing and repairs, and lubrication, is difficult to relate to various conditions of vehicle operation. One vehicle may be given constant maintenance attention at considerable cost, yet give no better service than another vehicle receiving a minimum of maintenance. Results of hard usage at one time may not require repairs until long afterwards; therefore, it is very difficult to evaluate maintenance cost for various conditions of vehicle operation. Research has shown that maintenance cost is affected by maintenance practices, vehicle age and condition, roadway conditions, engine power and speed, speed of travel, and weather (27).

The Highway Engineering Handbook (42) prorated maintenance cost for various types of vehicles according to speed on the basis of fuel, oil, and tire cost. Therefore, maintenance cost decreases with an increase in speed up to some optimal speed and then increases with an increase in speed.

The Washington State Highway Commission (39) reported that maintenance cost for a private passenger car was 0.715 cents per mile, while the maintenance cost for commercial vehicles ranged from 4.533 to 8.845 cents per mile for vehicles weighing 4,000 to 60,000 lb, respectively.

Concerning the subject of restrictive-type vehicular operation, Wiley (40) asserted that required maintenance of brakes and clutches could be attributed to vehicle-stops. He prorated maintenance cost according to a straight-line variation between no cost at 0 mph and 0.05 cents per mile at 50 mph.

In summary, maintenance cost increased with an increase in speed, beyond some optimal speed and in vehicle size and with a decrease in freedom of vehicular operation.

Depreciation is a lessening in value of the motor vehicle due to the passage of time and/or use. That part chargeable to time is due to a loss in value because improvements have outmoded the vehicle, making it less desirable. That portion of depreciation which is a use-element cost is a function of travel rather than age. The Oregon State Highway Department suggests that two-thirds of the depreciation of passenger cars be prorated to mileage and one-third to time and that all the depreciation cost of commercial vehicles be prorated to mileage (23). The American Association of State Highway Officials (AASHO) allocated one-half of the depreciation cost of passenger cars to both mileage and time (6).

Mileage depreciation is affected by the characteristics of the motor vehicle, the highway, and the operation of the motor vehicle. Depreciation due to mileage is normally calculated on a straight-line basis; that is, to divide the initial cost of the vehicle, less salvage value, by the anticipated number of vehicle miles to be traveled by the motor vehicle (6, 23, 34, 41, 43).

AASHO recommends 1.0 cent per mile as the depreciation cost for passenger cars (6), while the Highway Engineering Handbook suggests for paved surfaces 1.0 cent per mile for passenger cars and light commercial vehicles, 1.5 cents per mile for single-unit trucks, and 2.5 cents per mile for combination vehicles (42). Therefore, depreciation cost increases with an increase in vehicle size.

Time Cost

The cost of the driver's and passenger's time must also be considered in a realistic appraisal of the economics of motor vehicle movement. There is a general acceptance that savings of time for commercial vehicles has value in direct proportion to the wages of the drivers, fixed-time costs for the vehicles, and net operating profits to the owners (6, 9, 11, 17, 19). Fewer people accept values of time, either economic or leisure, for passenger cars although it is admitted that some value is justified (6). Economic time is time gained or lost which affects the cost of production, distribution, or conservation of goods and services. This includes passenger cars of salesmen, repairmen, executives, and all who travel during working hours (10). In this case, the method of evaluation of time cost should be no different from that of commercial vehicles (6, 17).

Leisure time is time gained or lost which causes a gain or loss of convenience. It includes pleasure traffic, commuter traffic, and business traffic in those cases where gain or loss of time does not affect the cost of production, distribution, or conservation of goods and services (10). The following three methods exist to evaluate leisure-time cost for passenger cars: (a) operating-cost data, (b) the extra distance operators will travel in order to save time, and (c) arbitrary time values (34).

The theory behind the operation-cost method is that fixed cost for one hour is a measure of the value of one hour of time. This is based on the assumption that fixed cost of a passenger car continues in full effect as an element of operating cost when the vehicle is stopped or slowed down. To obtain time cost, in dollars per hour, fixed cost per mile is multiplied by the average speed of the vehicle (34).

To determine the extra distance passenger car operators travel to save time, time cost is equated to the extra mileage cost of operating the vehicle plus any toll charge divided by the time saved (34).

Many references indicate that time costs for passenger cars have been arbitrarily selected (1, 2, 3, 4, 6, 13, 14, 20, 24, 42). The most widely used method was suggested by AASHO. A time cost of $1.35 per hour per vehicle is recommended. The value resulted from an arbitrary selection of a time cost of $0.75 per person and an average of 1.8 persons per passenger car (6).

Accident Cost

Development of accident costs for a given speed, on a cost per mile basis, is the product of the traffic-accident involvement rate for the given speed and the severity of the accident at this speed. Traffic-accident involvement rates at various speeds are dependent on the characteristics of the driver, the vehicle, and the highway. Accident severity, or cost per involvement, depends on the number of persons killed and injured per involvement and the economic worth of a death, an injury, and the property damage caused by the accident.

In 1953 and 1955, the Massachusetts Department of Public Works and the Massachusetts Registry of Motor Vehicles in cooperation with the U. S. Bureau of Public Roads conducted the first comprehensive study of economic costs of motor vehicle accidents on a statewide basis (21, 22, 35, 36).

There were 1,910 passenger cars involved in accidents for every 100 million passenger-car miles of travel on Massachusetts streets and highways in 1953. These involvements were composed of 3.0 fatal-injury involvements, 467 non-fatal-injury involvements, and 1,440 property-damage-only involvements. The 1955 commercial vehicle study revealed that there were 1,412 trucks involved in accidents for every 100 million truck-miles of travel, consisting of 4.0 fatal-injury involvements, 223 non-fatal-injury involvements, and 1,186 property-damage-only involvements (21, 22).

From the Massachusetts study, 281 passenger cars were involved in accidents for every 100 million passenger-car miles traveled in rural areas, and 2,002 were involved in urban areas for the same travel rate. The cars were involved in 1.5 fatal-injury, 67 non-fatal-injury, and 212 property-damage-only accidents in rural areas, and in 3.9 fatal-injury, 511 non-fatal-injury, and 1,488 property-damage-only accidents in urban areas (35, 36).

During 1957 and 1958, the U. S. Bureau of Public Roads cooperated with 11 States to conduct an investigation to obtain a better understanding of the relationship between travel speed and accidents. The study covered 3.7 billion vehicle-miles of travel on 600 miles of main, rural highways. Accident records of 10,000 drivers, together with speed observations and interviews with 290,000 drivers using these highways, provided data for the study. The study revealed that accident involvement rates for both 2- and 4-lane divided highways decreased with a decreasing rate as speed was increased to approximately 60 to 65 mph, and then the accident involvement rates increased with an increasing rate with any further increase in speed. Accident involvement rates for speeds less than 50 mph were greater on 4-lane divided highways than on 2-lane highways, as can be seen by comparing Figures 3 and 4. Above 50 mph, the 2-lane involvement rates were higher than the corresponding rates on 4-lane highways (32, 38).

The study also disclosed that in the range from 20 to 60 mph the night involvement rates were approximately twice the day rates. At speeds below 20 mph the night involvement rates were less than twice the day rates, while at speeds above 60 mph the night involvement rates were several times higher than the day rates (32, 38).

In conclusion, accident involvement rates are higher for passenger cars than for commercial vehicles, higher in urban areas than in rural areas, higher on 4-lane divided highways than on 2-lane highways at speeds less than 50 mph, and higher during nighttime than during daytime.

Accidents occurring at moderate and high speeds were more severe than those at low speeds. For example, at 40 mph there were 31 persons fatally or non-fatally injured per 100 accident-involved vehicles, while at 65 mph 70 persons were fatally or non-fatally injured per 100 accident-involved vehicles. The amount of property damage per involvement increased at an increasing rate with an increase in speed. At 20 mph property damage per involvement was $250, at 65 mph, $430 (32, 38).

Comfort and Convenience Cost

Operation, time, and accident costs are tangible costs and are easily evaluated; however, comfort and convenience cost is intangible and difficult to evaluate in relative, quantitative measures. Nevertheless, benefits gained from comfort and convenience are real and should be appraised.

The use of toll facilities is evidence that some drivers place a monetary value on comfort and convenience. People who could have driven to their destination in fewer miles and with little difference in time on a free but a more congested route have elected to pay for the privilege of traveling on the toll road. Therefore, it must be of some value to the person to drive without frequent brake application, stops and starts, or tension created by traffic or roadside interference.

Positive identification of values for assignment to various degrees of comfort and convenience is not possible because presently there are no methods available to determine unit values of the many factors entering the evaluation of comfort and convenience costs. Some of these factors are highway type, services rendered to different traffic components, type of trip being made, trip length, and degree of interference on alternate routes (6).

AASHO arbitrarily selected the following values for various degrees of comfort and convenience: free type of operation, 0 cent per vehicle-mile; normal type, 0.5 cent per vehicle-mile; restricted type, 1.0 cent per vehicle-mile. AASHO defined type of operation by the ratio of the 30th highest hourly traffic volume to the practical capacity of the roadway. The types of operation are identified from these ratios as restricted operation for ratios greater than 1.25, as normal for ratios of 0.75 to 1.25, and as free for ratios less than 0.75 (6).

PROCEDURE

Rural Highways

Rural highways are defined, for the purposes of this study, as those routes which have no or very little roadside development along their rights-of-way and where traffic-controlled intersections are a mile or more apart.

Operation Cost.—The most recent and reliable data concerning operation cost for passenger cars and commercial vehicles is in the Highway Engineering Handbook. Operation-cost data presented in this reference were developed by Winfrey (42) through adjustment, reconciliation, and trending of a large number of published reports plus personally collected data. It was assumed that unit prices of fuel in cents per gallon and oil in cents per quart were 32 and 40, 30 and 34, and 28 and 25 for passenger cars and light commercial vehicles, single-unit trucks, and combination vehicles, respectively. Price per unit of tire wear for the three vehicular groups was not stated, but tire cost per mile was based on the depth of tread and the rate of tread wear. Maintenance cost for the various vehicular groups was prorated according to speed on the basis of fuel, oil, and tire cost. Depreciation, cost which was assumed to be attributable to mileage use, was estimated at 1.0, 1.5, and 2.5 cents per mile for passenger cars and light commercial vehicles, single-unit trucks, and combination vehicles, respectively.

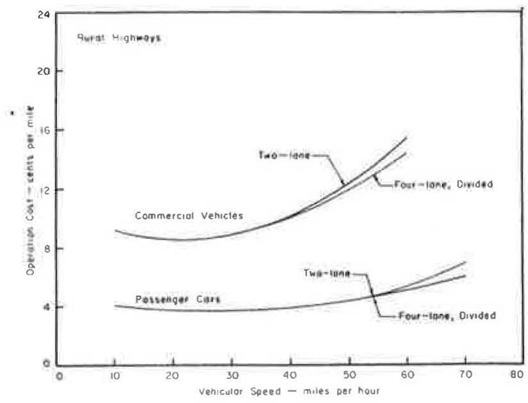

Figure 1. Operation cost vs vehicular speed, rural highways.

Total operation cost for passenger cars and commercial vehicles on 2- and 4-lane divided highways in rural areas is shown in Figure 1. Operation cost for commercial vehicles was prorated for a representative commercial traffic stream composed of 30.6 percent light commercial vehicles, 29.83 percent single-unit trucks, and 39.57 percent combination vehicles (7). Operation costs on 4-lane divided highways were obtained by using the ratio of 2-lane operation costs to 4-lane divided operation costs developed by AASHO (6). Passenger-car operation costs are a minimum at 26.5 mph for 2-lane highways and at 27.5 mph for 4-lane divided highways, whereas commercial-vehicle operation costs are a minimum at 21.0 mph for both highway types.

Time Cost.—In view of the general disagreement in the value of time for passenger cars, a conservative value is desirable so as to provide realistic and identifiable monetary benefits due to time saved. Therefore, a time cost of $0.75 per person, suggested by AASHO (6), was used in this study. The U. S. Bureau of Public Roads found on rural highways an average of 1.9 persons per passenger car (16). Therefore, the average value of time for passenger cars in rural areas was assumed to total $1.425 per hour per vehicle, or 2.375 cents per minute per vehicle.

The Highway Engineering Handbook suggests the following conservative values of time for the three groups of commercial vehicles: light commercial vehicles, $1.80 per hour; single-unit trucks, $2.10 per hour; and combination vehicles, $2.64 per hour (42). Based on a representative commercial-traffic stream in rural areas, a representative time cost for all commercial vehicles of $2.22 per hour was developed (7). Time cost per mile for passenger cars and commercial vehicles on rural highways as a function of travel speed is shown in Figure 2. Time cost is inversely proportional to the speed of the vehicle.

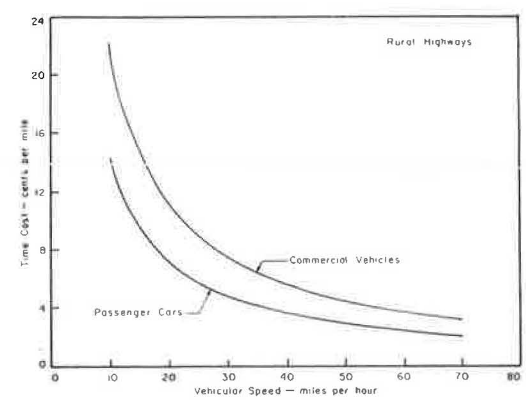

Figure 2. Time cost vs vehicular speed, rural highways.

Accident Cost.—Accident cost for a given speed is equal to the product of the accident involvement rate for that speed and the severity of the accident at the same speed. Involvement rates for passenger cars and commercial vehicles in rural areas were developed from data provided by the U. S. Bureau of Public Roads (32, 38) and North Carolina (12).

Passenger car and commercial vehicle involvement rates on 2- and 4-lane divided rural highways and for daytime and nighttime conditions are shown in Figures 3 and 4. For each curve, there is a speed

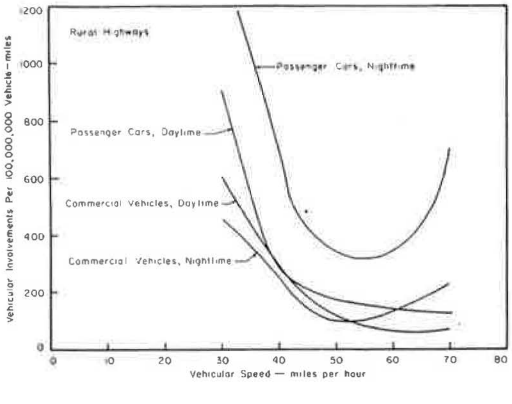

Figure 3. Vehicular involvements vs vehicular speed, 2-lane rural highways.

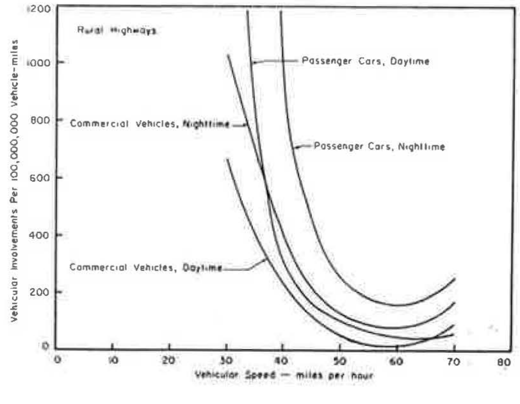

Figure 4. Vehicular involvements vs vehicular speed, 4-lane divided rural highways.

at which the involvement rate was a minimum. Speeds at which the minimum rates occurred are less for commercial vehicles than for passenger cars for each highway type and travel condition. Nighttime involvement rates are generally higher than daytime rates, and 4-lane involvement rates are higher than 2-lane rates at lower speeds, whereas the reverse is true for higher speeds. Commercial vehicle accident-involvement rates are much less than those for passenger cars at corresponding speed values.

Accident severity, expressed as cost per vehicular involvement, is dependent on the number of persons killed or injured per involvement and on the unit costs of a death, an injury, and the property damage caused by the accident. The number of persons killed or injured per passenger car and commercial vehicle involvement was developed from accident data provided by the Bureau of Public Roads (32, 38) and North Carolina (12). The National Safety Council suggested that the economic loss incurred by a death is \$30,000 and that by an injury is \$1,600. These values are based on wage losses, medical expenses, and overhead costs of insurance (33). Property damage per passenger car and commercial vehicle involvement for various speeds was provided by accident information collected and summarized by the Bureau of Public Roads (32, 38) Massachusetts (21, 22).

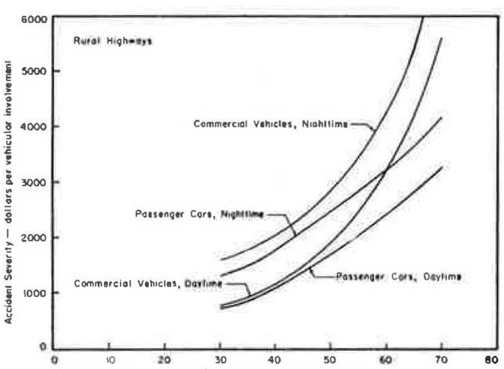

Figure 5. Accident severity vs vehicular speed, 2-lane rural highways.

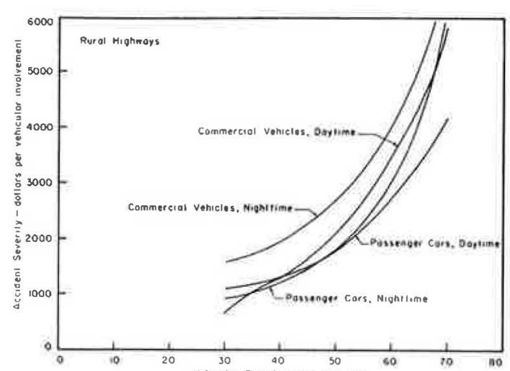

Figure 6. Accident severity vs vehicular speed, 4-lane divided rural highways.

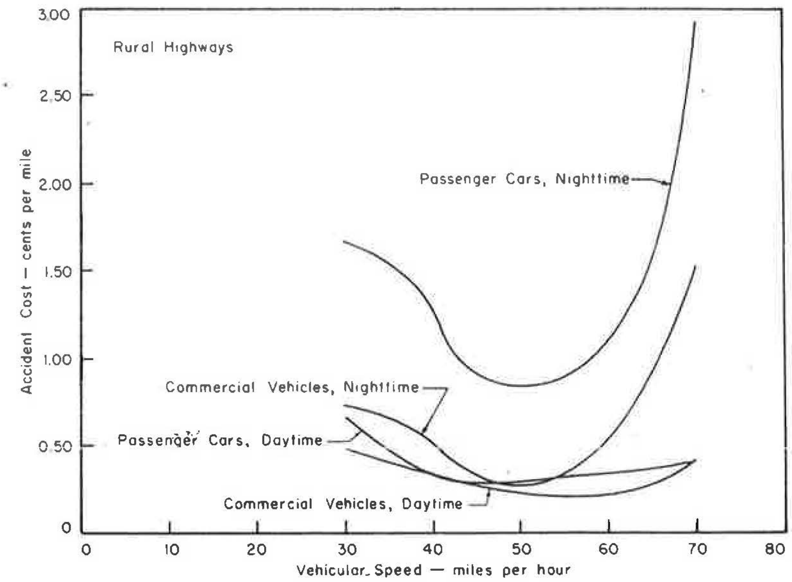

Figure 7. Accident cost vs vehicular speed, 2-lane rural highways.

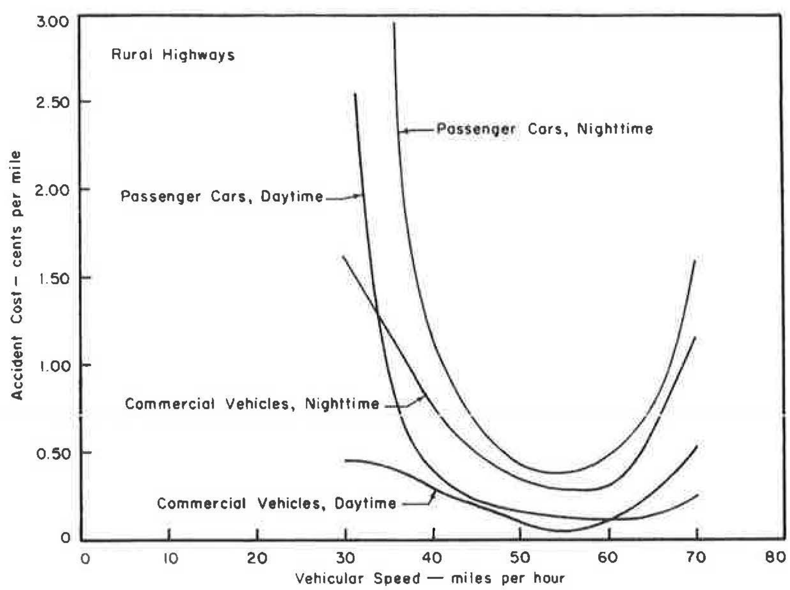

Figure 8. Accident cost vs vehicular speed, 4-lane divided rural highways.

The total accident severity of an involvement is obtained from the sum of the property-damage cost plus the product of the number of killed or injured persons and their resulting economic loss. Figures 5 and 6 show passenger car and commercial vehicle severity on 2- and 4-lane divided highways for daytime and nighttime travel. There is an increase in accident severity at an increasing rate with an increase in speed. Nighttime accident severity is higher than daytime except for passenger-car travel at low speeds on 4-lane divided highways. Accident severity is greater for commercial vehicles than for passenger cars, because the number of persons fatally injured or nonfatally injured per involvement is higher for commercial vehicles than for passenger cars.

Accident costs for various speeds on 2- and 4-lane divided highways for daytime and nighttime travel conditions are shown in Figures 7 and 8. Nighttime accident costs are higher than daytime costs throughout the speed range. In general, accident costs are less for commercial vehicles traveling in rural areas than for passenger cars under the same conditions. Optimum speeds for accident costs on rural highways are indicated in the following:

Vehicle Type	Speed (mph)			
	2-Lane		4-Lane, Divided	
	Daytime	Nighttime	Daytime	Nighttime
Passenger car	46.0	49.5	60.0	54.0
Commercial vehicle	57.5	50.0	57.0	56.5

Comfort and Convenience Cost.—Comfort and convenience cost is an intangible that is difficult to evaluate. However, it can be assumed that this cost element is higher at low speeds (driver impatience) and at high speeds (driver tension), whereas at intermediate speeds, the comfort and convenience cost is minimized in the region of driver satisfaction (30). No justifiable method of assigning values in terms of dollars and cents has been found. Therefore, comfort and convenience costs were not determined in this study.

Urban Streets

Urban streets are defined as those routes which have high or complete roadside development along their rights-of-way and where traffic controlled intersections are less than a mile apart.

Operation Cost.—The criterion used to develop operation costs for passenger cars in urban areas rests on the assumption that the same operation costs used for free-type vehicular operation can be used for restrictive-type operation if additional costs for slowdowns and stops are included in the total operation cost (6). Because this study was restricted to vehicular flow during free-flowing traffic volumes, it was assumed that the only slowdowns made by the drivers will result from complete stops for traffic-control devices. Therefore, operation costs in urban areas can be prorated, if data are available, to provide operation costs for both free-type operation at various speeds and for a normal stop from the same corresponding speeds. Operation cost for a normal stop is defined as that extra cost resulting when a typical driver decelerates from a given speed to a stop and then immediately accelerates to the same speed (5). This information is tabulated in the Highway Engineering Handbook (42).

Figure 9 shows the extra passenger car and commercial vehicle operation costs for a normal stop. Extra operation costs for commercial vehicles were prorated for an

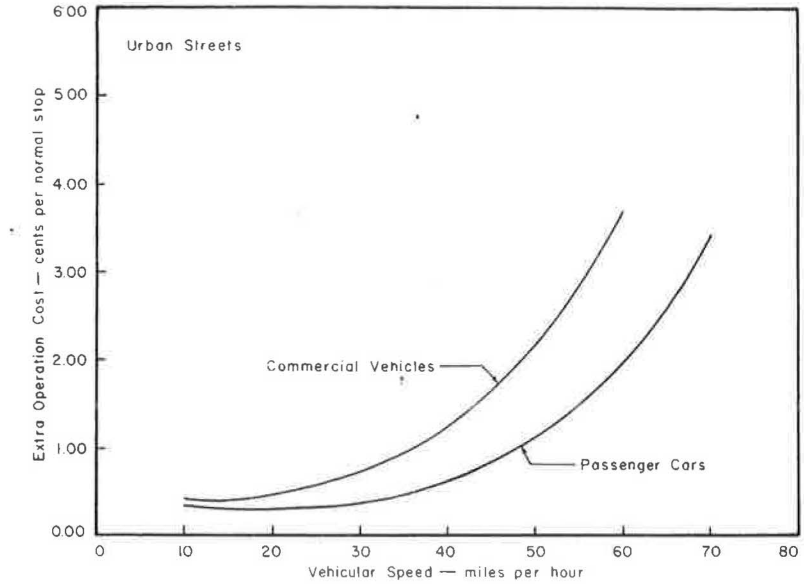

Figure 9. Extra operation cost vs vehicular speed, urban streets.

average urban, commercial-traffic stream composed of 55.77 percent light commercial vehicles, 27.98 percent single-unit trucks, and 16.25 percent combination vehicles (15). At speeds above 20 mph, extra operation costs for both passenger cars and commercial vehicles increased at an increasing rate with an increase in speed. Throughout the speed range, extra operation costs are higher for commercial vehicles than for passenger cars.

To obtain the total operation cost for a desired speed in an urban area, the operation cost for a mile of free-type operation is added to the extra operation cost per stop per mile times the number of stops per mile. Unlike highways in rural areas, operation costs were not prorated for both 2- and 4-lane streets because very few urban streets are divided by a median of adequate width to separate physically traffic movement and thus reduce operation costs. Therefore, these operation costs are applicable only to passenger car and commercial vehicle operation on all undivided urban streets.

Time Cost.—The method used to prorate passenger car time cost on urban streets was the same as that used on rural highways. The Bureau of Public Roads found that there was an average of 1.6 persons per passenger car traveling on urban streets (16). Based on the assumption that time cost equals $0.75 per person, the value of time for passenger cars in urban areas resulted in a total of $1.20 per hour per vehicle, or 2.00 cents per minute per vehicle (6).

Based on the average distribution of travel in urban areas for commercial vehicles, a representative value of time for all commercial vehicles of $2.02 per hour was evolved, somewhat less than the rural value of $2.24. This is explained by the presence of a larger percentage of light commercial vehicles (low value of time) and by a smaller percentage of combination vehicles (high value of time).

Figure 10 indicates that the extra time cost for passenger cars increased linearly with speed, whereas the extra time cost for commercial vehicles increased at an increasing rate with an increase in speed. The extra time consumed for a normal stop by a passenger car, light commercial vehicle, and a single-unit truck was obtained from a study by Claffey (5) while the extra time consumed by an average combination vehicle in performing a normal stop was abstracted from a paper by Sawhill (31).

To compute the total time cost per mile at a given speed in an urban area, the time cost per mile at the given speed is added to the extra time cost per mile multiplied by the number of stops per mile.

Accident Cost.—Unlike in the rural areas, there has been no investigation to ascertain the relationship between travel speed and accidents in urban areas. Therefore, a method was developed which tried to synthesize involvement rates at various speeds.

The 1959 national mileage (26) was proportioned to obtain urban mileage (37), urban passenger-car mileage and commercial vehicle mileage (37), and then urban daytime and nighttime passenger-car and commercial vehicle mileage (26). The absence of any valid information prevented a further breakdown between 2- and 4-lane streets. After making the assumption that the 1959 North Carolina urban speed distributions are typical for the nation (12), the daytime and nighttime mileage was distributed to the various speed groups in proportion to the number of passenger cars and commercial vehicles traveling in that speed group.

The number of fatal, non-fatal, and property-damage involvements were obtained from ratios of passenger-car involvements and commercial vehicle involvements to all-vehicle involvements. These breakdowns were developed from the 1959 North Carolina accident statistics (12) and were used to convert the 1959 all-vehicle involvement data, as estimated by the National Safety Council (26), into passenger-car and commercial vehicle fatal, non-fatal, and property-damage involvements for daytime and nighttime travel conditions.

The number of involvements divided by the number of vehicle-miles traveled resulted in the involvement rates shown in Figure 11. Daytime involvement rates are higher than nighttime rates at lower speeds, but the trend is reversed in the study conducted by the Bureau of Public Roads (32, 38). Urban involvement rates are larger than rural involvement rates, and urban minimum involvement rates occurred at lower speeds than the corresponding rural values. Furthermore, passenger-car and commercial vehicle involvement rates are very similar, except urban daytime commercial vehicle rates are greater than corresponding rates for passenger cars. The reverse is true for nighttime.

The accident severity of an involvement is obtained from the sum of the property-damage cost plus the product of the number of killed or injured persons and their resulting economic loss. The Massachusetts study (21, 22) provided the property-damage costs, the accident statistics from North Carolina (12) and the National Safety Council (26) provided the number of killed and injured at various speeds, while the National Safety Council gave the economic worth of a death and an injury (33). Both daytime and nighttime accident severity increased at an increasing rate with an increase in speed (Fig. 12). Nighttime accident severity is higher than daytime throughout the speeds considered. Accident severity for commercial vehicles in urban areas is higher than that for passenger cars in urban areas, but is lower than either in rural areas.

Accident costs, which are the products of the accident involvement rates and the accident severities, for passenger cars and commercial vehicles in urban areas are shown in Figure 13. Nighttime accident costs are less than daytime accident costs at low speeds, but daytime accident costs are less than nighttime accident costs at high speeds. Optimum speeds for accident costs on urban streets are indicated in the following:

Vehicle Type	Speed (mph)	
	Daytime	Nighttime
Passenger car	39.0	37.0
Commercial vehicle	33.5	32.0

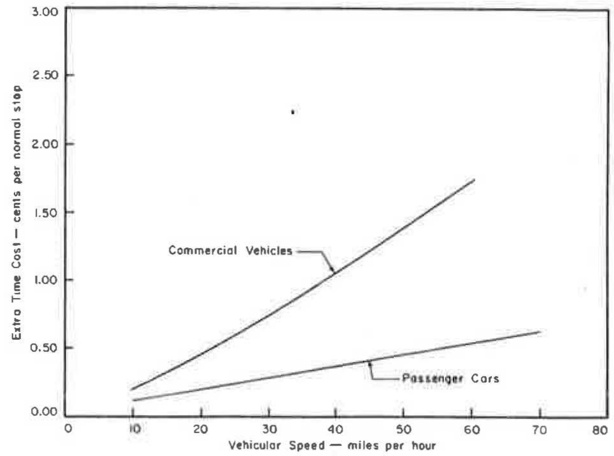

Figure 10. Extra time cost vs vehicular speed, urban streets.

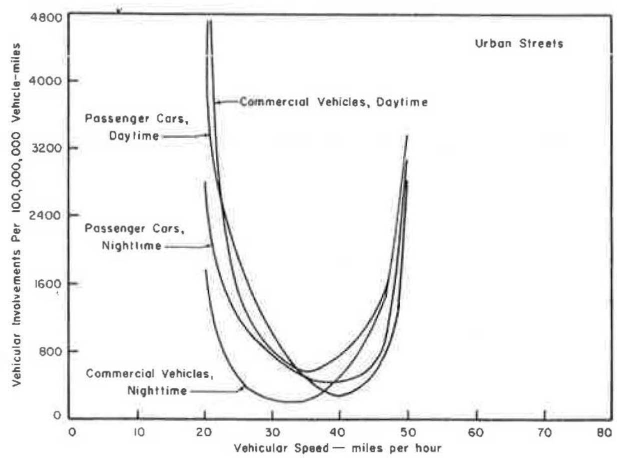

Figure 11. Vehicular involvements vs vehicular speed, urban streets.

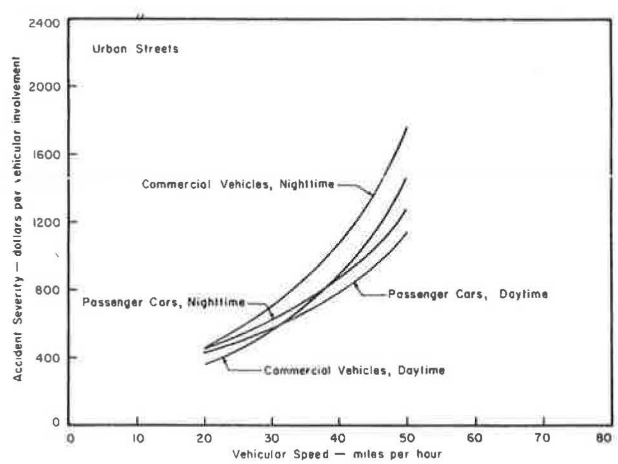

Figure 12. Accident severity vs vehicular speed, urban streets.

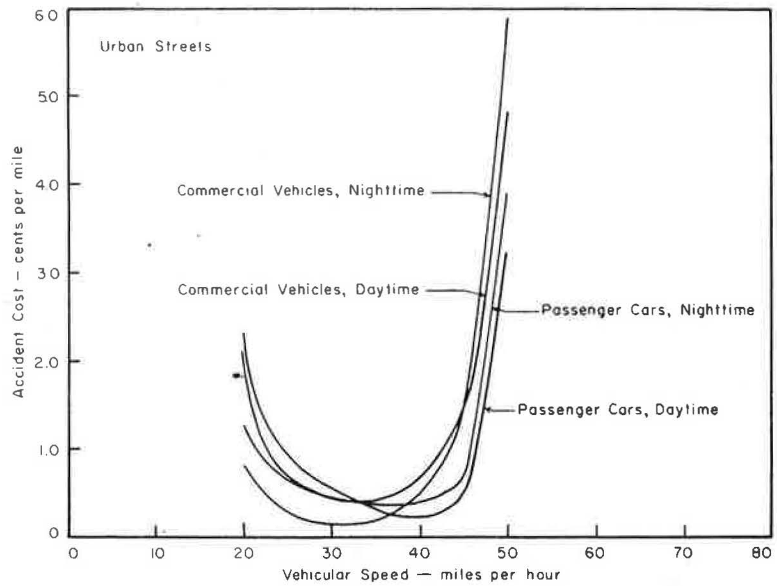

Figure 13. Accident costs vs vehicular speed, urban streets.

RESULTS

Rural Highways

Results of this investigation to determine the cost of traffic movement on rural highways are summarized in Figures 14 through 21. These diagrams represent relationships between vehicular speed and operation cost, time cost, accident cost, and total cost of traffic movement. Total cost is the arithmetic sum of these three elements. In each of the eight total cost curves, there is a travel speed at which the total traffic movement cost is minimized. Therefore, a speed that optimizes the cost of traffic movement for various motor vehicles, highway types, and travel conditions can be rationally determined. Optimum speeds for each rural condition are summarized in the following:

Vehicle Type	Speed (mph)			
	2-Lane		4-Lane, Divided	
	Daytime	Nighttime	Daytime	Nighttime
Passenger car	48.0	48.5	52.1	51.5
Commercial vehicle	40.0	41.0	41.0	44.0

At speeds both above and below these optimal points, total cost increases at an increasing rate.

For passenger cars on 2-lane highways (Fig. 14) the total cost is 7.600 cents per mile at the optimal daytime speed of 48.0 mph. Total cost of traffic movement ranged from 9.121 cents per mile at 30.0 mph down to the optimal value and then back up to 9.438 cents per mile at 70.0 mph.

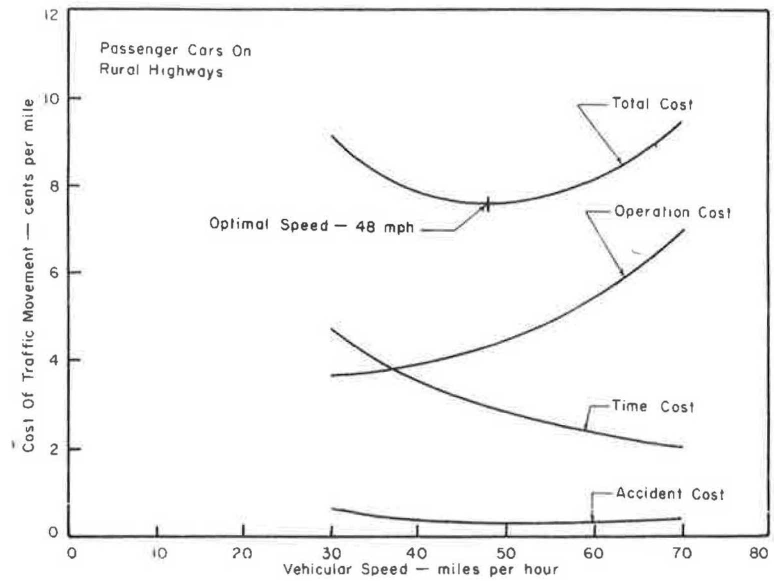

Figure 14. Cost of traffic movement vs vehicular speed, 2-lane, daytime, passenger cars on rural highways.

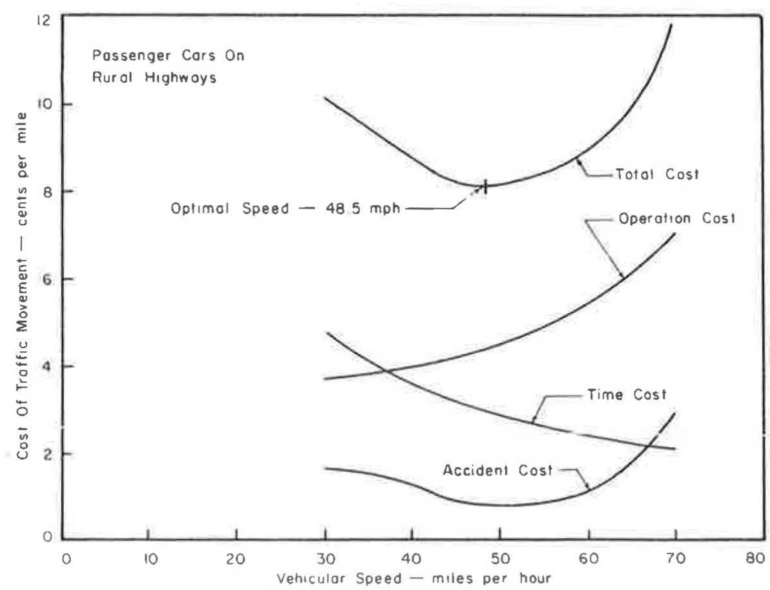

Figure 15. Cost of traffic movement vs vehicular speed, 2-lane, nighttime, passenger cars on rural highways.

Because accident cost is higher for passenger cars on two-lane rural highways for nighttime than it is for daytime, total cost of nighttime traffic movement. (Fig. 15) is slightly larger than for daytime. Figure 15 shows the total cost of traffic movement as 8.140 cents per mile at the 48.5 mph optimal speed.

In Figure 16, total cost of daytime traffic movement for passenger cars on 4-lane rural highways varied from 10.987 cents per mile at 30.0 mph down to 7.400 cents per mile at the optimal speed of 52.0 mph and then back up to 8.281 cents per mile at 70.0 mph. This high total cost at the lower speeds is the result of high accident costs in this region.

Figure 17 shows total cost of traffic movement to be higher for nighttime travel than for daytime travel (Fig. 16) throughout the entire speed range. At the optimal speed of 51.5 mph, total cost of traffic movement is 7.660 cents per mile.

For commercial vehicles on 2-lane rural highways for daytime travel (Fig. 18), the total cost of traffic movement is 16.083 cents per mile at the optimal speed of 40.0 mph, whereas at 30.0 mph and 60.0 mph, total cost of traffic movement is 16.851 cents per mile and 19.199 cents per mile, respectively.

Total cost of traffic movement for commercial vehicles on 2-lane rural highways for nighttime travel (Fig. 19) did not vary appreciably from daytime travel (Fig. 18). At the optimal speed of 41.0 mph, the total cost of traffic movement is 16.220 cents per mile.

For commercial vehicles on 4-lane rural highways for daytime travel (Fig. 20), total cost of traffic movement varied from 16.764 cents per mile at 30.0 mph down to 15.900 cents per mile at the optimal speed of 41.0 mph and then up to 18.212 cents per mile at 60.0 mph.

For commercial vehicles on 4-lane rural highways for nighttime travel (Fig. 21) the cost of traffic movement was observed to be slightly higher than daytime total cost. At the optimal speed of 44.0 mph total cost of traffic movement is 16.320 cents per mile, while at 30.0 mph and 60.0 mph total cost is 17.932 cents per mile and 18.451 cents per mile, respectively.

It is evident that the commercial vehicle total costs are approximately twice the passenger car total costs. Total costs for nighttime travel are consist-

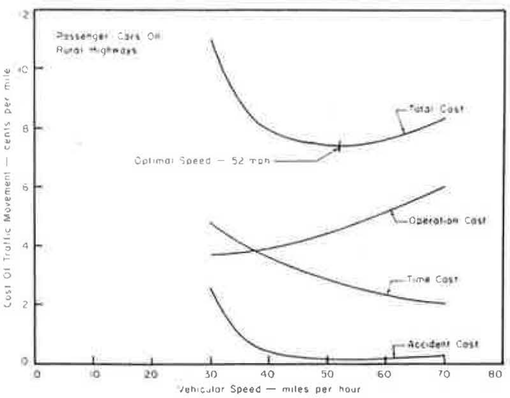

Figure 16. Cost of traffic movement vs vehicular speed, 4-lane divided, daytime, passenger cars on rural highways.

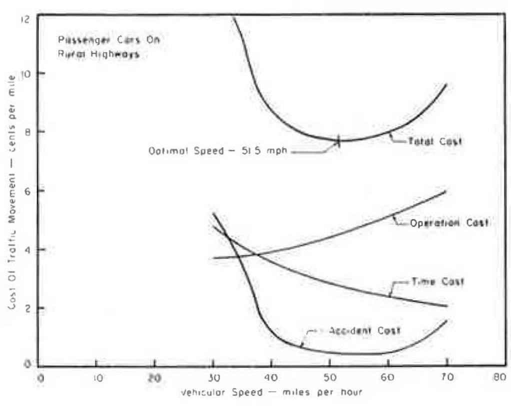

Figure 17. Cost of traffic movement vs vehicular speed, 4-lane divided, nighttime, passenger cars on rural highways.

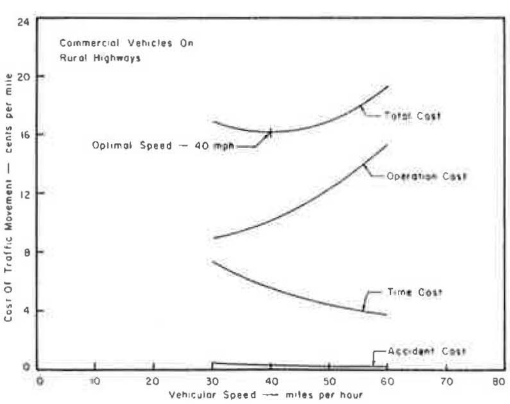

Figure 18. Cost of traffic movement vs vehicular speed, 2-lane, daytime, commercial vehicles on rural highways.

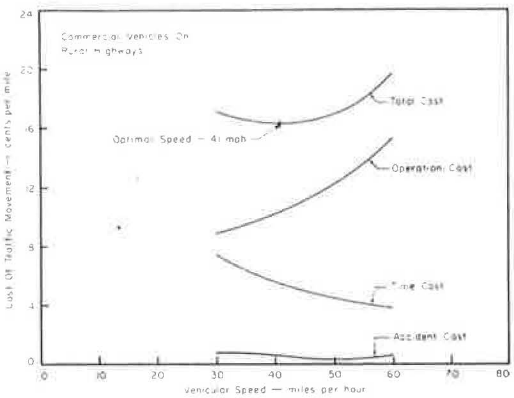

Figure 19. Cost of traffic movement vs vehicular speed, 2-lane, nighttime, commercial vehicles on rural highways.

ently higher than for daytime travel. Also, total costs for 2-lane highways are higher than for 4-lane divided highways except at lower speeds where very high accident costs on 4-lane divided highways produce higher total costs.

Urban Streets

Figures 22 through 25 show the results of this study of vehicle costs on urban streets. These figures depict cost of traffic movement for various speeds, vehicle types, stops per mile, and travel conditions. For each of the various stops per mile, an optimal speed minimizing cost of traffic movement was found.

For passenger cars on urban streets for daytime travel (Fig. 22), optimal total costs of traffic movement ranged from 7.080 cents per mile at an optimal speed of 42.0 mph for 0 stops per mile to 18.420 cents per mile at an optimal speed of 27.0 for 16 stops per mile.

For passenger cars on urban streets for nighttime travel (Fig. 23), optimal total costs of traffic movement ranged from 7.300 cents per mile at an optimal speed of 41.5 mph to 18.240 cents per mile at an optimal speed of 24.5 mph for 0 stops per mile and 16 stops per mile, respectively.

Total cost of traffic movement for commercial vehicles on urban streets is approximately 1.75 times larger than for passenger cars on urban streets. For commercial vehicles on urban streets for daytime travel (Fig. 24), optimal total costs of traffic movement varied from 12.580 cents per mile at an optimal speed of 37.5 mph for 0 stops per mile to 24.117 cents per mile at an optimal speed of 25.0 mph for 8 stops per mile.

For commercial vehicles on urban streets for nighttime travel (Fig. 25), total costs are less than total costs for daytime travel for each of the various stops per mile. Optimal total costs of traffic movement ranged from 12.420 cents per mile at an optimal speed of 37.5 mph to 23.730 cents per mile at an optimal speed of 25.0 mph for 0 stops per mile and 8 stops per mile, respectively.

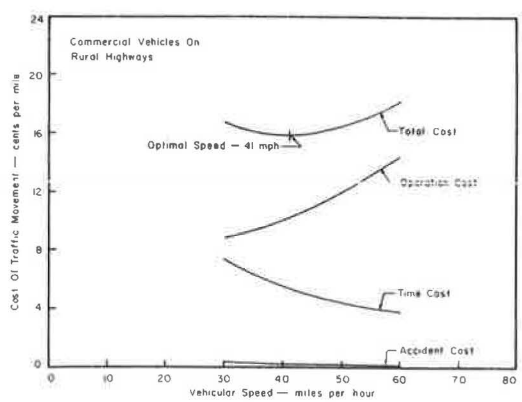

Figure 20. Cost of traffic movement vs vehicular speed, 4-lane divided, daytime, commercial vehicles on rural highways.

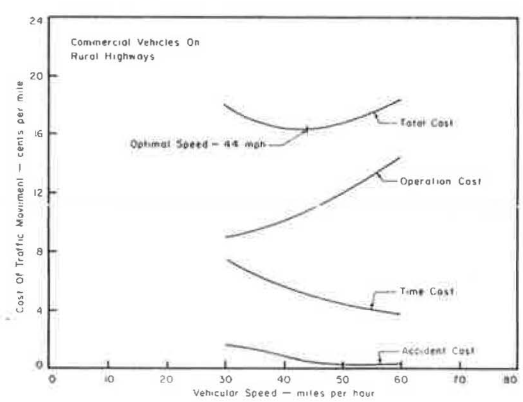

Figure 21. Cost of traffic movement vs vehicular speed, 4-lane divided, nighttime, commercial vehicles on rural highways.

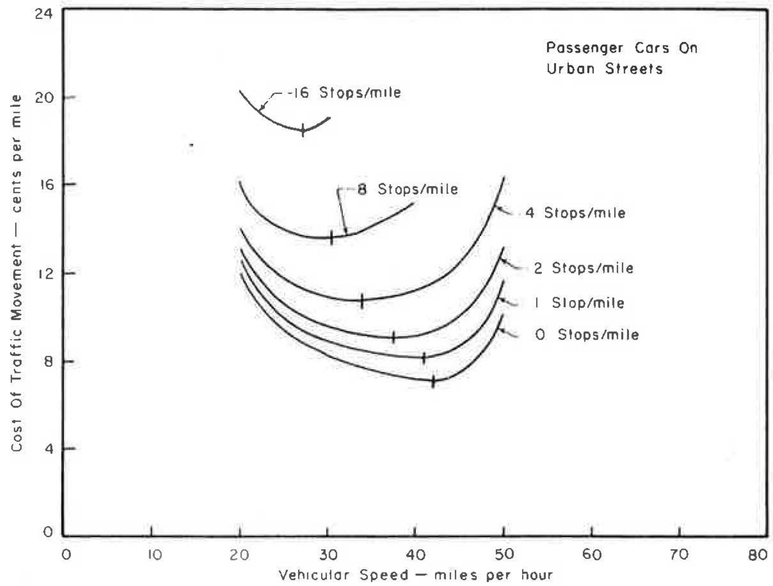

Figure 22. Cost of traffic movement vs vehicular speed, daytime, passenger cars on urban streets.

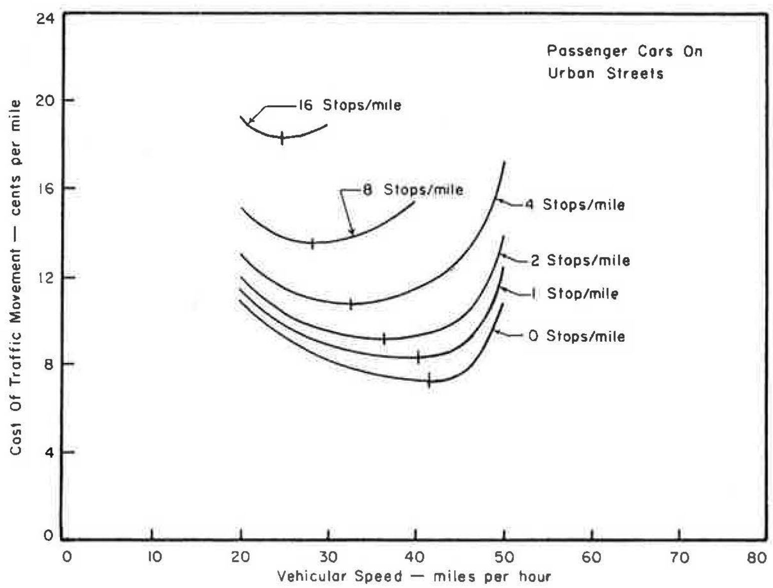

Figure 23. Cost of traffic movement vs vehicular speed, nighttime, passenger cars on urban streets.

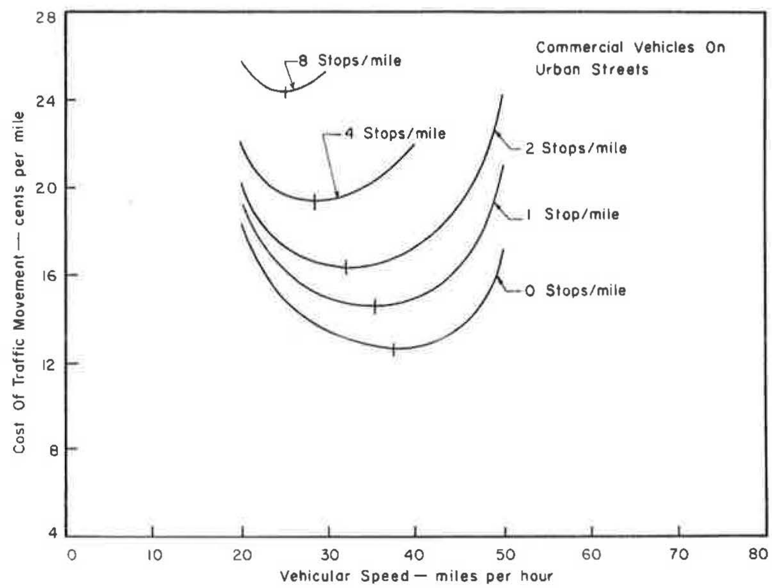

Figure 24. Cost of traffic movement vs vehicular speed, daytime, commercial vehicles on urban streets.

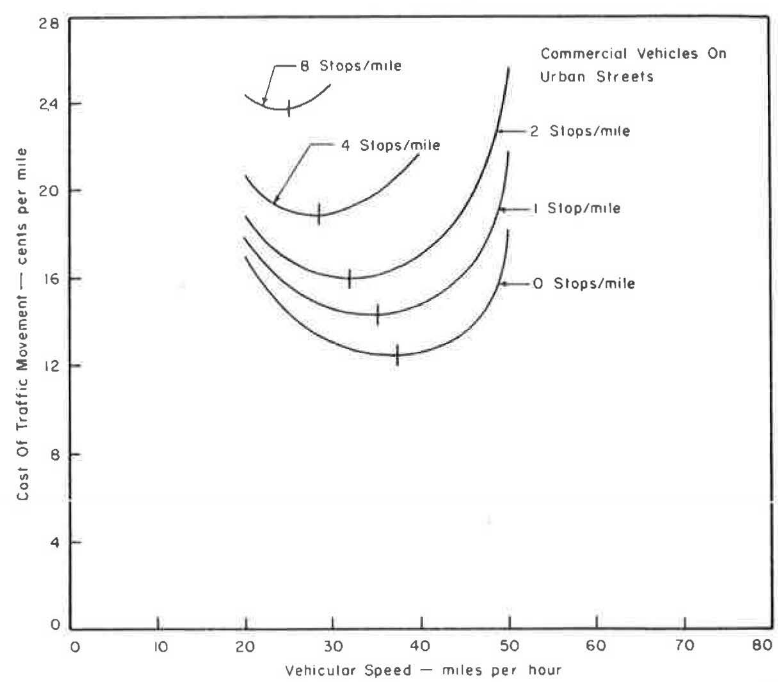

Figure 25. Cost of traffic movement vs vehicular speed, nighttime, commercial vehicles on urban streets.

The following relationships between optimal speeds and stops per mile were established:

Passenger car, daytime:

$$Y = 41.0 - 11.63 \log X \quad (1)$$

Passenger car, nighttime:

$$Y = 40.5 - 13.29 \log X \quad (2)$$

Commercial vehicle, daytime and nighttime:

$$Y = 35.5 - 11.63 \log X \quad (3)$$

in which

Y = optimal speed in mph, and
X = number of stops per mile.

Figure 26 shows optimal speeds for stops ranging from 1 to 16 for passenger cars on urban streets for daytime and nighttime travel, and Figure 27 shows optimal speeds for stops varying from 1 to 8 for commercial vehicles on urban streets for daytime and nighttime travel.

A method was developed to estimate the number of stops due to traffic signals a motor vehicle made over a certain distance in an urban area, by assuming that under free-flowing urban traffic conditions, the probability of being stopped at any given traffic signal was inversely proportional to the ratio of green time to cycle time (G/C). The probable number of stops per mile for various numbers of traffic signals and G/C ratios is shown in Figure 28. Of course, the number of interruptions by stop signs per mile must be added to the value in Figure 28 before the total number of stops by the motor vehicle can be estimated.

To illustrate the procedure for obtaining optimal speed on an urban street, assume that for a 1-mi section of the given street there are 4 intersections. One of these intersections is regulated by a stop sign and the other three by traffic signals having G/C ratios of 0.60, 0.50, and 0.40, respectively. The number of probable stops per mile caused by the three traffic signals with an average G/C ratio of 0.50 is 1.5 stops per mile (Fig. 28). After the extra stop for the stop-sign-controlled intersection is added, the total probable number of stops for the street is 2.5. The optimal speeds obtained are 36.4 and 35.2 mph, respectively, for passenger cars during daytime and nighttime travel (Figs. 26 and 27). Commercial vehicles for both daytime and nighttime travel have an optimal-speed value of 30.9 mph.

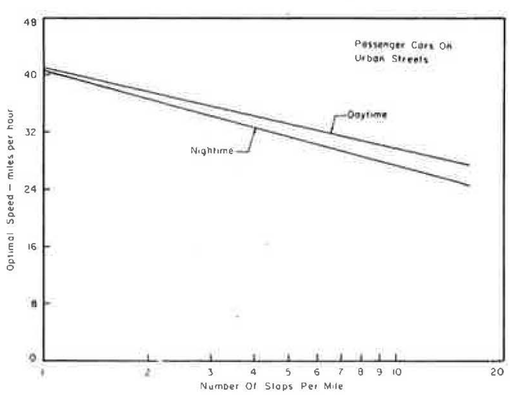

Figure 26. Optimal speed vs number of stops, passenger cars on urban streets.

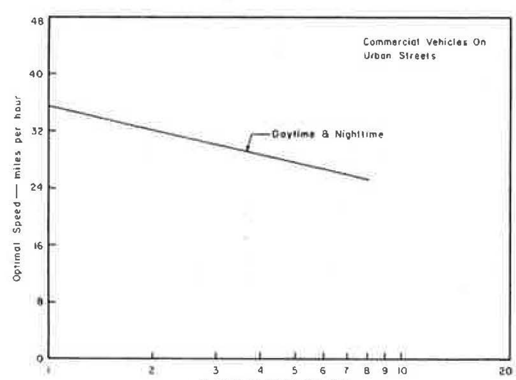

Figure 27. Optimal speed vs number of stops, commerical vehicles on urban streets.

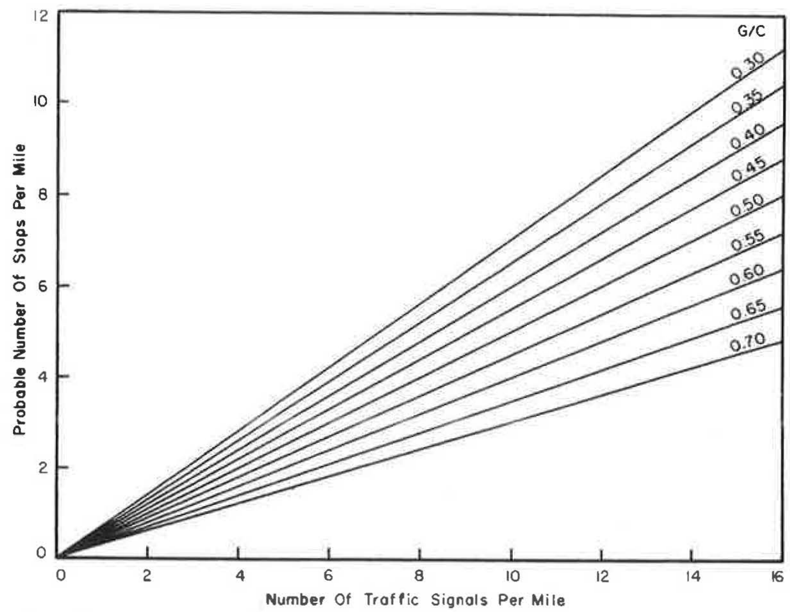

Figure 28. Probable number of stops vs number of traffic signals.

CONCLUSIONS

The most important conclusion that was drawn from this investigation is that a vehicle-operating speed does exist which minimizes cost of traffic movement for each of the various conditions considered. It is also concluded that differences up to 11 mph were observed between the optimal speeds of passenger cars and commercial vehicles, whereas there were lesser differences between optimal speeds on 2- and 4-lane rural highways and even smaller differences between daytime and nighttime optimal speeds.

Application of the results of this study, which are the consolidated results of many published articles on the subject of traffic movement costs, will probably be restricted to the establishment of statewide or areawide maximum or minimum speed limits. At this time, it is not possible to speed zone for specific locations using these results because the data necessary to make the analysis are not available for a micro analysis.

Data developed in this investigation can also be used to help complete data lacking in the present road-user benefit analyses. In the past, commercial vehicles and accident costs were omitted from the analyses because of the lack of available data. Highway engineers now have a broader knowledge of the actual benefits received by the road-user through highway improvements.

SUGGESTION FOR FURTHER RESEARCH

One difficulty encountered in this evaluation was the lack of adequate data on the values of time and accident involvement rates. An acceptable value of time for passenger car leisure trips should be ascertained and an urban accident study similar to the one conducted in rural areas by the Bureau of Public Roads should be initiated (32, 38). Driver comfort and convenience should also be studied to determine its proper place in appraising the actual cost of traffic movement. When more data become available, it is suggested that individual cost elements, along with total cost of traffic movement, be re-evaluated.

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