Regression Model for Projecting Vehicle-Miles of Travel in a Metropolitan Region

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A regression model has been developed for the projection of mileage traveled by motor vehicles in a metropolitan region. The model represents such a mileage projection for the Tri-State region, but its framework should be applicable to other regions as well. The model was built on the premise that travel parameters are influenced by the urban form which is primarily characterized by the distribution of population densities. Upon evidence of a functional relationship between population densities and trip generation rates, the vehicular travel mileage was correlated with vehicular trip-end densities. Statistically meaningful correlation between these variables verified the study's premise. Since it has been shown that population distribution patterns remain relatively stable in time, it was reasoned that the patterns of regional travel parameters should likewise remain stable. Consequently, a projective model was developed. It utilizes annual travel mileage per vehicle, which has remained stable over the past decades, and constant average miles per trip to establish the projection control totals.

•THE automobile ceased to be a novelty about three decades ago. With the perfection of mass production techniques, it has become one of the implements which characterize the civilization of the 20th century. At an average in this country, one automobile was registered for 13.1 persons in 1920, 5.4 in 1930, 3.8 in 1950 and 2.9 in 1960. The seating capacity of automobiles has long since exceeded the national population.

The ubiquity of automobiles transformed the concept of accessibility. Streets and roads had to be paved for the accommodation of the ever-increasing number of motor vehicles. Every parcel of land mapped for development must now be provided with accessibility by motor car. Automobile use has spread throughout developed areas as much as other services which are considered indispensable for maintaining the activities of an average household.

Population densities, depending upon their level, seem to embrace different sets of constraints for motor travel. A kind of kinship prevails between the forms of travel and other forms that are inherent in development density.

This study explores the relationships between vehicular trip densities, which derive from population densities, and vehicle-miles of travel. The existing relationships have been defined, and methods for projecting future travel mileage have been developed.

THE URBAN FORM AND TRAVEL

The urban form is characterized primarily by the distribution of population densities. At high development intensities not only are the structures tall, but all other facilities are arranged in a manner which conserves space. The overall spatial frame-

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work of activities is compact and its utilization intensive. As densities decrease, the compactness of activities, such as residential, shopping, entertainment, and recreation gets relaxed, and distances between activity points grow.

Because of this variation in the spatial framework of activities, the regional urban form contains services which vary with development intensities. Travel is one such service, and its forms change, especially in regions where the difference between the highest density and the lowest is great. Travel cost, convenience, safety, the utilization of travel modes, and a host of other considerations influence the forms of communication. Use of automobiles in high densities likewise is confronted by constraints which are absent in low-density areas. If the regional urban form is definable, one may reason that there should also be discernible patterns of regionwide services such as travel.

Travel mileage generated in all parts of the region depends on the number of trips made in these areas; travel mileage is a consequent of trip-making. If a generalization for the travel mileage was sought, the trip-making factor would be a logical choice for an independent variable. The trip-generating propensity stands in close relationship to population density. Since population densities depict the urban form, trip-making and travel mileage generation must show coextensiveness with such a form.

The regional urban form may be described in the most rudimentary manner by defining the structure of population density distribution. A number of studies have been made in this field. Here, however, it will suffice to quote Berry's affirmative statement (1) that "No city has yet been studied for which a statistically significant fit of the expression

$$d_x = d_o e^{-bx} \tag{1}$$

does not obtain."

where

d_x = population density d at distance x from the city center;

d_o = central density, as extrapolated in city's central business district; and

b = the density gradient.

In a more recent study of household and residential patterns for two time periods, twelve years apart, in the Greensboro, N. C. metropolitan region, Swerdloff (2) found that "gross density has consistently increased in each ring. The density gradient has flattened out slightly, indicative of a less compact population distribution in 1960 than in 1948 and characteristic of a suburbanizing region." Otherwise, curves of the same character as defined by Eq. 1 provided statistically significant descriptions of population distribution patterns.

Two aspects of these findings are pertinent to the thesis of this paper: first, that the population distribution pattern in the region is definable; and second, that this pattern remains stable in time. The distribution form does not change, but some of its parameters undergo a gradual adjustment. Consequently, should the nature of coextensiveness between regional services, such as travel, and elements of the urban form be defined, this definition could be employed for projecting the demand of services in the future.

A number of regional studies have found good correlation between population densities and trip generation. Levinson and Wynn (3) summarized the various equations which have been used for estimating trip generation from population densities, or other population characteristics and state (3, p. 50):

> The studies clearly show the reductive effect of density on total trip generation, both between various cities, and within each city. (Trip generation is generally expressed as a - bx, or a - b log x, in which x is a density function.)

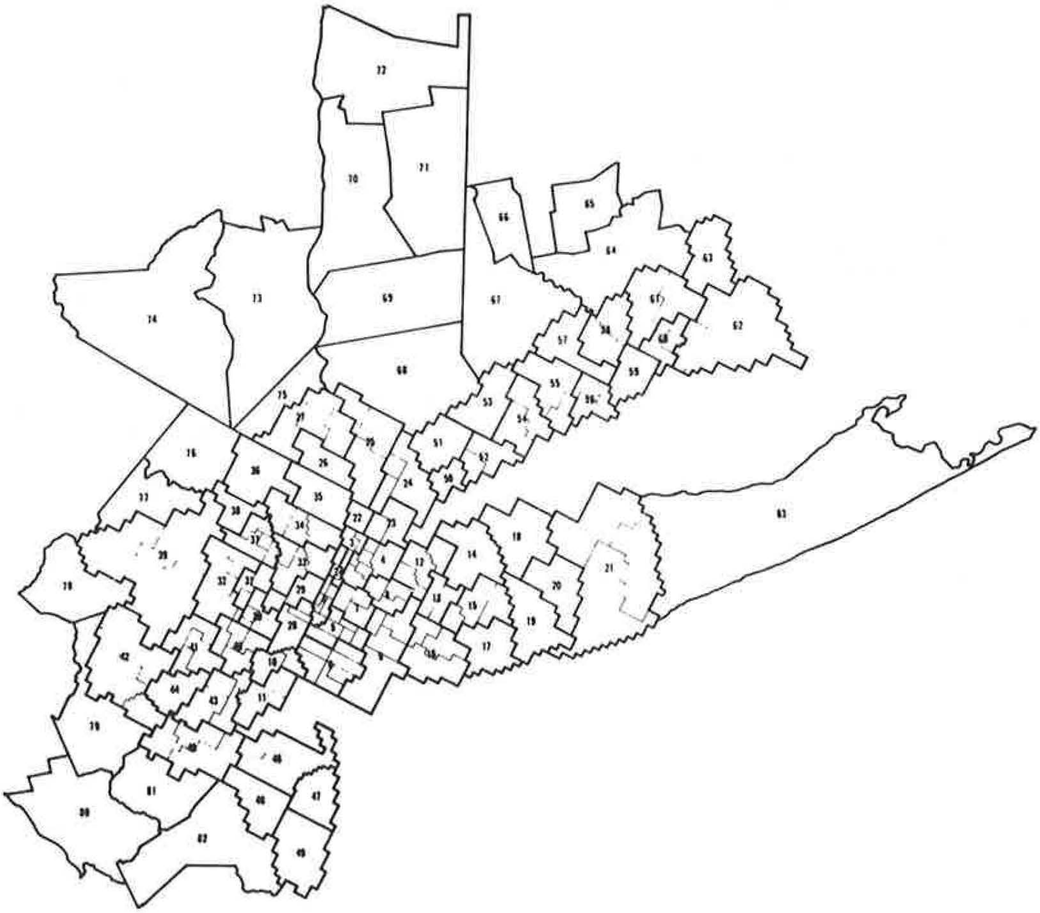

Figure 1. Analysis districts, Tri-State Metropolitan Region.

It may be stated, therefore, that trip density is a function of population density. However, it has been hypothesized that travel mileage stands in close relationship to trip density, and it may be shown that the travel mileage per square mile, m, is a function of trip density, p, which, in turn is a function of population density, δ.

$$m = f\,[p\,(\delta)]$$

This study works with vehicular trip destinations and p represents such densities. As the relationship between δ and p is outside the scope of this paper, only trip-end density will be used as the independent variable.

The hypothesis which underlies the formulation of the regression model stipulates the existence, in a regional context, of a statistically definable relationship between vehicle-miles of travel and trip-end densities. In the stipulated variation,

$$m \propto p \tag{2}$$

stating that vehicle-miles vary in a manner similar to trip densities, there is a transitive property which makes both variables equal. This property is $m/p = \bar{d}$, the average travel mileage per trip. It measures the travel intensities in areas of different levels of development and may be determined after establishing the correlation between m and p.

DISTRIBUTION OF VEHICLE-MILES AND TRIP DENSITY

In order to verify the hypothesis and to provide a statistical basis for model formulation, vehicle-miles of travel in the urbanized part (the cordon area) of the Tri-State metropolitan region (Fig. 1) were correlated to trip-end densities. The scatter diagram and regression line are shown in Figure 2.

For this purpose the cordon area, consisting of 3,509 square miles, was divided into 63 analysis districts—larger in low densities and smaller in high. (The size of analysis districts does not appreciably change the regression constants; larger aggregates, however, tend to decrease the dispersion.) In delineating the district boundaries, consideration was given to the trip distribution patterns. Under the assumption that each trip is associated with some kind of activity, the trip distribution data were looked upon as an indication of activity patterns. Each district contains one or more trip concentrations. Boundaries delineating the districts, as much as was practical from the data aggregation point of view, were located in low-density areas (Fig. 1).

Trip generation data were obtained from the Tri-State home interview survey. The highway inventory provided measurements of vehicle-miles. Both sets of data were aggregated by analysis district. In the regression analysis each district provided one observation item. District average trip density and average vehicle-miles per square mile were the two data series for which correlation was sought.

In Figure 2, the average miles of travel in each district are plotted against corresponding trip densities. These data have been fitted with a regression line, the equation of which is

$$m = 36.09p^{0.8122}$$
$$R^2 = 0.86 \qquad (3)$$

(R^2 was computed from natural values; the regression equation from logarithmic transformations.)

This correlation verifies the hypothesis. Density explains 86 percent of total travel mileage variance. By this measure, there is a significant correlation between the range of trip densities in the region and vehicle-miles of travel at these densities.

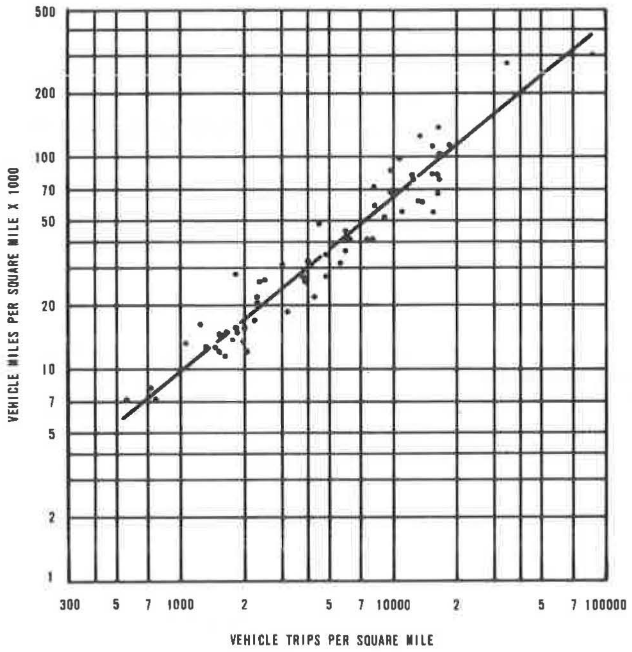

Figure 2. Regional vehicle-mile distribution.

According to Eq. 3, at densities of 500 trips per square mile, vehicles produce 5,600 miles of travel per square mile; at a density of 50,000 trips per square mile the corresponding mileage is 236,600; that is, for the trip density change from 500 to 50,000, or a ratio of 1:100, vehicle-miles increase only by the ratio of 1:42. This indicates that the travel mileage for this range of densities grows less than a half as much as trip densities. Evidently the average vehicle-miles per trip end varies with density.

Dividing Eq. 3 by p, the number of trip ends per square mile, an equation is obtained for the distribution of average miles per trip.

$$\bar{d} = 36.09p^{-0.1878} \qquad (4)$$

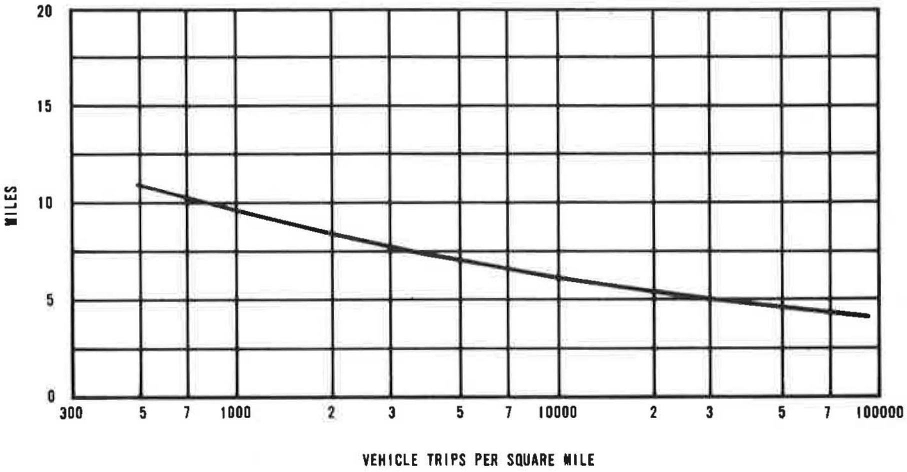

Figure 3. Vehicle-miles per average trip.

The distribution of $\bar{d}$ is shown in Figure 3. The average vehicle-miles per trip varies from about 4 miles in high densities to 11 in low.

A distinction is to be made between the average miles per trip, $\bar{d}$, and a parameter known as the average trip length, frequently denoted as $\bar{r}$. These two parameters represent different averages: $\bar{d}$ for a given area is obtained by dividing all the vehicle-miles traveled within the defined area by the number of trip destinations in this area; $\bar{r}$ is obtained by summing up the total lengths of all trips with one end in the area, regardless of whether this travel is made within the analysis district or without, and dividing this sum by the number of such trip ends in the district. Averaging these two parameters for areas as large as the entire region, $\bar{d}$ and $\bar{r}$ should tend to be equal.

Eqs. 3 and 4 defined the regional patterns of vehicle-mile variation. These equations indicate how the travel mileage intensities change in the metropolitan context with changing densities. Since it has been established that the regional urban form remains relatively stable in time, there is good reason to believe that the patterns of travel intensities will likewise remain stable. The population in different districts may grow in the future, or decline somewhat; but these changes will be reflected in trip densities and, ultimately, in travel mileage generation rates. These equations, therefore, may be utilized in constructing a tool for the prediction of travel mileage by analysis districts.

PROBLEMS ENCOUNTERED IN PROJECTIONS

In employing a regression equation for the projection of events in the future, two questions are likely to arise:

1. Will the equation which has been established on present observations remain valid in the future?
2. How may the regression equation be employed in view of the fact that most of such data observations are either above or below the regression line?

It has been shown that the pattern of travel and trip density relationships is collinear with factors characterizing the urban form. Studies which defined the urban population distribution structure by Eq. 1 and subsequent research (2, 4) demonstrated the stability of this population distribution form over time. These findings strongly suggest that the vehicle mileage distribution pattern as shown by Eq. 3 will prevail for some time to come.

Regional plans in most instances predict future population growth for most districts. Population growth and the anticipated increase in average household income lead to the projection of higher vehicle ownership rates and these to higher vehicular trip densities.

TABLE 1

VEHICLE-MILE PROJECTIONS, TRI-STATE METROPOLITAN AREA

Area	1963			1985		
	VMT	VMT per Trip	Annual VMT per Vehicle	VMT	VMT per Trip	Annual VMT per Vehicle
Core Counties: Manhattan, Brooklyn, Bronx, Queens, Hudson	33,795,644	6.48	8,455	41,550,671	6.61	7,495
Inner Counties: Essex, Passaic, Union, Nassau, Westchester, Richmond, Bergen	48,326,648	6.42	9,543	77,607,994	6.70	10,213
Outer Counties: Mercer, Middlesex, Suffolk, Morris, Rockland, Dutchess, Orange, Putnam, and all six Connecticut Planning areas within Tri-State Region	61,580,804	9.11	14,506	128,997,594	8.75	12,203
Region	143,703,096	7.37	10,800	248,156,259	7.58	10,465

Ratio 1963 VMT per trip to 1985 estimated from Eq. 3 = 1.05
Ratio 1963 VMT per vehicle to 1985 estimated from Eq. 3 = 1.12

Adjustment factor (mean of the two ratios) = 1.09

VMT = vehicle-miles of travel.

With future vehicular trip densities moving upward, according to Figure 3, the regional average mileage per trip would tend to decline.

The available historical data are inadequate to support or to contradict this indication. There are planners who allow for some trip length growth (5) while others believe that the average mileage per trip will remain virtually constant (6). The latter premise, however, may be substantiated by the average annual vehicle-miles of travel per vehicle.

The national average miles per vehicle has been constant for the last 20 years at about 9,670 miles (7), and it provides the most stable control figure for the estimation of vehicle-miles on a large area basis. Considering the two control figures—constant average trip miles and constant miles per vehicle—it is possible that the constancy in the latter is due to the constancy in the former. This may also be seen in Table 1, showing the estimated results for the Tri-State region.

Regional averages of miles per vehicle and miles per trip were utilized for projecting that part of the travel mileage increase over time which is attributable to causes other than the growth in trip ends. Both parameters employed for establishing control totals are regional averages. The resulting adjustment criterion, therefore, applies uniformly for the entire region. Uniform adjustment of the regional vehicle-mile totals would be attained by applying the adjustment factor either to the regional total vehicle-miles estimated from Eq. 3, or to such totals for each analysis district, or to the regional average vehicle-miles per trip.

Factors required for the development of such a criterion are denoted as follows:

M_o = present total vehicle-miles;
M_f' = future vehicle-miles estimated by Eq. 3;
M_f = final projection of total vehicle-miles;
D_o = present number of trips;
D_f = future number of trips;
N_o = present number of vehicles;
N_f = future number of vehicles.

Since some fluctuation is in evidence from year to year in the average miles per vehicle, and very likely there is also some in the average miles per trip, in developing the control criterion these two parameters may be given equal weight. Consequently, denoting the correction factor as C(t),

$$M_f = C(t) \times M_f' = \frac{M_o}{2}\left(\frac{D_f}{D_o} + \frac{N_f}{N_o}\right)$$

$$C(t) = \frac{M_o}{2M_f'}\left(\frac{D_f}{D_o} + \frac{N_f}{N_o}\right) \qquad (5)$$

Eq. 5 represents the correction factor for escalating the initial estimates up to the total control figures.

Before formulating a projective tool, another obstacle resulting from irregularities in the real world remains to be resolved. Some districts generate less vehicle-miles of travel than corresponding regional averages represented by the regression line, others more. The question is whether the initial quantities will move up parallel to the regression line, as the result of increased densities, or in some other way.

Three possibilities suggest themselves for projecting individual district vehicle-mile values.

1. To converge such values on the regression line;
2. Shift vehicle-mile values to projected densities parallel to regression line; and
3. Project between these two extremes.

The regression model was constructed for the third possibility. A "corresponding density" was computed from the regression Eq. 3 for each district's actual vehicle-mile values. The projected density increases were added to the corresponding densities and future travel mileage was estimated for these new densities.

The three projection possibilities are shown in Figure 4. Segment 3′ - 3′ represents the vehicle-mile projection for the future density increase. This projection is carried over to show it in relationship with the other two projection possibilities. The projection 3 somewhat higher than projection 2—parallel to the regression line, and lower than projection 1—converging to the line (Fig. 4).

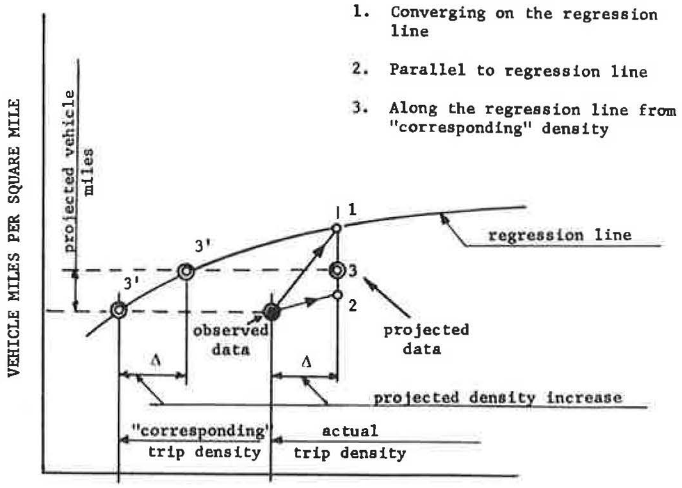

Figure 4. Three projection possibilities.

The projected trip-end density increases are primarily due to population growth. Projection 3 considers the possibility that future intensification of residential activities may tend to bring the vehicle-mile generation rates somewhat closer to the customary intensities that correspond to given densities, regardless of causes underlying the present vehicular mileage data dispersion. About the same regional total figure results whether projecting district data parallel to the regression curve or on the basis of corresponding densities. The latter technique, however, seems to produce a more realistic distribution of mileage among districts.

THE MODEL

The regression model for projecting vehicular travel mileage in a metropolitan region is built upon the regression Eq. 3. It may be rewritten in logarithmic form:

$$\log m = 1.5574 + 0.8122 \log p$$

and from this

$$\log p = 1.2312 \log m - 1.9175$$

or

$$p = \frac{m^{1.2312}}{82.70}$$

It p is computed from this equation for a given district's vehicle-mile observation m_i, the corresponding density may be denoted p_i' and the above equation restated as follows:

$$p_i' = \frac{m_i^{1.2312}}{82.70} \qquad (6)$$

Denoting the amount of future increase or decrease in trip densities for the individual analysis district as Δ_i, the future trip density p_{if}', for which the vehicle-miles are to be projected, can be shown as

$$p_{if}' = p_i' + \Delta_i = \frac{m_i^{1.2312}}{82.70} + \Delta_i$$

If p_{if}' is substituted for p in Eq. 3 the projective equation for the individual analysis district becomes

$$a_i m_{if} = a_i\,(0.4364\, m_i^{1.2312} + 36.09\, \Delta_i)^{0.8122} \qquad (7)$$

where

m_{if} = the projected vehicle-miles for the given district from Eq. 3, and
a_i = the size of the same area in square miles.

Thus, the projected total vehicle-miles for the entire region is equal to the sum of all districts:

$$M_f' = \sum_{i=1}^{n} a_i m_{if}$$

Incorporating the correction factor shown in Eq. 5 and substituting Eq. 7 for $a_i m_{if}$ evolves the projective model:

$$M_f = \sum_{i=1}^{n} a_i \frac{M_o}{2M_f'} \left(\frac{D_f}{D_o} + \frac{N_f}{N_o} \right) \left(0.4364 m_i^{1.2312} + 36.09\, \Delta_i \right)^{0.8122} \qquad (8)$$

Constants shown in Eq. 8 are those which were derived for the Tri-State region. The framework of the model, however, should be valid for other metropolitan regions as well.

PROJECTIONS FOR THE TRI-STATE REGION

The vehicle-miles of travel were projected for the Tri-State metropolitan area from 1963 (the data collection year) to 1985. The projection was carried out at the analysis district level. A summary of the projection results is given in Table 1.

The vehicle-miles are aggregated in three rings: a core, an inner, and an outer ring. The largest travel growth is anticipated to take place in the outer ring—109 percent. The inner ring will increase its travel mileage only moderately—61 percent, and the core only 23 percent. The region's total motor vehicle travel mileage will grow 73 percent.

Table 1 also shows the relative measurements of travel: average vehicle-miles per trip, and annual miles per vehicle. These parameters were computed utilizing trip and vehicle data derived from different criteria. Consequently, Table 1 lists three independent projections of travel parameters. This juxtaposition provides a visual check of the projection results.

The initial vehicle-mile projections obtained from the regression equation have been adjusted upward by 9 percent. The constant vehicle-miles per trip criterion indicated the need for a 5 percent upward adjustment and the constant miles per vehicle, 12 percent. The average upward adjustment, therefore, amounted to 9 percent.

The average vehicle-miles per trip end, while varying between the three rings, remains practically equal for 1963 and 1985 in each ring. The average mileage per vehicle, however, varies. The core indicates a drop in such mileage from 8,455 to 7,495. A similar drop is also in evidence for the outer ring, from 14,506 to 12,203. The projected increase in the automobile ownership rates might account for this change. In the core area, the future automobile ownership might have been projected to increase as a result of higher median household income. Similar projections for the outer ring may have anticipated the expansion of ownership of second and third cars. The total regional vehicle-mile figures maintains reasonably equal average miles per trip and miles per vehicle for 1963 and 1985.

CONCLUSIONS

A statistically significant correlation between vehicular trip-end densities and vehicle-miles of travel on an analysis district basis provides a rationale for the formulation of a regression model by which the future vehicle-miles in such districts may be projected. The regression equation which resulted from this correlation defines the pattern by which the vehicular travel mileage changes with changing trip densities. Stability in annual miles per vehicle and a constant regional average trip mileage provide control totals for assessing the change of travel miles over time resulting in an adjustment factor for the Tri-State region of the order of 9 percent. The application of the regression model in projecting the vehicle-miles traveled in the Tri-State region by 1985 demonstrated the workability of this tool.

Estimates of total vehicle-miles and the defined variation pattern of the vehicular travel mileage provide the basis for further steps in travel analysis.

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