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# A general theory of traffic movement

## The 1955 ITE past presidents' award paper

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Every day our city streets become more clogged with ever-increasing traffic—yet to date we have failed to develop a simple theory explaining the urban traffic patterns which have evolved. It is realized generally that a clear understanding afforded by such a theory would be most beneficial in selecting the proper remedies for our traffic ills. Though several attempts have been made in that direction, the fact remains that we are still without this basic hypothesis.

Most of the attempts have centered around the so-called "land use" approach. These pilot studies sought to establish a relationship between a particular type of land use and the traffic it generates. In other words, it was hoped that by analyzing specific land uses, such as industrial areas, it might be discovered that a certain amount of industrial floor area would produce a given number of trips. Unfortunately, this approach has run into many obstacles, related in most cases to the numerous variables that exist.

Nevertheless, these studies have revealed some basic fundamentals on traffic movement. One of the most important findings was that traffic movement to any area was greatly affected by distance or by air travel time. For example, it was found that the number of people traveling to an industrial site from a residential zone two miles away was greater than the number traveling from a similar residential zone located six miles away (see Fig. 1). In fact, such observed relationships have served as the basis for procedures which have been proposed to estimate traffic movement. One of the most thorough techniques of this type was that developed by F. Houston Wynn to approximate traffic movement to central business districts (Wynn 1955).

But such concepts fall short in explaining all movement in urban areas since they are limited to a particular urban district or type of land use. Furthermore, these techniques do not reflect the impact of the competition between similar land uses—a factor of major

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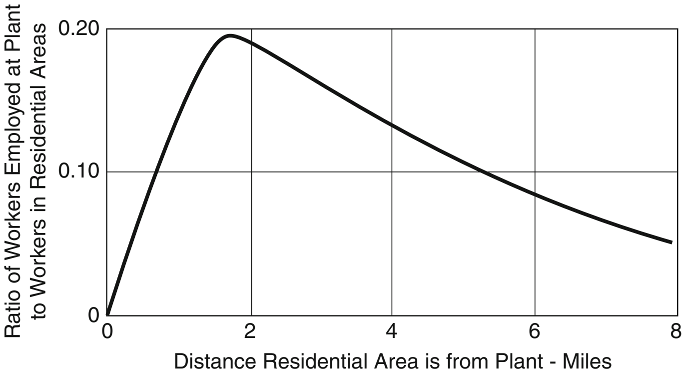



**Fig. 1** The distribution pattern of workers employed at the Bendix plant in South Bend, Indiana. *Source* Alan M. Voorhees, Basic Characteristics of Work Trips

importance. This was brought out in a recent Highway Research Board report entitled, "Basic Characteristics of Work Trips" (Voorhees 1955). In this study it was shown that distance is not the sole criterion for establishing a trading area. Rather, the competitive relationship among various shopping centers in terms of distance and selections is the important element.

Therefore, any theory that attempts to explain the origin and destination of various types of trips in urban areas must reflect the competitive factors of similar types of land uses. But if any such theory is to be applicable, the frequency of the various types of trips must first be established.

## Trip frequency

The frequency of trips depends upon what type of trip is being considered. In this connection, Table 1 reveals an important concept of urban traffic movement. It indicates that 40 % of all trips start from home and about the same percentage are trips returning to the home. This means that 80 % of all the trips made in an urban area have their origin or destination at home. This table, based solely on information from Grand Rapids, is fairly representative of the pattern found in other urban areas.

The remaining trips take place between non-residential areas, such as a trip from an industrial area to a commercial area and back again. In most cases these trips occur during the off-peak hours and are very often short trips. Accordingly, they have a very small effect on the total traffic picture, and therefore, will not be considered in this discussion.[1]

The frequency of the trips per family has a wide range. The variation, however, seems to be related primarily to car ownership. Though much more research is needed to get the complete story, generally it has been found that about seven trips a day will be made by an average one-car family.

Since 80 % of the trips made by residents in urban areas have their origin or destination at home, this would mean that on a typical day an average family with one car would make about six trips to or from its home—three from home and three to return home. Since in

[1] The research on this type of trip has been very limited and quite unproductive mainly because of the many variables involved.

**Table 1** The percentage of all trips by purposes made by residents in Grand Rapids, Michigan

| | Work | Business | Medical dental | School | Social recreation | Change mode of travel | Eat meal | Shopping | Serve passenger | Home | Totals |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Work | 2 | 1 | [a] | [a] | [a] | [a] | 2 | [a] | 1 | 13 | 19 |
| Business | [a] | 2 | [a] | [a] | [a] | [a] | [a] | [a] | [a] | 4 | 6 |
| Medical dental | [a] | [a] | [a] | [a] | [a] | [a] | [a] | [a] | [a] | 1 | 1 |
| School | [a] | [a] | [a] | [a] | [a] | [a] | [a] | [a] | [a] | [a] | [a] |
| Soc.-Rec. | [a] | [a] | [a] | [a] | 3 | [a] | [a] | 1 | [a] | 12 | 17 |
| Change mode | [a] | [a] | [a] | [a] | [a] | [a] | [a] | [a] | [a] | [a] | [a] |
| Eat meal | 1 | [a] | [a] | [a] | [a] | [a] | [a] | [a] | [a] | [a] | 2 |
| Shopping | [a] | [a] | [a] | [a] | [a] | [a] | [a] | 2 | [a] | 7 | 10 |
| Serve pass. | 1 | [a] | [a] | [a] | [a] | [a] | [a] | [a] | 1 | 2 | 5 |
| Home | 13 | 4 | 1 | [a] | 12 | [a] | [a] | 7 | 2 | [a] | 40 |
| Totals | 17 | 7 | 1 | [a] | 18 | [a] | 3 | 10 | 4 | 40 | 100 |

*Source* The Grand Rapids Metropolitan Area Traffic Study, Michigan State Highway Department

[a] Less than one-half of 1 %

practically all cases, the return trip is identical to the one starting from home, we really need only to analyze the outbound trip.

On the basis of origin and destination studies, the frequency of these outbound trips can be broken down by mode of travel. Such a breakdown is presented in Fig. 2. This figure largely reflects factors developed by Messrs. Sharpe, Wynn, and Carroll in various research projects (Wynn 1955; Sharpe 1953; Unpublished papers by Douglas Carroll on Travel Habit, in the Detroit metropolitan area). However, much more work must be done to pin down the variables evolved. The direct relationship between auto driver or auto passenger trips and car ownership is quite apparent. When car ownership in a residential area runs between 0.6 and 1.4, transit usage on the average seems to be quite regular although in areas with very low auto ownership transit usage steps up.

Also the frequency of trips for certain purposes by various modes of travel can be determined from origin and destination studies. The findings based on several of these studies made by the author are set forth in Table 2. Though there is a need for more exploratory work the table clearly shows the importance of the work trip—about a third of all the trips emanating from a residential zone.

Additional research in this field has indicated that with increased car ownership in the residential area there is a like increase in the number of auto driver and auto passenger trips made for working and shopping purposes (Voorhees et al. 1955; Voorhees 1955). Therefore, it can be assumed that frequency of trips for various purposes is going to be related directly to car ownership within the area. Accordingly, auto driver and auto passenger trips for various purposes should be corrected for car ownership.

With this understanding of the frequency pattern, it becomes quite evident that if we can establish a simple theory on the destination of trips emanating from residential areas, we will be able to account for the largest portion of the traffic movement in an urban area.

## Trip destination

As already mentioned, studies have shown that trip destinations seem to reflect the competition between existing land uses. For example, if a house wife is leaving her home to go

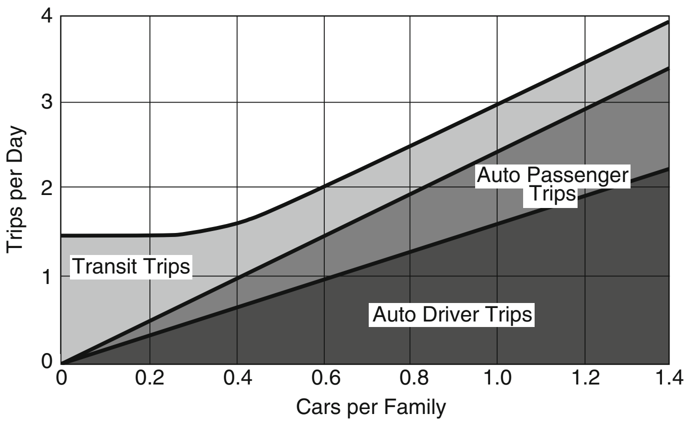



**Fig. 2** Frequency of trips by various modes of travel starting from a residential area. Based on data from: origin and destination studies

**Table 2** The approximate number of trips per day by purpose and mode of travel starting from residential area with 1,000 one car families

| Purpose of trip | Mode of travel | | | |
|---|---|---|---|---|
| | Auto driver | Auto passenger | Transit | Total |
| Work | 600 | 150 | 250 | 1,000 |
| Business | 200 | 50 | 50 | 300 |
| Social | 300 | 300 | [a] | 600 |
| Shopping | | | | |
| Convenience | 200 | 100 | [a] | 300 |
| Shopping goods | 100 | 50 | 50 | 200 |
| Recreational | 100 | 100 | 100 | 300 |
| Other | 100 | 50 | 150 | 300 |
| Total | 1,600 | 800 | 600 | 3,000 |

This table is only applicable for residential area having car ownership between 0.6 and 1.4 car per family. The frequencies of the auto driver and auto passenger trips must be corrected for car ownership

[a] Insignificant

to a store, she probably will visit the shopping center which is most convenient and which provides an adequate selection of the merchandise she wants at a price she is willing to pay. In making this decision, she has many choices—she can go downtown where there is a wide selection, probably at lower prices, or she can go to numerous suburban shopping centers with varying degrees of selection and at different distances from home. The center which she chooses for a particular trip will depend upon her immediate needs and the importance of the above factors to the trip. On one trip she may be attracted to the downtown area because she is interested in a broader selection; another time she might head for the nearest shopping center because she is shopping for a stock item and is interested primarily in saving time.

In many ways these various shopping areas exert a “pull” on shoppers. This depends upon many factors, but in general the strength of the pull seems to follow the gravitational principle. In other words, the pull of a shopping area on a group of shoppers seems to be related to the size of the attractor (shopping area and inversely to the distance the shoppers live from the area).

Research has shown that in applying this principle, the distance factor should be raised to some power depending upon the type of trip, and that best results are obtained if distance is expressed as “auto driving time”. In selecting the units to express the size of the “attractor”, it has been found these should be in line with the type of trip under consideration.

In the case of shopping goods trips—those normally related to merchandise found in a department store—it has been found that the distance factor should be squared and the retail floor area dedicated to apparel in the shopping center should he used to measure the size of the attractor.

This relationship is often referred to as Reilly’s law. Figure 3 illustrates the close similarity between a theoretical curve computed on this basis and the actual habits of shoppers. This figure was based upon analysis of shopping habits for people living in a so-called “corridor” between the central business district of Washington, D.C., and a suburban shopping center called Silver Spring. It indicates the destination of shopping trips made downtown or to a suburban center. From the shape of the curve, the strong pull of the downtown area is quite evident—of course, this reflects its size.

In considering convenience-goods trips—those associated with supermarkets, drug stores and the like—it was found that best results were obtained if the distance was used as a cubed function and the floor area dedicated to groceries and drugs used as an indication of the "size of the center".

Figure 4 substantiates this general conclusion. This is based on a study of the shopping habits of people living between two suburban shopping areas. As can be seen, the "observed trips" pattern follows very closely the theoretical curve, using the distance factor to the third power.

This gravitation principle seemed to work so well for shopping trips that the author has made some recent studies on other types of trips. The first of these studies dealt with work trips and was based on information obtained from origin and destination studies made in Fort Wayne, Indiana (see Fig. 5). This revealed that the principle of gravitation worked satisfactorily, but in this case the distance factor was a square root function rather than a squared function. The size of the "pull" is best expressed by the number of workers employed, including shift workers.

In applying this principle with work trips, it may be necessary to divide the workers into several categories. This pattern may have to be established for white collar workers and their places of employment for blue collar workers and their places of employment, etc. But in light of the limited work of the author, it appears that in cities up to 200,000 population the people are rather heterogeneously placed throughout a community and therefore this step is probably unnecessary. But in larger cities where there is considerable "colonization" of various social groups, it may be necessary to make such breakdowns in applying this principle.

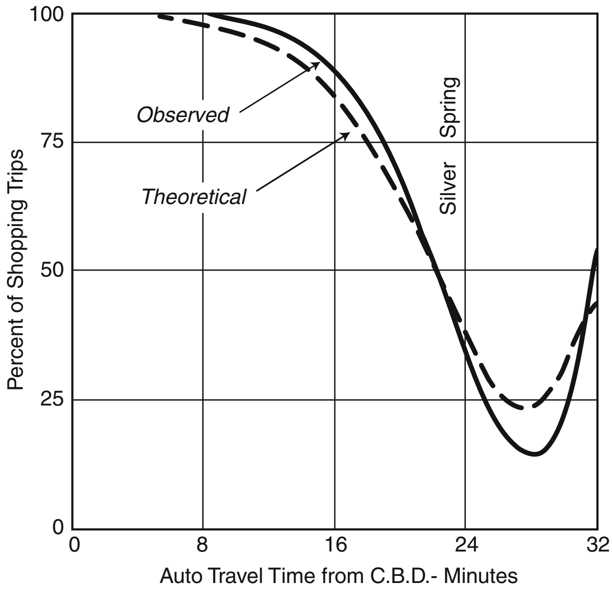



**Fig. 3** Proportion of shopping trips destined downtown by residents of a corridor from C.B.D. through the Silver Spring Shopping Center. *Source* Voorhees et al. (1955)

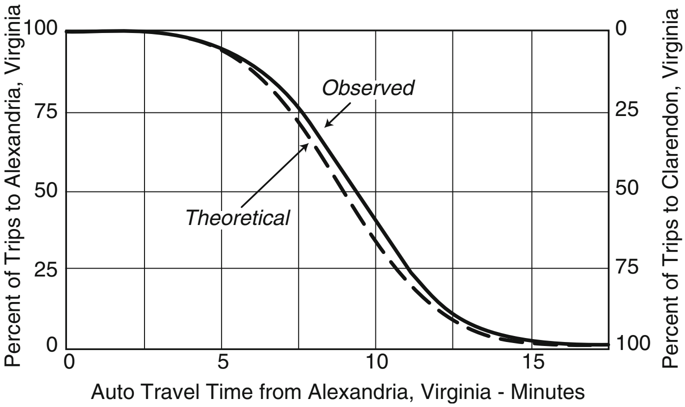



**Fig. 4** Destination of shopping trips by residents of a corridor between the Alexandria, Virginia, and Clarendon Shopping Center. *Source* Voorhees et al. (1955)

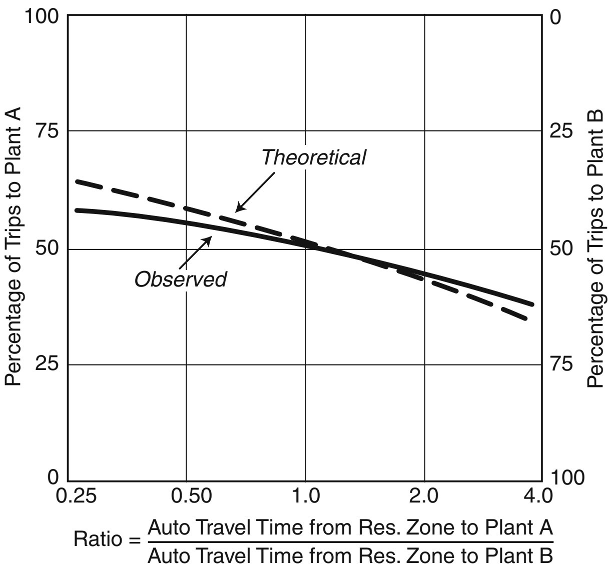



**Fig. 5** Proportion of work trips destined to plant A and B from residential zones in Fort Wayne, Indiana. *Note* Plant A and B employ the same number of persons. Based on data from "Metropolitan Area Traffic Survey"' Fort Wayne, Indiana

Another important trip classification is the social-recreational trip. The social trip usually refers to a trip made between residential areas on a visit to a friend, while the recreational trip applies generally to a trip to a theatre, stadium, night spot, etc. A preliminary study of these types of trips, based on Fort Wayne origin and destination data, was made by the author. The conclusion reached was that in applying the gravitational principle to these trips, different factors had to be used. For social trips, the number of people in a residential area should be used to indicate the size of the "attractor" and the distance factor should be raised to the third power (see Fig. 6).

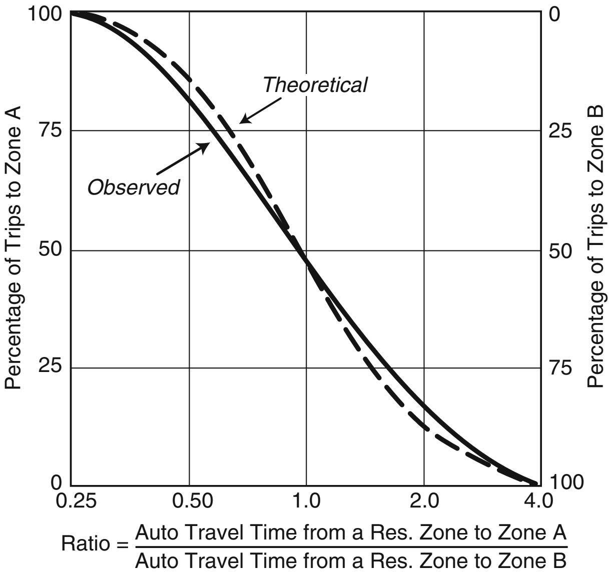



**Fig. 6** Proportion of social trips destined to residential zones A and B from other residential zones in Fort Wayne, Indiana. *Note* Residential zones A and B have the some number of residents. Based on data from "Metropolitan Area Traffic Survey" Fort Wayne, Indiana

Unfortunately it was impossible to complete sufficient research on recreational trips, but from very preliminary investigations it appears these are quite similar to shopping goods trips. This probably reflects the fact that in many cases the recreational facilities found in shopping areas are comparable to the shopping goods display. Further research may find that the number of seats at theaters may be the best indication of the size of the "attractor" and that distance should be raised only to the first power. But until additional research can be completed it does not appear that fairly satisfactory results can be obtained if recreational trips are considered in the same manner as shopping goods trips.

In most origin and destination studies, business trips are separated from the work trip. These usually are differentiated from the work trip in that they indicate the trips made for personal business. Unfortunately, very little work has been done in evaluating the orientation of these trips. However, it does appear from limited observations that they do follow the shopping goods trips very closely. Therefore, until more research is complete, all that can be done at this time is to assume they follow the same general pattern as shopping goods trips.

In addition to these various breakdowns of trip purposes, most origin and destination studies group the remaining trips in a category called "other". These include such trips as those to school, to the doctor, and to a restaurant. In total these represent only a very small percentage of the trips made in an urban area. Here again is a field that needs much more additional work, but rather limited observations indicate these trips follow very closely the pattern of shopping goods trips. Hence, until better values are established it is probably all right to assume the distance factor should be raised to the second power and the floor area dedicated to apparel should be used to measure the size of the "attractor".

Table 3 is a summary of the factors affecting the destination of trips made for various purposes regardless of the mode of travel used. With this data and the information on trip frequency (see Table 2) it is possible to determine the frequency of all trips emanating from a residential area and the destination of these trips. But if this pattern is broken down into modes of travel, certain other factors must be weighed.

## Mode of travel

In considering the mode of travel used on a particular trip, we must recognize that in any family with a car some of the trips may be made by transit—either from choice or because the car is not available at the desired time. However, it has been found that in most cases the trip—be it auto driver, auto passenger, or transit—starting from home, follows the relationships presented in Table 3, with the exception of trips made downtown.

Therefore, with the indices set forth in Tables 2 and 3, it is possible to determine the frequency and destination of all trips made by various modes with the exception of those to the central business district. Trips to the downtown area must be adjusted to account for

**Table 3** The apparent factors affecting the destinations of trips starting from a residential area

| Purpose of trip | Unit to express "size of attractor" | Effect of "distance factor" |
|---|---|---|
| Work | No. of workers employed | $\sqrt{D}$ |
| Social | Dwelling units | $D^3$ |
| Shopping | | |
| Convenience goods | Floor area in foods and drugs | $D^3$ |
| Shopping goods | Floor area in apparel | $D^2$ |
| Business | (1) | (1) |
| Recreational | (1) | (1) |
| Other | (1) | (1) |

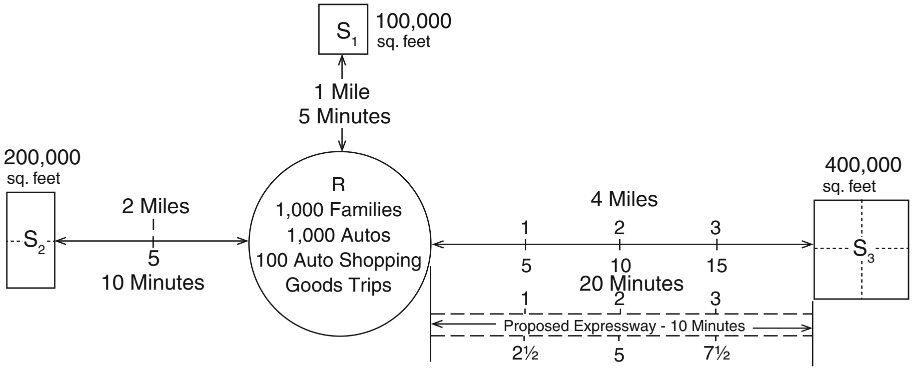
(1) In light of existing research it is recommended that these trips be considered as shopping goods trips

**Table 4** The approximate frequency of auto driver trips during the peak hour

| Purpose of trip | Trips per 1,000 families |
|---|---|
| Work | 100 |
| Business | 20 |
| Social | 5 |
| Shopping | |
| Convenience goods | 15 |
| Shopping goods | 5 |
| Recreational | 5 |
| Other | 10 |
| Total | 160 |

This table is based on one car per family greater use of mass transit. This can be achieved by applying a method recently developed by Wynn (1955).

Furthermore, the same approach can be used in predicting peak-hour traffic patterns if the indices in Table 4 are used and if the proper correction is made for trips to the central business district.




| | | % of Total "pull" | No. of Trips | Vehicle Miles |
|---|---|---|---|---|
| **Existing "Pull"** | | | | |
| from $S_1 = \frac{100{,}000}{5^2}$ | = 4,000 | 57 | 57 | 57 |
| from $S_2 = \frac{200{,}000}{10^2}$ | = 2,000 | 29 | 29 | 58 |
| from $S_3 = \frac{400{,}000}{20^2}$ | = 1,000 | 14 | 14 | 56 |
| **Total "Pull"** | **7,000** | **100%** | **100** | **171 miles** |
| **Pull after Expressway is Built** | | | | |
| from $S_1 = \frac{100{,}000}{5^2}$ | = 4,000 | 40 | 40 | 40 |
| from $S_2 = \frac{200{,}000}{10^2}$ | = 2,000 | 20 | 20 | 40 |
| from $S_3 = \frac{400{,}000}{10^2}$ | = 4,000 | 40 | 40 | 160 |
| **Total "Pull"** | **10,000** | **100%** | **100** | **240 miles** |

**Increase in Vehicle Mileage:**

69 miles or 40% increase

**"Extra" trips on Expressway:**

26 trips or 185% increase

**Fig. 7** Illustration of theory. On the basis of Table 2, 100 trips per day will be made from this area for "shopping goods"

According to Table 2, this would mean that 100 shopping trips each day would start from this residential area. On the basis of the calculation shown in Fig. 7, 57 trips would be made to $S_1$, 29 trips to $S_2$, and 14 trips to $S_3$.

But let us assume that a new expressway is built, making it possible for people living in this residential area to get to $S_3$ in half the time, or 10 min. On the basis of the accompanying calculation, this would mean that the 100 trips would be reoriented in the following manner: 40 to $S_1$, 20 to $S_2$ and 40 to $S_3$. Thus there would be 69 more vehicles miles, or an increase of nearly 40 %.

Furthermore, 26 more trips would be using the expressway than would be expected on the basis of previous travel patterns—an increase of nearly 185 % over expected traffic.

This example clearly shows the impact of such an expressway. Similar reorientation in traffic movement would be observed if a new shopping center or another type of land use were established in the vicinity. Thus this general theory can be used as an effective tool in spotting future traffic bottlenecks.

## Summary

The general theory on traffic movement outlined herein is based on the premise that all trips emanating from a residential area are attracted, or “pulled”, to various land uses in accordance with certain empirical values. Though much more research is needed to refine these values, suggested indices have been set forth in this paper which will permit one to employ this theory to estimate or predict the frequency and the origin and destination of most trips made in an urban area.

This technique is particularly useful in undeveloped areas in estimating traffic volumes and establishing the street pattern which will be required.

Since this theory makes it possible for us to understand existing and future urban traffic patterns, it can be most helpful in analyzing present traffic ills as well as guiding future traffic plans.

**Acknowledgments** This paper, which has been re-published with the kind permission of the Institute of Transportation Engineers, was chosen by Martin Richards as a tribute to Al Voorhees, his mentor and friend, who died in 2005. In republishing it, Martin has made a few changes to the text, correcting apparent minor errors in the original and recognising changes in society since the paper was written.

## References

Sharpe, G.B.: Travel to commercial centers in the Washington DC, metropolitan area. Bulletin 79 Highway Research Board, Washington DC (1953)

Voorhees, A.M., Sharpe, G.B., Stegmaier, J.T.: Shopping habits and travel patterns. Special report 11-B, Highway Research Board, Washington DC (1955)

Voorhees, A.M.: Basic characteristics of work trips. Thesis, Bureau of Highway Traffic, Yale University, May (1955)

Wynn, F.H.: Intra-city traffic movements. Paper presented at the annual meeting of Highway Research Board, Washington DC (1955)

## Author Biography

**Alan M. Voorhees** After a decade with the Automotive Safety Foundation, when he wrote this paper, Al Voorhees left in 1961 to found Alan M. Voorhees and Associates, a company that became one of the leading transportation planning consultancies, pioneering the development of planning models and methods, and responsible for the development of major urban transport projects around the world. Al served as both President of the American Institute of Planners and Chairman of the Transportation Research Board, and received the first Harland Bartholomew Award of the American Society of Civil Engineers for his contribution to urban planning. He left his company in 1978 to become dean of the College of Architecture, Art and Urban Science at the University of Illinois at Chicago Circle, before returning to the Washington area where he became an investor as well as a collector of historic documents, including many old maps portraying the development of Virginia, now in the US Library of Congress and with the State of Virginia. He also endowed the Alan M. Voorhees Transportation Center at Rutgers, established in 1998, and the Voorhees Computing Center at Rensselaer Polytechnic Institute, among others. Alan M. Voorhees passed away in 2005.