Transportation Planning Analysis Used in Small and Medium-Sized Communities
1982
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Ismart, Dane, Federal Highway Administration, U.S. Department of Transportation, 400 7th Street, S.W., Washington, DC 20590
Modlin, David G., Jr., Division of Highways, North Carolina Department of Transportation, Raleigh, NC 27611
Newnam, James T., Jr., Division of Highways, North Carolina Department of Transportation, Raleigh, NC 27611
Stephanedes, Yorgos J., Department of Civil and Mineral Engineering, University of Minnesota, Minneapolis, MN 55455
Evaluating Plan Alternatives: Energy, Safety, and Air Pollution

DAVID G. MODLIN, JR., AND JAMES T. NEWNAM, JR.

The development and "selling" of a thoroughfare plan generally tests to the limit both the technical and public relations skills of the transportation planner. A method is presented by which energy, accident, and air pollution indices may be developed for the evaluation of alternative plans. These indices can be related in a positive manner that somewhat offsets the general negative feelings aroused by talk of widenings, building new facilities, and displacing homes and businesses. The results obtained by applying the proposed analysis method were very good. The method is extremely efficient: Since all three indices are developed from the same vehicle-miles-of-travel summary, only one summary needs to be developed for each alternative to be tested.

In recent years, citizen involvement in the urban transportation planning process has been more vocal than in the past and has had a significant impact on the decision-making process (1). During this period of public meetings in which the plan is "sold" to the citizenry, tough questions are often posed to the engineer-planner, who must defend the merits of his or her work before a generally antagonistic forum. It is imperative that all available analysis tools be used in the process of evaluating plan alternatives so that a good defense of the recommended plan can be made. The analysis tools need not be complex or intricate to be useful. The purpose of this paper is to illustrate how existing techniques can be used to produce reliable energy, accident, and air pollution indices by which alternative transportation system plans can be compared.

The use of the word "system" is important in that the numerical values presented in this paper involve some rather significant assumptions that would not be generally valid in the individual project-level analysis. For example, delay at individual traffic signals is assumed to be common to all alternatives; in other words, a base signal system and resulting average delays are assumed. The relations between functional classification, volume/capacity (V/C), level of service, and operating or overall travel speed are generally related to Highway Capacity Manual (2) definitions; however, the numerical indices presented are based on very average, generalized conditions. Therefore, the analyses suggested in this paper will give more reliable results when applied to the entire highway network, where deviations within analysis units will tend to offset one another.

Typically, three major areas are addressed in the analysis of alternative transportation system plans. They are existing or future capacity deficiency, damage to both public and private property, and alternatives to im-
The objective now is to enter the new speeds into the loaded network records. Since it is not desirable to alter the calibrated trip routings at this point, the historical record containing the modified speeds for a particular network, the "original" calibrated trees and paths for point, the historical record containing the modified speeds for a particular network, the "original" calibrated trees and paths for a particular network, and the final "original" trip table for a particular network are used to produce the loaded network file reflecting the new speeds, which have been modified to reflect the anticipated congestion levels caused by future trip desires.

The North Carolina Department of Transportation (NCDOT) has developed computer capability for summing vehicle miles of travel (VMT) by functional classification and speed increments. The literature provides works on energy consumption rates (4-6), accident potential rates (6-11), and pollution rates (12), all based on VMT, speed, and/or functional classification. The key to correctly applying the rates, however, is the development of VMT by the proper speed increments. Following the procedure outlined in Figure 1 will produce VMT by speed groups consistent with anticipated levels of congestion.

ENERGY ANALYSIS

The proposed energy analysis will provide an estimate of total gallons of gasoline used daily on a systemwide basis. Functional classification and operating (or overall) speed are the key parameters. Data published in two reports (4,6) were combined with level-of-service qualifiers (12,13) to develop the information given in Table 1.

The rates given represent very average conditions and should not be used to evaluate individual projects that vary greatly in operating particulars. The published gasoline consumption rates (11) were assumed to be representative of level-of-service B operating conditions on a daily basis, and factors (3) were developed to adjust the consumption rates as a function of four average levels of congestion. For the arterial, collector, and local classifications, the level-of-service B rate was based on 5.75, 6.25, and 4.50 stops/mile, respectively.

After the V/C analysis, facilities are assigned a speed that corresponds to the indicated level of service. VMT is summarized by computer by functional classification and new speed increments. Next, a manual calculation is made by using the following equation:

\[
\text{TOTGAL} = \sum_{i} \sum_{j} (\text{VMT}_{ij}) (\text{rate}_{ij})
\]

where

\[
\text{TOTGAL} = \text{estimated total gallons of gasoline used daily},
\]

\[
\text{rate} = \text{rate of gasoline consumption},
\]

\[
i = \text{functional classification index},
\]

\[
j = \text{speed increment index}.
\]

Two points concerning this analysis need to be made. The fuel consumption rates are representative of early 1970 vehicles. Since system alternatives are to be compared, it is the relative difference

Table 1. Energy factors for alternative plan analysis.

<table>
<thead>
<tr>
<th>Functional Classification</th>
<th>Factor</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freeways and expressways</td>
<td>Avg. operating speed (mph)</td>
<td>55</td>
<td>50</td>
<td>40</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>V/C ratio</td>
<td>0.50</td>
<td>0.62</td>
<td>0.75</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>Level of service</td>
<td>B</td>
<td>C</td>
<td>D</td>
<td>E</td>
</tr>
<tr>
<td></td>
<td>Fuel consumption (gal/mile)</td>
<td>0.0801</td>
<td>0.0817</td>
<td>0.0841</td>
<td>0.0865</td>
</tr>
<tr>
<td></td>
<td>Avg. miles per gallon</td>
<td>12.48</td>
<td>12.24</td>
<td>11.89</td>
<td>11.56</td>
</tr>
<tr>
<td>Arterials</td>
<td>Avg. overall speed (mph)</td>
<td>35</td>
<td>30</td>
<td>25</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>V/C ratio</td>
<td>0.70</td>
<td>0.80</td>
<td>0.90</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>Level of service</td>
<td>B</td>
<td>C</td>
<td>D</td>
<td>E</td>
</tr>
<tr>
<td></td>
<td>Fuel consumption (gal/mile)</td>
<td>0.0831</td>
<td>0.1010</td>
<td>0.1084</td>
<td>0.1195</td>
</tr>
<tr>
<td></td>
<td>Avg. miles per gallon</td>
<td>10.74</td>
<td>9.90</td>
<td>9.23</td>
<td>8.37</td>
</tr>
<tr>
<td>Collectors</td>
<td>Avg. overall speed (mph)</td>
<td>30</td>
<td>25</td>
<td>20</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>V/C ratio</td>
<td>0.70</td>
<td>0.80</td>
<td>0.90</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>Level of service</td>
<td>B</td>
<td>C</td>
<td>D</td>
<td>E</td>
</tr>
<tr>
<td></td>
<td>Fuel consumption (gal/mile)</td>
<td>0.1050</td>
<td>0.1092</td>
<td>0.1104</td>
<td>0.1216</td>
</tr>
<tr>
<td></td>
<td>Avg. miles per gallon</td>
<td>10.53</td>
<td>9.69</td>
<td>9.06</td>
<td>8.22</td>
</tr>
<tr>
<td>Locals and centroid</td>
<td>Avg. overall speed (mph)</td>
<td>20</td>
<td>15</td>
<td>10</td>
<td>&lt;10</td>
</tr>
<tr>
<td></td>
<td>V/C ratio</td>
<td>0.70</td>
<td>0.80</td>
<td>0.90</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>Level of service</td>
<td>B</td>
<td>C</td>
<td>D</td>
<td>E</td>
</tr>
<tr>
<td></td>
<td>Fuel consumption (gal/mile)</td>
<td>0.0910</td>
<td>0.0940</td>
<td>0.1025</td>
<td>0.1165</td>
</tr>
<tr>
<td></td>
<td>Avg. miles per gallon</td>
<td>10.89</td>
<td>10.64</td>
<td>9.76</td>
<td>8.59</td>
</tr>
</tbody>
</table>

*Desirable operating speed = 55 mph.*
*Desirable overall speed = 30 mph.*
*Desirable overall speed = 35 mph.*
*Desirable overall speed = 20 mph.*
between TOTAL values that will be evaluated; these rates, even though somewhat dated, will correctly indicate the best fuel-efficient plan. Evaluated on a percentage basis, these rates versus 1980 rates should provide essentially the same numerical results. However, as new rates, in a desirable form, are published, Table 1 should be updated.

The second point is that a common basic level of stop delays, side friction, traffic control functions, etc., is inherent in all of the alternatives to be compared. The assumption has been made that, on a systemwide basis, deviations in traffic operations will average out and that the results of the analysis will be valid for the comparison of system alternatives.

ACCIDENT POTENTIAL ANALYSIS

The proposed accident analysis will provide an estimate of annual potential accidents as a function of functional classification and level of service being provided. Table 2 (7-12) was developed from rates published in the literature (8,10). Factors were developed, following the work of May (9) and Rykken (7,11), to modify the published accident rates to reflect four basic levels of congestion.

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capacity-restrained adjustments, and calibrated speeds adjusted for year 2005 V/C ratios, discussed, it is appropriate to describe what was network with the calibrated speeds adjusted for year 2005 V/C ratios. Since energy and accident analyses have not heretofore been used in North Carolina studies, the comparison of unadjusted versus adjusted speeds seemed pointless in attempting to justify the merits of using adjusted speeds. It is sufficient to say that speed adjustments that correspond to estimated future operating conditions are more reasonable and give more realistic analytical results.

The numerical results from the energy and accident analyses are given in Table 4. The recommended thoroughfare plan makes significant contributions to the predicted quality of traffic flow measured in terms easily understood by any audience. In developing a "1-mile/gal gasoline saving" and a "5-mph speed improvement" on a systemwide basis, significant delays and excessive stops due to congestion are eliminated through implementation of the thoroughfare plan recommendations.

The mobile air-quality analysis used all four network options. A comparison should be made not only between A5 and A6 but also between 05 and A5 and 06 and A6. Air-quality analyses have normally been made by using the calibrated speeds for existing as well as future networks. The latter suggested comparisons will show significant differences between emission estimates using calibrated versus V/C adjusted speeds. Although the absolute value of pollutants, particularly CO and HC, increases when the adjusted speeds are used versus the calibrated speeds, it is felt that these are the most realistic values and, consequently, should be the values that are reported.

The numerical results of the mobile air-quality analysis, determined by using Mobile 1 factors, are given in Table 5. The most critical and most often limited pollutant variations in North Carolina with respect to transportation are for CO and HC.

**CONCLUSIONS**

The analyses described in this paper are extremely time-efficient to perform and provide alternative plan comparisons that are easily understood by any audience. In addition, the absolute numerical results obtained by the outlined procedure are superior to those obtained by the "old way of doing things." Efforts should now be directed toward updating the energy consumption rates and improving the accident rate format so that even more reliable results might be obtained.
Mobile Source Emissions and Energy Analysis at an Isolated Intersection

DANE ISMART

A simplified technique is presented for evaluating the effect improvements will have on mobile source emissions and energy use at an isolated intersection. The procedure relates emissions of CO, HC, and NOx and energy analysis to traffic-flow conditions at an intersection. A level of service is determined by using the critical movement analysis technique. By use of empirical data from a Federal Highway Administration report, stopped delay per vehicle is converted to the number of vehicles idling, slowing down, and stopping. Based on an NCHRP project, stopped delay per vehicle is related to the level of service. The change from a base condition in idling time and vehicles stopping and slowing down as a result of an intersection improvement is used as the basis for determining the total reduction in pollutant emissions and energy use. The reductions are stated in terms of pounds and gallons as well as percentage reduction from the base condition. The procedure is designed to be a sketch planning tool for planners in small urbanized areas who have limited technical resources and data. The information necessary to use the procedure includes (a) total traffic entering the intersection, (b) turning movements, (c) number of approach lanes, (d) exclusive-use lanes, (e) approach speed, and (f) an estimate of the average upstream and downstream distance from the intersection where vehicle speeds are affected.

The procedure described in this paper will relate the emissions of air pollutants and energy to traffic-flow conditions at an isolated intersection. Traffic flow will be analyzed under the following classifications:

1. "Idling"—Vehicle hours of stopped delay.
2. "Slowdowns"—Total number of speed changes, and
3. "Stopping"—Total number of vehicles stopping.

By determining the changes in the number of vehicles idling, slowing down, and stopping, and by applying appropriate energy and emission rates, it will be possible to estimate the reduction in energy use and pollutants emitted as a result of the improvement of traffic operations at an intersection.

ENERGY USE AND EMISSION RATES

The table below (1) indicates fuel consumed and pollutant emissions for every 1000 vehicle-h of idling (January 1975 conditions for fuel consumption):

<table>
<thead>
<tr>
<th>Item</th>
<th>Amount per 1000 Vehicle Hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline (gal)</td>
<td>650</td>
</tr>
<tr>
<td>Pollutants (lb)</td>
<td></td>
</tr>
<tr>
<td>Carbon monoxide (CO)</td>
<td>2430</td>
</tr>
<tr>
<td>Hydrocarbon (HC)</td>
<td>160</td>
</tr>
<tr>
<td>Nitrogen oxides (NOx)</td>
<td>50</td>
</tr>
</tbody>
</table>

Figure 1 shows the additional fuel consumed for 1000 speed changes for various speeds (fuel consumption rates prevailing in January 1975 (2)). This graph is used to determine the additional fuel consumed by vehicles that slow down as they approach an intersection. As a driver approaches an intersection, he will slow down his vehicle if there is a queue or if the light he approaches is in a red phase. If the queue dissipates or the signal changes before the vehicle reaches the intersection, the driver may only slow down and then return to his original speed. Figure 1 determines the additional fuel consumed based on this type of speed change.

For vehicles that stop completely, Figure 1 can also be applied. In this case, a stopped vehicle would be considered as going from the initial speed to 0 mph and then returning to the initial speed.

Figures 2-4 indicate the CO, HC, and NOx emissions per 1000 speed changes. As was the case for fuel consumption, these figures can be applied for vehicles that slow down and stop.

REFERENCES

TRAFFIC-FLOW CHARACTERISTICS

In order to evaluate proposed intersection improvements, changes in traffic flow must be analyzed. The general strategy for this evaluation is to relate level of service to stopped delay per vehicle. Changes in idling, slowdowns, and stopping are based on stopped delay per vehicle.

The following relations were developed empirically from a Federal Highway Administration (FHWA) report (2).

Stopping

Percent stopping = \( 0.5497 \log_{10} (ADPV) - 0.1404 \)  

\[ ADPV = 1.3 \times SDPV \]  

where \( ADPV \) is approach delay per vehicle (approach delay divided by the total number of vehicles passing through the intersection approach during a period of time, in vehicle seconds per vehicle) and \( SDPV \) is stopped delay per vehicle (stopped delay divided by the total number of vehicles passing through the intersection approach during a period of time, in vehicle seconds per vehicle).

Substituting \( SDPV \) for \( ADPV \) yields

\[ \text{Percent stopping} = 0.5497 \log_{10} (SDPV \times 1.3) - 0.1404 \]

To determine the number of vehicles stopping, multiply percent stopping times the total traffic entering the intersection (TTEI) for a specific time period:

\[ \text{Number of stopped vehicles} = (0.5497 \log_{10} (SDPV \times 1.3) - 0.1404) \times \text{TTEI} \]

To determine additional fuel consumption due to stopping, multiply the number of stopped vehicles times the additional fuel consumption rate (FCR) per speed change. The rate is obtained from Figure 1 by dividing by 1000. This will convert the rate from gallons per 1000 speed changes to gallons per speed change.
Table 1. Excess hours consumed per speed-change cycle beyond hours consumed by continuing at initial speed (for passenger cars).

<table>
<thead>
<tr>
<th>Initial Speed (mph)</th>
<th>Speed Reduced To and Returned From (mph)</th>
<th>Stop</th>
<th>5</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>25</th>
<th>30</th>
<th>35</th>
<th>40</th>
<th>45</th>
<th>50</th>
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<tbody>
<tr>
<td>5</td>
<td></td>
<td>1.02</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>10</td>
<td></td>
<td>1.51</td>
<td>0.62</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>45</td>
<td></td>
<td>4.90</td>
<td>4.06</td>
<td>3.28</td>
<td>2.57</td>
<td>1.93</td>
<td>1.34</td>
<td>0.83</td>
<td>0.42</td>
<td>0.13</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td></td>
<td>5.37</td>
<td>4.34</td>
<td>3.75</td>
<td>3.01</td>
<td>2.24</td>
<td>1.71</td>
<td>1.15</td>
<td>0.68</td>
<td>0.35</td>
<td>0.11</td>
<td></td>
</tr>
<tr>
<td>55</td>
<td></td>
<td>5.84</td>
<td>5.02</td>
<td>4.21</td>
<td>3.45</td>
<td>2.74</td>
<td>2.08</td>
<td>1.47</td>
<td>0.94</td>
<td>0.57</td>
<td>0.28</td>
<td>0.09</td>
</tr>
</tbody>
</table>

To determine excess energy consumption and emissions due to slowdowns at an intersection, multiply Equation 15 by the FCR and the emission rates (ERs) from Figures 1, 2, 3, and 4. The final forms of the equations for slowdowns are as follows (hours per speed change obtained from Table 1):

Excess fuel consumption (gal) = \[\frac{TTEI \times (0.04 \text{ SDPV} + 0.30)}{1000 \times \text{hours per 1000 speed changes}} \times \text{FCR (Figure 1)} \] \((16)\)

\[\text{CO (lb)} = \frac{TTEI \times (0.04 \text{ SDPV} + 0.30)}{1000 \times \text{hours per 1000 speed changes}} \times \text{ER (Figure 2)} \] \((17)\)

\[\text{HC (lb)} = \frac{TTEI \times (0.04 \text{ SDPV} + 0.30)}{1000 \times \text{hours per 1000 speed changes}} \times \text{ER (Figure 3)} \] \((18)\)

\[\text{NOx (lb)} = \frac{TTEI \times (0.04 \text{ SDPV} + 0.30)}{1000 \times \text{hours per 1000 speed changes}} \times \text{ER (Figure 4)} \] \((19)\)

Idling
Fuel consumption and emissions due to idling can be computed by multiplying the number of vehicles entering the intersection by the stopped delay per vehicle times the rates given in the text table at the beginning of this paper. The equations for idling would be as follows:

Energy (gal) = \[\frac{TTEI}{3600} \times \text{SDPV} \times 0.65 \text{ gal} \] \((20)\)

\[\text{CO (lb)} = \frac{TTEI}{3600} \times \text{SDPV} \times 2.43 \text{ lb} \] \((21)\)

\[\text{HC (lb)} = \frac{TTEI}{3600} \times \text{SDPV} \times 0.16 \text{ lb} \] \((22)\)

\[\text{NOx (lb)} = \frac{TTEI}{3600} \times \text{SDPV} \times 0.05 \text{ lb} \] \((23)\)

IMPLEMENTATION STRATEGY
The equations developed for determining energy use and vehicle emissions are based on stopped delay per vehicle. In the following table from NCHRP Project 3-28 (based on a synthesis of various data), stopped delay can be related to level of service: (V/C = volume/capacity)

<table>
<thead>
<tr>
<th>Level of Service</th>
<th>Typical V/C Ratio</th>
<th>Delay Range (s/vehicle)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.00-0.60</td>
<td>0.0-16.0</td>
</tr>
<tr>
<td>B</td>
<td>0.61-0.70</td>
<td>16.1-22.0</td>
</tr>
<tr>
<td>C</td>
<td>0.71-0.80</td>
<td>22.1-28.0</td>
</tr>
<tr>
<td>D</td>
<td>0.81-0.90</td>
<td>28.1-35.0</td>
</tr>
<tr>
<td>E</td>
<td>0.91-1.00</td>
<td>35.1-40.0</td>
</tr>
</tbody>
</table>
| F                | Varies            | >40.1                   

To determine the time lost due to vehicles slowing down but not stopping, the following equation is used:

\[\text{Slowdown delay} = \text{total approach delay} - \text{time in queue delay} \] \((9)\)

From FHWA (3),
\[\text{Time in queue delay} = \frac{(\text{stopped delay per stopped vehicle})}{11.33} \times 0.76 \] \((11)\)

\[\text{Total approach delay} = 1.3 \times \text{SDPV} \times \text{TTEI} \] \((10)\)

\[\text{Stopped delay per stopped vehicle} = 0.96 \times \text{SDPV} + 11.10 \] \((12)\)

Substituting Equation 9 for SDPV in Equation 8,
\[\text{Time in queue} = \frac{(0.96 \times \text{SDPV} + 11.10 - 11.33)}{0.76} \times \text{TTEI} \] \((13)\)

\[\text{Slowdown delay} = \frac{TTEI \times 1.3 \times \text{SDPV} - \left(0.96 \times \text{SDPV} + 11.10 - 11.33\right)}{0.76} \times \text{TTEI} \] \((14)\)

To convert the slowdown delay in seconds to the number of vehicles slowing down in units of 1000, divide the slowdown delay by the excess hours consumed per 1000 speed-change cycles from Table 1 (4):慢
\[\text{Slowdowns per 1000 speed changes} = \frac{TTEI \times (0.04 \text{ SDPV} + 0.30)}{1000 \times \text{hours per 1000 speed changes}} \] \((15)\)

The equations developed for determining energy use and vehicle emissions are based on stopped delay per vehicle. In the following table from NCHRP Project 3-28 (based on a synthesis of various data), stopped delay can be related to level of service: (V/C = volume/capacity)
Delay values relate to the mean stopped delay incurred by all vehicles entering the intersection. Note that traffic-signal coordination effects are not considered and could drastically alter the delay range for a given V/C ratio. By relating level of service to stopped delay per vehicle, the equations in this paper could be used to analyze vehicle emissions and energy. The technique would be most applicable in determining what effect an intersection improvement, such as constructing a left-turn lane, will have on energy consumption and air pollutant emissions.

The first step in the process is to determine the level of service by using the critical movement technique (4) for both the existing intersection and the intersection with the proposed improvement. The level of service would be correlated with the stopped delay from the table above. For example, from the critical movement technique it can be determined that an existing intersection has a level of service C and a critical intersection volume of 1100. The table below (1) gives intersection capacity by level of service for the critical movement technique (* indicates a special case):

<table>
<thead>
<tr>
<th>Level of Service</th>
<th>Capacity Range (vehicles/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low</td>
</tr>
<tr>
<td>A</td>
<td>0</td>
</tr>
<tr>
<td>B</td>
<td>901</td>
</tr>
<tr>
<td>C</td>
<td>1051</td>
</tr>
<tr>
<td>D</td>
<td>1201</td>
</tr>
<tr>
<td>E</td>
<td>1351</td>
</tr>
<tr>
<td>F</td>
<td>-</td>
</tr>
</tbody>
</table>

Level of service C has a capacity range of 1051-1200 for the critical movement technique, and the preceding table indicates that level of service C has a stopped-delay range of 16.1-22 s/vehicle. Therefore, prorating the level of service, the delay for the existing intersection would be calculated as follows:

\[
\frac{1100 - 1051}{(1200 - 1051)} = \frac{(X - 16.1)}{(22 - 16.1)}
\]

where \( X = \text{SDPV} \)

\[
49/149 = (X - 16.1)/5.9
\]

\[
149X = 2688
\]

\[
X = 18 \text{ s/vehicle}
\]

The same process would be used to determine the SDPV with the proposed intersection improvement.

The second step in the process is to use the existing and improved intersection stopped-delay values in the energy and emission equations. For simplifying purposes, it is assumed that the average vehicle slowing down but not stopping will reduce its initial speed by one-half. If, for example, the initial approach speed for an intersection is 30 mph, the reduction for the average vehicle would be 15 mph. Approach speed is defined as the speed limit of the approach lanes to the intersection. By using Table 1, for this example, 1.24 excess hours would be consumed per 1000 speed-change cycles.

After the energy and vehicle emissions are computed, the third step would be to compare the results for the existing intersection with those for the improved intersection. The difference in the results between the existing and proposed intersections is the reduction in energy use and air-quality emissions (due to fewer vehicles stopping, slowing down, and idling).

**APPLICATION**

Significant changes in energy use and vehicle emissions as a result of an intersection improvement will only occur with a change in the level of service. For an intersection at low volumes, there may be no difference in the level of service between the existing and the improved facility. Both facilities may operate at a high level of service with low volumes. Consequently, there would be little change in the percentage of vehicles stopping, idling, and slowing down.

The evaluation for an intersection should be broken into peak and nonpeak analysis periods. The analysis periods should be based on the intersection operating at the same level of service for the entire analysis period. If there is a significant difference in the level of service in the peak or nonpeak period, it may be necessary to break down the analysis into smaller time units. The minimum time period that can be analyzed is 1 h.

Another problem in any emissions and energy analysis is the change in vehicle characteristics. In the future, the fuel consumption and vehicle emission rates will change. To compensate for this change, the rates should be modified periodically.

In evaluating an existing versus improved intersection, the percentage reduction in fuel consumption and emissions, as well as the absolute values, should be considered. To compute the percentage reduction for fuel, determine the total amount of fuel consumed at the existing intersection. At this point it has been demonstrated how to calculate the additional fuel consumed due to speed changes and idling. For the speed changes, the fuel consumed is in addition to the fuel consumed for traversing the same distance at a uniform speed. To obtain the total amount of fuel consumed, use Figure 5 (2) and add the fuel consumption indicated for a uniform speed to the consumption for speed changes and idling.

In Figure 5, the uniform speed is cross-referenced with consumption in gallons per 1000 vehicle miles. The uniform speed would be the approach speed for the intersection. By entering into Figure 5 with a uniform speed, the consumption rate can be determined. This rate is multiplied by vehicle miles at the intersection in units of 1000 to estimate fuel consumption at a uniform speed for all vehicles entering the intersection. To determine vehicle miles, an estimate must be made of the distance upstream from the intersection, where vehicles are initially affected by the intersection, and the distance downstream, where they have re-
covered their original speed. Normally, this distance will vary depending on the characteristics of the intersection. A reasonable estimate must be obtained from an individual who is familiar with the intersection in question.

The equation for uniform-speed fuel consumption is as follows:

\[
\text{Fuel (gal)} = \left( \frac{\text{TTEI}}{1000} \right) \times \text{FCR} \times \text{Intersection Distance} \tag{24}
\]

After the uniform fuel consumption is added to

Figure 8. Format for total and incremental fuel consumption.

<table>
<thead>
<tr>
<th>INCREMENTAL FUEL CONSUMED</th>
<th>BASE</th>
<th>ALTERNATIVE</th>
<th>REDUCTION (GALLONS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stopping</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slowdowns</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Idling</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>INCREMENTAL FUEL CONSUMED</strong></td>
<td></td>
<td></td>
<td><strong>REDUCTION</strong></td>
</tr>
<tr>
<td>Uniform Speed</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>TOTAL FUEL CONSUMED</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**EQUATIONS**

- Stopping (Gals.) = \[ \sqrt{3497 \times \log_{10} \left( \frac{\text{SDPV} \times 1.3}{\text{TTEI} \times \text{FCR}} \right)} \times \frac{1404}{1000} \times \text{FCR} \times \text{Figure 1} \] \tag{5}
- Slowdowns (Gals.) = \[ \frac{\text{TTEI} \times \left( 0.04 \times \text{SDPV} + 0.7 \right)}{3600 \times \text{Hours/1000 speed changes (Table 2)}} \times \text{FCR} \times \text{Figure 1} \] \tag{16}
- Idling (Gals.) = \[ \frac{\text{TTEI} \times \left( \text{SDPV} \times 0.65 \right)}{3600} \] \tag{20}
- Uniform Speed (Gals.) = \[ \frac{\text{TTEI} \times \text{FCR} \times \text{Figure 5} \times \text{Intersection Distance}}{1000} \] \tag{24}

**WHERE:**

- SDPV = Stop delay per average vehicle
- TTEI = Total traffic entering intersections
- FCR = Fuel consumption rate
- Intersection Distance = Estimate of average total distance in miles, upstream and downstream from the intersection (example .1 miles) where the average vehicle's free flow speed is affected.

Figure 7. Format for sum and total incremental air-quality emissions.

<table>
<thead>
<tr>
<th>CO (Pounds)</th>
<th>Base</th>
<th>Alternative</th>
<th>Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stopping</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slowdowns</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Idling</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Uniform Speed</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sum</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HC (Pounds)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stopping</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slowdowns</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Idling</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Uniform Speed</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sum</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NO (Pounds)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stopping</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slowdowns</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Idling</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Uniform Speed</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sum</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[ \sum \text{Reduction} \]

<table>
<thead>
<tr>
<th>CO</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>HC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NO</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
the consumption due to speed changes and idling, total fuel consumed has been determined. This value, when calculated for an existing intersection, will be used as the base for determining the percentage reduction for a proposed improvement. For example, at an intersection 1000 gal are consumed. With the construction of a left-turn lane, 100 gal less will be consumed. Therefore, the left-turn bay will reduce consumption by 100/1000, or 10 percent.

For vehicle emissions, Figures 2-4 represent total emissions for vehicles changing speeds. To simplify the analysis, it is assumed that for existing intersections most vehicles will experience a speed change at the intersection. Thus, for congested intersections, the emissions for idling, stopping, and slowing down represent total emissions. Total emissions for the existing intersection would be used just as in the analysis of energy as a base to determine the percentage reduction.

In the case of an improved intersection, total emissions would include vehicles that do not experience a speed change. The number of vehicles that do not stop or slow down can be estimated by equating it to the reduction of vehicles stopping when an existing intersection is improved.

For example, if the addition of a left-turn bay reduced the percentage of vehicles stopping from 10 to 70 percent and 4000 vehicles entered the intersection during the analysis period, it would be estimated that 400 vehicles (10 percent x 4000) will experience little interference when traversing the intersection. Then, to determine vehicle miles, the number of free-flowing vehicles would be multiplied by the distance from the intersection where vehicle movement is affected. This would be the same distance estimated for the energy analysis.

From Figure 5, pollutant emissions in units of 1000 vehicle miles for vehicles traveling at a uniform speed can be obtained. These emissions rates multiplied by vehicle miles would determine the emissions for uniform-speed vehicles. The equation is as follows:

\[ \text{CO, HC, NO}_x = \left( \frac{\text{TTEI}}{1000} \right) \times \text{ER} \times \text{intersection distance} \times \text{percent reduction of vehicles stopping} \]  

When these emissions are combined with emissions due to slowdowns, stopping, and idling, the total emissions for an improved intersection can be calculated.

**SUMMARY**

The procedure described in this paper is designed as a sketch planning tool for planners. Whereas the critical movement technique is a sketch planning tool for analyzing intersection capacity, this tool is a sketch planning tool for evaluating vehicle emissions and energy. It can be applied quickly and can provide reasonable estimates of reductions in energy use and vehicle emissions. The quick-response characteristics of the method are demonstrated by the limited amount of data necessary to do an evaluation.

To simplify the application of the technique, the equations given in this paper for pollutant emissions (Equations 9-11, 17-19, 21-23, and 24) and the formats shown in Figures 6 and 7 should be used.

**REFERENCES**


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**Improved Demand Estimation for Rural Work Trips**

**YORGOS J. STEPHANEDES**

A critical review of the most widely accepted rural demand estimation models is performed. Based on data collected in two rural towns, a disaggregate specification for rural work-trip modal choice is proposed. The new model includes a set of socioeconomic and a set of policy-relevant variables and can be used for implementing a wide range of transportation policy changes that can also improve rural transit system performance. Model variables produce coefficients consistent with the literature and are sensitive to changes in rural economic development.

The major objective of this study is to determine whether such policies will, in time, cause changes in rural economic development, a project was recently initiated (6). An immediate need for a demand estimation specification to estimate work-trip modal choice was identified.

The evaluation of rural transportation projects that operate with federal or state support has been considered an essential part of government-subsidized transportation programs during the past decade. Transportation policies that can improve the efficiency and effectiveness of transport operations have recently been proposed (1), and data on performance measures for evaluating such operations are now available (1-3) and are being compiled by a number of states (4-5). In response to a need for identifying transportation policies that can also improve rural mobility and the need to determine whether such policies will, in time, cause changes in rural economic development, a project was recently initiated (6). An immediate need for a demand estimation specification to estimate work-trip modal choice was identified.

The major objective of this study is to determine the most reliable rural demand estimation model suitable for implementing level-of-service transportation policies and sensitive to long-term mobility and economic changes that may take place in a community. This determination depends on certain basic criteria: (a) the ability of the selected model to estimate modal choice for work trips directly, (b) inclusion of level-of-service independent variables for implementing transportation policies that can improve the efficiency and effectiveness of a transit system, (c) inclusion of mobility and socioeco-
nomic variables so that long-term changes in resi-
dent mobility and the local economy can be taken
into account when modal choice is determined, (d)
data availability, (e) model performance, (f) caus-
ally justifiable independent variables, and (g) the
potential for model transferability to other rural
areas.

A critical review of the most significant exist-
ing demand estimation models is performed first. This
review includes a summary of performance char-
acteristics that emphasizes effectiveness and the
drawbacks of each model from limited tests found in
the literature. Subsequently, a new demand esti-
mation specification for rural work-trip modal
choice is proposed and compared with the best of the
existing models. The comparison tests are based on
six data sets collected in two rural towns over a
three-month period.

The major findings can be summarized in two
parts. First, results from tests of the performance
of the existing rural demand models (7,8) are mostly
in agreement with previous studies (7–11). More
specifically, the existing models are found to be
easy to comprehend but hard to apply to a specific
trip purpose, as in work-trip estimation. Further-
more, because of the lack of a strong causal justi-
fication and the dearth of appropriate level-of-
service variables, their use for policy analysis is
not warranted. Finally, they result in significant
estimation errors; because of this and the above
characteristics, their potential for transferability is
questionable at best. These observations rein-
force the need for the development of more rigorous
and more accurate rural demand estimation specifi-
cations.

This is accomplished by the proposed specifi-
cation, which, in agreement with recent research find-
ings, results in an increased importance of travel
cost and household income in rural areas. The tests
show that the proposed specification performs better
than the existing ones.

BACKGROUND

Review of Rural Estimation Models

The existing approaches to modeling the steady-state
demand sector of the rural transportation system fall
into three general categories: (a) attitudinal stud-
ies, in which each model from the lit, and rough trips
rate estimates (12–15); (b) mathematical techniques
based on aggregate analysis (7–9); and (c) disaggre-
gate mathematical techniques (1).

Lack of rigorous analysis does not justify the
use of approaches belonging to the first category
for reliable policy analysis. Methods in the second
category have relied on simple regression techniques
(7,9) or used cross-classification techniques in
combination with probabilistic assumptions (8). Due
to their structure and assumptions, these methods
often result in models that are descriptive rather
than causal, models with large forecasting errors,
questionable transferability properties, and little
applicability to policy analysis. When such models
are used, the sensitivity of prediction to errors in
parameter estimates can be high, and the lack of
emphasis on level-of-service variables makes predic-
tion insensitive to proposed changes in transportation policy. On the contrary, disaggregate models are capable of capturing the causal relations be-
tween transportation level of service, household
socioeconomic characteristics, and travel behavior
and therefore provide a more meaningful analysis of
various transportation policy options (16).

Aggregate Models

The first comprehensive work in this area (7) aimed
to produce forecasting methods at area-wide and
route levels that are specific enough to enable
local planners to use [the] method as the basis for
initial operations of small-scale transit sys-
tems...and simple enough to be applied by local
planning staff personnel. Five econometric models
were presented, two applicable to fixed-route sys-
tems and three to demand-responsive systems. For
each kind of system, there are models at the county
(macro) level, and at the route (micro) level. By
using regression analysis, route ridership is fore-
cast as a (log) linear function of aggregate route
characteristics such as total population along
routes and route length and destination population.
The choice of independent variables is often
arbitrary, and specifications are correlative rather
than causal; e.g., excessive attention is paid to
achieving a high R², but little attention is given
to identifying variables that cause a specific
ridership to be created. Ridership estimates are
not sensitive to changes in transportation policy,
household socioeconomic characteristics, or even
cost (i.e., simple to understand, easy to apply, and
low cost in nature)...allow the possibility of
transferability, and are capable of identifying the
needs generated by specific target populations
along routes, such as the elderly, carless, or
households with low income" (8).

The Poisson model was introduced as a technique
supplementary to ones previously used. It is a sim-
ple and appealing model but is subject to criticism
similar to those directed at previous research.
Independent variables used for cross classification
are rather arbitrary. Ridership estimates are
insensitive to changes in transportation policy and to
the level of service of competing alternatives.
Although regression methods are criticized, they are
used to improve on the Poisson model when it proves
to be a poor performer (and the specification chosen
is correlative rather than causal). Finally, the
model is based on questionable assumptions (e.g.,
the decision to ride the bus is a random event or that
such events for rural households are inde-
pendent of each other) and does not contribute to a
better understanding of the transit structure, a
fact acknowledged by its authors (8). Although some
of the objectives, such as low cost, ease of appli-
cation, and need identification, are satisfied, they
are not met. The model is confusing, largely not
accurate, and it does not have potential for
transferability (1).

A more recent modeling attempt (9) used simple
regression and was developed for demand-responsive
service. It could be criticized along earlier (7)
lines. The major criticism, however, was that it
allocated fixed daily rural service that were relevant to this
more work was needed to measure the effect of a study and could be tested are summarized as follows: The macro model (7) is expressed as

\[
\text{LOG (RTPASS/MO)} = -0.353 + 0.407 \text{ LOG BMILES} + 0.533 \text{ LOG FREQ} + 0.611 \text{ LOG RESTPOP} - 0.123 \text{ LOG COMPBMS}
\]  

(1)

where

- RTPASS/ MO = round-trip passengers per month,
- BMILES = total vehicle miles per month,
- FREQ = average monthly round-trip frequency,
- RESTPOP = people who may use the system (000s), and
- COMPBMS = monthly vehicle miles of competing systems in the area.

The micromodel (2) is expressed as

\[
\text{LOG (OWPASS/DAY)} = -6.344 + 0.697 \text{ LOG FREQ} - 2.547 \text{ LOG D} + 0.533 \text{ LOG FREQ} + 0.611 \text{ LOG RESTRPOP}
\]  

(2)

where

- OWPASS/DAY = one-way passengers per day on a specific route;
- FREQ = round trips per day on that route;
- D = round-trip distance from farthest origin point served to main destination (miles);
- POPo = population of area traversed minus population of largest city, which is defined as the destination population (00 000s); and
- POFd = population of the largest city traversed (00 000s).

The Poisson mode (8) is expressed as

\[
T = 0.003 05 R^{1.496}
\]  

(3)

where

- T = trip ends per operating day,
- R = route mileage, and
- U = number of dwelling units within 0.25 mile of a route.

**Disaggregate Models**

The inadequacies of aggregate modeling techniques for rural transportation demand estimation led to an early attempt to formulate rigorous disaggregate specifications (1). A limited analysis was conducted of the effects on ridership of certain transportation level-of-service attributes and of socioeconomic characteristics of individuals. The limited scope of the study could only result in an indication that rural residents are more sensitive to travel cost than urban residents. This was a significant conclusion because previous researchers (2-9), using aggregate analysis, had decided that this particular characteristic did not play a significant role in rural ridership estimation. Furthermore, in the course of the study it became evident that disaggregate demand estimation for rural transportation was feasible. It was determined that more work was needed to measure the effect of a number of level-of-service variables on demand modal choice before such demand models could be used for policy analysis.

**PROPOSED MODEL**

Because of the disadvantages of the existing models, it was decided that a new model should be developed that should fulfill the criteria set forth at the beginning of this paper. In addition, the new model should make efficient use of data and should be at least as accurate as previous techniques. Given its known characteristics and advantages over aggregate methods, it was decided that a disaggregate formulation should be adopted.

For predicting the choice of transportation mode to work from among three modes—transit, drive alone, and shared ride—a multinomial logit model structure was chosen. The statistical properties of the logit model and its successful application in analyzing discrete modal choice are well documented (17-19) and are not restated here. The particular form of the model used was as follows:

\[
P(m;M_t) = \exp(X_{mt})/\sum \exp(X_{mt})
\]  

(4)

where

- \(P(m;M_t)\) = probability of worker \(t\) selecting mode \(m\) from choice set \(M_t = \{\text{transit, drive alone, rideshare}\}\),
- \(X_{mt}\) = vector of independent variables for alternative \(m\) and worker \(t\), and
- \(\beta\) = vector of coefficients estimated by using the maximum likelihood method (17).

The vector of independent variables \(X_{mt}\) can be expressed in the general form

\[
X_{mt} = X_m (L_m, S_t)
\]  

(5)

where \(L_m\) is a vector of level-of-service characteristics of mode \(m\) and \(S_t\) is a vector of socioeconomic characteristics of worker \(t\).

**VARIABLES AND DATA**

Three level-of-service variables and six socioeconomic variables were included in the logit formulation. These variables and their expected coefficients are summarized in Table 1. The level-of-service variables are defined as in urban worktrip modal-choice models (19). Of the socioeconomic variables, the variable automobiles per household worker is introduced as a replacement for automobiles per licensed driver and workers per household; it is hypothesized that the former is of direct and overriding concern in rural areas, where individual workers have been found to be increasingly dependent on the automobile (10). A dummy variable is introduced to associate home ownership with driving alone, which is a significant expense in rural areas and would most likely be expected of homeowners. Finally, length of residence is introduced to account for long delays involved in the decision to ride a transit vehicle or share a ride in rural areas, a sociological characteristic also pointed out in the literature (1,10). Automobile availability per licensed driver for shared ride is not assigned an expected sign in Table 1 as a result of two observations: (a) It has been shown that in urban areas the effect of this variable on shared ride is less than it is on drive alone, and (b) across-the-board increased automobile availability in rural areas, when combined with the previous observation, may result in an unpredictable effect on shared ride.

Approximately 500 households from the rural towns of Cloquet and Le Sueur, Minnesota, were contacted, and household characteristics were recorded for those who were potential riders of the commuter rural transit service. Sample demographic and socioeconomic characteristics are summarized in the following table:
These data were supplemented by information on level-of-service characteristics of the transportation system. To minimize the effect of a variety of trip choices on the choice of mode to work, only simple home-based trips were considered, i.e., trips from home to work to home. The final sample of 77 observations was divided into two subsamples: 40 Cloquet observations and 37 Le Sueur observations. A disaggregate model was then developed for each subsample to allow evaluation of model transferability. Finally, a model was developed for the complete sample so that higher statistical significance could be obtained.

### ESTIMATED COEFFICIENTS

Three basic disaggregate models to estimate rural work-trip modal choice were derived from the Minnesota data—one from the Cloquet sample (model 1), one from the Le Sueur sample (model 3), and one from the combined Minnesota sample (model 5). These models are presented in Table 2. The previously stated hypotheses about the positive influence of home ownership on driving alone and of length of residence were reflected by the parameters associated with variables DROWN and RESL, respectively. The two parameters have the expected sign, and, in the combined sample model, are significant at the 8 and 7 percent levels, respectively. The two variables were not included in the Cloquet model, since almost all Cloquet respondents owned their home and length of residence was uniform across individuals. A third hypothesis being entertained—that automobile availability per worker has a positive influence on driving alone and carpooling—is reflected in model 5 by the parameter associated with variable AALD. That parameter is also of the expected sign and is significant at the 5 percent level.

For all estimated coefficients, significance improved drastically when the sample size increased, as seen in Table 2, with the exception of the in-vehicle travel time coefficient (IVTT). All other coefficients in the combined Minnesota model are significant over the 8 percent level. Very short commuting trips in Le Sueur probably account for the perceived lack of importance of IVTT in that town.

For the convenience of prospective model users, two alternative models were derived for each town and these are also presented in Table 2. Models 2 and 4 differ from models 1 and 3, respectively, in that the former two do not use the variable AALD but, rather, its components. In addition, automobile availability per licensed driver (AALD) was not found to be significant for work-trip modal choice in Cloquet and was not included in any demand model for that town.

The combined Minnesota rural work-trip modal-choice model is again presented in Table 3 along with two existing urban models. An inspection of the model coefficients confirms the observation found in the literature (1) that rural residents are more sensitive to travel cost than urban residents. Furthermore, remaining household income (RHINC) is seen as having an influence on rural modal choice greater than in urban areas by an order of magnitude, which also indicates the increased importance of financial considerations for transportation decisions in rural areas. Finally, it should be noted that the increased importance placed by urban commuters on OVTT in relation to IVTT is also observed in rural commuting and is of the same order of magnitude.

### MODEL TESTING AND EVALUATION

#### Method

In testing the demand estimation models, six data sets were used. The following table summarizes these data sets and gives the monthly transit ridership for each data set:

<table>
<thead>
<tr>
<th>Location</th>
<th>Data Set</th>
<th>Transit Route</th>
<th>Round-Trip Passengers per Month</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cloquet</td>
<td>1</td>
<td>Cloquet-Potlatch</td>
<td>292</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Cloquet-Diamond Match</td>
<td>292</td>
</tr>
<tr>
<td>Le Sueur</td>
<td>3</td>
<td>Le Sueur-Green Giant</td>
<td>157</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Le Sueur-Hospital</td>
<td>257</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>Le Sueur-Telex</td>
<td>268</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>Henderson-Telex</td>
<td>268</td>
</tr>
</tbody>
</table>

Because of its small size, data set 2 could not be used alone but only in combination with data set 1. Similarly, data set 4 had to be used in combination with data set 3. Six estimation models were tested: Micromodel (2), Micromodel (7), Poisson model (9), disaggregate Cloquet model 1, disaggre-

### Table 1. Rural work-trip modal-choice model: definition of variables.

<table>
<thead>
<tr>
<th>Variable Code</th>
<th>Definition</th>
<th>Expected Sign of Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>D&lt;sub&gt;a&lt;/sub&gt;</td>
<td>1 for drive alone, 0 otherwise</td>
<td>Negative</td>
</tr>
<tr>
<td>D&lt;sub&gt;s&lt;/sub&gt;</td>
<td>1 for shared ride, 0 otherwise</td>
<td>Negative</td>
</tr>
<tr>
<td>OPTC/HINC</td>
<td>Round-trip out-of-pocket travel cost (¢) + household annual income (1968$)</td>
<td>Negative</td>
</tr>
<tr>
<td>IVTT</td>
<td>Round-trip in-vehicle travel time (min)</td>
<td>Negative</td>
</tr>
<tr>
<td>IVTT/DIST</td>
<td>Round-trip out-of-vehicle travel time (min) + one-way distance (miles)</td>
<td>Negative</td>
</tr>
<tr>
<td>AALD&lt;sub&gt;d&lt;/sub&gt;</td>
<td>Number of automobiles per licensed driver for drive alone, 0 otherwise</td>
<td>Positive</td>
</tr>
<tr>
<td>AALD&lt;sub&gt;s&lt;/sub&gt;</td>
<td>Number of automobiles per licensed driver for shared ride, 0 otherwise</td>
<td>Unknown</td>
</tr>
<tr>
<td>WPW&lt;sub&gt;s&lt;/sub&gt;</td>
<td>Number of workers in the household for shared ride, 0 otherwise</td>
<td>Positive</td>
</tr>
<tr>
<td>AAPW&lt;sub&gt;s&lt;/sub&gt;</td>
<td>Number of automobiles per household worker for automobile and shared ride, 0 otherwise</td>
<td>Positive</td>
</tr>
<tr>
<td>RHINC&lt;sub&gt;s&lt;/sub&gt;</td>
<td>Household annual income - 800 (number of persons in the household) for drive alone and shared ride (1968$), 0 otherwise</td>
<td>Positive</td>
</tr>
<tr>
<td>DROWN&lt;sub&gt;s&lt;/sub&gt;</td>
<td>1 for own residence and drive alone, 0 otherwise</td>
<td>Positive</td>
</tr>
<tr>
<td>RESL&lt;sub&gt;s&lt;/sub&gt;</td>
<td>Length of residence (years) for transit and shared ride, 0 otherwise</td>
<td>Positive</td>
</tr>
</tbody>
</table>

Note: a = drive alone, s = shared ride (carpool), and t = transit.
gate Le Sueur model 3, and disaggregate combined Minnesota model 5.

Four error measurements were computed for each data set and model. These measurements included (a) absolute error (AE) and (b) percentage of absolute error (PAE), defined as a percentage of actual ridership. For data sets that were themselves combinations of other data sets, the sum absolute error (SAE) was calculated to measure the total absolute error of the component data sets. Percentage of sum absolute error (PSAE) was also calculated for SAE as a percentage of actual ridership. These error measurements are defined as follows:

\[
AE = \text{actual ridership - estimated ridership}, \\
PAE = \frac{\text{actual ridership - estimated ridership}}{\text{actual ridership}}, \\
SAE = \sum_{i=1}^{N} \left| \frac{\text{actual ridership}_i - \text{estimated ridership}_i}{\text{actual ridership}_i} \right|, \\
\text{PSAE} = \frac{\sum_{i=1}^{N} \left| \frac{\text{actual ridership}_i - \text{estimated ridership}_i}{\text{actual ridership}_i} \right|}{N}
\]

where \(N\) is the total number of component data sets within a data set.

In testing the three aggregate models (Macro, Micro, and Poisson) certain application problems were encountered. For example, in both Le Sueur and Cloquet, the transit systems only serve work trips at specific destinations. The market for these systems is therefore smaller than the general population. The aggregate models tested do not seem to be suited for handling these cases since the values of independent variables such as RESTPOP, POPo, and POPd in the Macromodel and Micromodel become very small and may lead to inaccurate results.

Other variables in the aggregate models also appear to be unclear in some applications. The variable SMILES in the Macromodel makes no distinction between deadhead miles and miles driven with passengers aboard. In certain cases, such as the Le Sueur system, which has one route between Le Sueur and Henderson 6 miles away, the deadhead miles are a significant portion of the total bus miles. In Cloquet, all service is within the city and deadhead miles are also further reduced as twice a day the bus drops off workers of one shift and leaves with workers from the previous shift without having to deadhead to the plant. These two situations are quite different, and it is unlikely that this model accurately handles both cases. Similar problems exist in applying the variable \(R\), used by the Poisson model to account for system route mileage. Finally, it should be noted that, when applying the Macromodel and Micromodel, no corrections were made for fare, since in both cities the transit fare is the "base fare".

### Results

The absolute error (AE) measurement for the six models tested is presented in Table 4 in two ways,
CONCLUSIONS

A disaggregate demand specification was developed to estimate rural work-trip modal choice. The inclusion of a set of policy-relevant variables allows the use of the model for implementing a wide range of transportation policies to improve transit system performance. The inclusion of mobility and socioeconomic variables allows one to take into account long-term changes in resident mobility and the local economy when determining modal choice. Although not indicated in Table 4 and the table above, the error always represents underestimation. This observation supports previous remarks on the performance of the Poisson model (8,9) but not on that of the Macromodel (8,11).

1. At all times and for any individual data set, the proposed disaggregate specification performs substantially (up to 88 percent) better than the Micromodel. To be sure, this conclusion is drawn from testing the disaggregate models on a town different from that used in model development.

2. In testing model performance on combined data sets, the sum absolute error (SAE) again reveals the superiority of the disaggregate models. This conclusion can be drawn from the following table in which the Cloquet model, when applied to combined Le Sueur data sets, performs substantially better than the Micromodel (data sets 3 and 4 are treated as one data set):

3. At all times and for any data set, the proposed disaggregate specification developed by using the combined Minnesota data performs substantially better than the Micromodel.

The Macromodel and Poisson model perform substantially (up to 78 percent) worse than the Micromodel. Although not indicated in Table 4 and the table above, the error always represents underestimation. This observation supports previous remarks on the performance of the Poisson model (8,9) but not on that of the Macromodel (8,11).

Conclusions

First, the error value is given so that conclusions on model performance can easily be drawn; evidently, lower errors indicate better model performance. Second, each model is compared with the Micromodel, and the deviation of its error with respect to that of the Micromodel is presented. A negative deviation means that the model in question has a smaller error than the Micromodel and is therefore more desirable. Table 4 also includes a relative error measurement (PAE), which indicates the relative size of the absolute error with respect to the actual ridership value.

From the test results and the relative performance comparisons of Table 4, the following conclusions can be drawn:

1. At all times and for any individual data set, the proposed disaggregate specification performs substantially (up to 88 percent) better than the Micromodel. To be sure, this conclusion is drawn from testing the disaggregate models on a town different from that used in model development.

2. In testing model performance on combined data sets, the sum absolute error (SAE) again reveals the superiority of the disaggregate models. This conclusion can be drawn from the following table in which the Cloquet model, when applied to combined Le Sueur data sets, performs substantially better than the Micromodel (data sets 3 and 4 are treated as one data set).

Table 3. Transferability of work-trip modal-choice model: rural versus urban.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Rural Minnesota</th>
<th>Urban</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>New Bedford</td>
</tr>
<tr>
<td>$D_1$ Coefficient</td>
<td>-6.356</td>
<td>-2.198</td>
</tr>
<tr>
<td>t-statistic</td>
<td>-2.933</td>
<td>-1.648</td>
</tr>
<tr>
<td>$D_2$ Coefficient</td>
<td>-6.832</td>
<td>-1.535</td>
</tr>
<tr>
<td>t-statistic</td>
<td>-3.378</td>
<td>-1.535</td>
</tr>
<tr>
<td>OPT/INC Coefficient</td>
<td>-136.99</td>
<td>-87.33</td>
</tr>
<tr>
<td>t-statistic</td>
<td>-1.437</td>
<td>-1.576</td>
</tr>
<tr>
<td>IVTT Coefficient</td>
<td>-0.02961</td>
<td>-0.019</td>
</tr>
<tr>
<td>t-statistic</td>
<td>-0.983</td>
<td>-0.484</td>
</tr>
<tr>
<td>OVT/DIST Coefficient</td>
<td>-0.4808</td>
<td>-101.3</td>
</tr>
<tr>
<td>t-statistic</td>
<td>-3.583</td>
<td>-2.903</td>
</tr>
<tr>
<td>AALD Coefficient</td>
<td>2.541</td>
<td>3.741</td>
</tr>
<tr>
<td>t-statistic</td>
<td>3.674</td>
<td>7.19</td>
</tr>
<tr>
<td>AALD Coefficient</td>
<td>0.4499</td>
<td>0.609</td>
</tr>
<tr>
<td>t-statistic</td>
<td>0.8478</td>
<td>1.87</td>
</tr>
<tr>
<td>WPI Coefficient</td>
<td>1.249</td>
<td>0.46</td>
</tr>
<tr>
<td>t-statistic</td>
<td>1.406</td>
<td></td>
</tr>
<tr>
<td>AAPW Coefficient</td>
<td>0.01239</td>
<td></td>
</tr>
<tr>
<td>t-statistic</td>
<td>1.500</td>
<td></td>
</tr>
<tr>
<td>WPI Coefficient</td>
<td>1.026</td>
<td>0.8101</td>
</tr>
<tr>
<td>t-statistic</td>
<td>1.379</td>
<td>3.28</td>
</tr>
<tr>
<td>EOTCA Coefficient</td>
<td>1.199</td>
<td>N.A.</td>
</tr>
<tr>
<td>t-statistic</td>
<td>0.60060</td>
<td>0.60017</td>
</tr>
<tr>
<td>Sum of chosen probabilities</td>
<td>49.29</td>
<td>N.A.</td>
</tr>
<tr>
<td>Log likelihood at convergence</td>
<td>-47.14</td>
<td>-156.5</td>
</tr>
<tr>
<td>Log likelihood at zero</td>
<td>-84.59</td>
<td>-436.4</td>
</tr>
</tbody>
</table>

Table 4. Estimation errors of six demand models.

<table>
<thead>
<tr>
<th>Location</th>
<th>Data Set</th>
<th>Model</th>
<th>SAE</th>
<th>PAE</th>
<th>Improvement Over Micromodel (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cloquet 1</td>
<td>3 and 4</td>
<td>Micro</td>
<td>365</td>
<td>86</td>
<td>--</td>
</tr>
<tr>
<td>Cloquet 2</td>
<td>3 and 4</td>
<td>Micro</td>
<td>113</td>
<td>27</td>
<td>69</td>
</tr>
<tr>
<td>Le Sueur</td>
<td>3 and 4</td>
<td>Micro</td>
<td>73</td>
<td>17</td>
<td>80</td>
</tr>
<tr>
<td>Combined</td>
<td>3 and 4</td>
<td>Micro</td>
<td>77</td>
<td>18</td>
<td>79</td>
</tr>
<tr>
<td>Cloquet 3</td>
<td>3 and 4</td>
<td>Micro</td>
<td>652</td>
<td>94</td>
<td>4</td>
</tr>
<tr>
<td>Le Sueur</td>
<td>3 and 4</td>
<td>Micro</td>
<td>627</td>
<td>91</td>
<td>--</td>
</tr>
<tr>
<td>Combined</td>
<td>3 and 4</td>
<td>Micro</td>
<td>127</td>
<td>18</td>
<td>80</td>
</tr>
</tbody>
</table>
Synthesized Through-Trip Table for Small Urban Areas

DAVID G. MODLIN, JR.

Research performed to develop an improved and simple-to-use set of models that would facilitate the synthesis of a through-trip table for urban areas of less than 50,000 population is described. The effects of functional classification, average daily traffic, percentage of trucks, route continuity, and urban area population were determined to be significantly correlated with through-trip patterns. A least-squares analysis led to the development of a set of simple multiple regression expressions that estimate (a) the percentage of through-trip ends at each station and (b) the distribution of these trip ends among stations. The relations developed are simple to apply. The introduction of the new parameters, especially route continuity, appears to have improved the accuracy of the resulting trip table as compared with previous applications of the technique.
The Planning and Research Branch of the North Carolina Department of Transportation (NCDOT) is responsible for implementing the 3-C (continuing cooperative, and comprehensive) planning process as mandated by the Federal-Aid Highway Act of 1962. In addition, the Branch provides planning services on a contractual basis to any of the smaller urban areas that wish to develop a thoroughfare plan. To date, 165 municipalities have taken advantage of this service and 133 of the thoroughfare plans developed have been mutually adopted by the individual areas and NCDOT.

The factors leading to the implementation of various elements of a given thoroughfare plan are many and varied in nature. However, the basic element in the determination of the need for and the structure of a given thoroughfare plan is traffic volume. An analysis of existing volumes provides the basis for the determination of deficient transportation corridors. Growth in traffic volumes and the corresponding need for new and/or improved facilities may be anticipated by using some future land use plan and an understanding of the causal relations of trip generation and attraction. Typically, in major planning studies these relations are studied through the use of data available from the external, internal, truck, and taxi origin-destination (O-D) surveys. Mathematical expressions are developed that simulate the traffic patterns determined by the O-D surveys. Alternative transportation systems are then evaluated by using the developed simulation models.

The cost today of conducting O-D surveys in order to develop unique simulation models for individual small urban areas is prohibitive. Recent cost factors reported by NCDOT are the following: portable traffic counter per installation per week, $5.55; hourly machine count per installation per week, $14.00; classification count per 8-h count, $92.00; external station interview per interview, $1.00; and internal home interview per interview, $25.00. Additional costs are incurred in the processing of the raw O-D data into final report form. The escalating costs described above mandate a synthesis of elements for determining travel patterns in small urban areas. Abundant literature exists that both describes and documents acceptable procedures for synthesizing internal-internal trips by modeling techniques. Given that the number of external-internal trips produced at each station could be determined by modeling techniques, then a procedure exists for their distribution among internal traffic zones.

The models discussed in this paper build on and validate previous attempts to synthesize through-trip (external-external) patterns by using multiple regression analysis and selected variables that are routinely available. Since the average daily traffic (ADT) at a cordon station is the sum of the external-external and external-internal traffic, if one can be estimated, the other is known. Thus, by successfully applying the procedures described in this paper, the total travel patterns for small urban areas can be synthesized and the benefits of long-range planning can be achieved at a minimum cost.

**REVIEW OF LITERATURE**

The Planning and Research Branch of NCDOT has been particularly successful in developing and applying techniques for synthesizing internal-internal travel patterns (1). This ability to synthesize internal-internal travel patterns helps to make long-range planning available to small urban areas (those with a population of less than 50,000). However, since the early 1970s, the cost of external O-D surveys has become a significant, and restrictive, factor in the provision of long-range planning services. To be viable, long-range planning must consider the data derived from the external O-D survey.

In 1969, a study (2) required by Section 17 of the 1968 Federal-Aid Highway Act provided a set of parameters that suggested a solution to the problem of estimating through-trip patterns. By using this information, data routinely available from the annual count program, and published external O-D data from small urban areas, I was successful in developing a procedure for estimating through-trip patterns (2). I used multiple regression analysis to develop two models. The first model estimated the percentage of through-trip ends at each cordon station and the second, a composite model made up of six individual equations, estimated the distribution of the through trips among cordon stations. The result of the application of the models is a triangular through-trip table.

In 1976, Pigman (3) published a report following my work that also included the results of a comparative cross-classification analysis. Pigman concluded that the regression analysis technique provided fewer data problems and provided sufficient accuracy to make its use appropriate for planning purposes.

Pigman (3) confirmed the importance of urban area population, ADT at the external station, and the percentage of trucks as estimators of through trips. The significance of the impact of functional classification was not proved in the estimation of through-trip productions; however, the distribution models were based on the functional classification of the origin station. The models developed by Pigman are considerably simpler and consequently less tedious to use than others (3) that have been reported. In achieving simplicity, however, there appears to be some minor loss of "statistical accuracy".

Pigman's work and continued interest by NCDOT to improve on its ability to offer transportation planning services have renewed interest in the simulation of through-trip movements. That interest and the desire to test the importance of new parameters and several modifications of old ones led to the effort reported in the remainder of this paper.

**MODEL DEVELOPMENT**

External O-D surveys of 14 cities and towns scattered throughout North Carolina that have populations ranging from 6,600 to 50,500 were the source of data for the analyses. Based on the work of others (2,5) and the experience of NCDOT staff, a basic set of independent variables had already been identified. The experiences of the staff in applying models (2) previously developed suggested that route continuity should be important in the distribution phase and that modified forms of other parameters might prove to be more useful.

External-External Generation Model: Percentage of Through Trips

The external-external trip model estimates the percentage of through-trip ends at each external cordon station. Data on urban area population, urban area employment, ADT, percentage of trucks excluding panels and pickups, and percentage of panels and pickups were tabulated for 14 urban areas (see Table 1). Multiple linear regression analysis was used to derive a prediction equation.

The total number of observations used in the analysis was 241. Models were developed under two scenarios: (a) Functional classification was significant, and (b) functional classification could be
The recommended equations for the distribution phase are given in Table 3. The addition of route continuity in the data set was beneficial, and the development of an ADT attraction factor, following Pigman (1), also proved to be significant. The distribution equations are much simpler and statistically better than those previously reported (3) and as simple as, and give better \( R^2 \) values than those reported by Pigman (1).

**STATISTICAL RESULTS OF MODEL DEVELOPMENT**

Statistics provides a basis for judging the worth of prediction equations such as those presented in this paper. The format of each equation can be defended logically, and this is a first test. The ease with which the values of the independent variables can be determined at a base year and the confidence with which they can be projected to a design year are also considerations in model development. The variables in the final equations are routinely available and can be projected with reasonable confidence.

**Table 1.** O-D reports used in developing through-trip estimation model.

<table>
<thead>
<tr>
<th>Urban Area</th>
<th>Year Conducted</th>
<th>Urban Area Population</th>
<th>Urban Area Employment</th>
<th>No. of Extremal Stations</th>
<th>ADT</th>
<th>Trucks (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lincoln</td>
<td>1975</td>
<td>18,500</td>
<td>9,400</td>
<td>17</td>
<td>220-9,850</td>
<td>1.8-19.1</td>
</tr>
<tr>
<td>Dunn-Erwin</td>
<td>1972</td>
<td>17,500</td>
<td>7,250</td>
<td>21</td>
<td>280-12,210</td>
<td>2.0-15.6</td>
</tr>
<tr>
<td>Tarboro-Princeville</td>
<td>1973</td>
<td>13,500</td>
<td>10,500</td>
<td>9</td>
<td>1,190-5,500</td>
<td>4.4-11.2</td>
</tr>
<tr>
<td>Mount Airy</td>
<td>1974</td>
<td>22,500</td>
<td>13,750</td>
<td>19</td>
<td>340-9,010</td>
<td>4.2-21.9</td>
</tr>
<tr>
<td>Statesville</td>
<td>1971</td>
<td>37,000</td>
<td>15,600</td>
<td>24</td>
<td>90-11,200</td>
<td>2.3-19.9</td>
</tr>
<tr>
<td>Hickory</td>
<td>1973</td>
<td>50,500</td>
<td>38,650</td>
<td>30</td>
<td>340-28,190</td>
<td>2.0-18.0</td>
</tr>
<tr>
<td>Sanford</td>
<td>1977</td>
<td>21,900</td>
<td>14,200</td>
<td>23</td>
<td>210-11,170</td>
<td>0.3-35.7</td>
</tr>
<tr>
<td>Farmville</td>
<td>1976</td>
<td>6,600</td>
<td>3,550</td>
<td>7</td>
<td>1,350-5,320</td>
<td>5.4-16.3</td>
</tr>
<tr>
<td>Boone</td>
<td>1976</td>
<td>16,000</td>
<td>6,300</td>
<td>6</td>
<td>880-12,220</td>
<td>3.6-9.3</td>
</tr>
<tr>
<td>Shelby</td>
<td>1973</td>
<td>31,500</td>
<td>13,600</td>
<td>23</td>
<td>150-18,170</td>
<td>1.2-12.8</td>
</tr>
<tr>
<td>Canton</td>
<td>1972</td>
<td>10,000</td>
<td>4,150</td>
<td>12</td>
<td>90-18,000</td>
<td>2.1-18.1</td>
</tr>
<tr>
<td>Morganton</td>
<td>1970</td>
<td>16,500</td>
<td>16,500</td>
<td>18</td>
<td>210-18,000</td>
<td>1.6-16.2</td>
</tr>
<tr>
<td>New Bern</td>
<td>1972</td>
<td>25,350</td>
<td>8,650</td>
<td>10</td>
<td>180-11,400</td>
<td>0.6-10.5</td>
</tr>
<tr>
<td>Monroe</td>
<td>1974</td>
<td>15,900</td>
<td>8,300</td>
<td>20</td>
<td>300-16,110</td>
<td>1.3-19.5</td>
</tr>
</tbody>
</table>

**Table 2.** O-D reports used in developing through-trip distribution models.

<table>
<thead>
<tr>
<th>Functional Classification</th>
<th>O-D Reports</th>
<th>ADT</th>
<th>Through-Trip Ends (%)</th>
<th>No. of Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interstate</td>
<td>Dunn-Erwin, Hickory, Canton, and Morganton</td>
<td>10,000-28,190</td>
<td>48.1-97.5</td>
<td>135</td>
</tr>
<tr>
<td>Principal arterial</td>
<td>Tarboro-Princeville, Mount Airy, Hickory, Farmville, Boone, Shelby, and New Bern</td>
<td>3,660-16,230</td>
<td>26.6-71.8</td>
<td>179</td>
</tr>
<tr>
<td>Minor arterial</td>
<td>Tarboro-Princeville, Mount Airy, Farmville, Shelby, and Morganton</td>
<td>2,220-8,700</td>
<td>20.2-50.9</td>
<td>85</td>
</tr>
<tr>
<td>Major collector</td>
<td>Tarboro-Princeville, Mount Airy, Hickory, Farmville, Boone, Shelby, Morganton, and New Bern</td>
<td>1,550-8,320</td>
<td>6.6-25.4</td>
<td>106</td>
</tr>
<tr>
<td>Minor collector</td>
<td>Mount Airy, Boone, Shelby, and Morganton</td>
<td>1,020-2,400</td>
<td>6.2-18.1</td>
<td>86</td>
</tr>
<tr>
<td>Local</td>
<td>Mount Airy, Hickory, Boone, Shelby, Morganton, and New Bern</td>
<td>400-2,400</td>
<td>4.8-18.9</td>
<td>118</td>
</tr>
</tbody>
</table>

The second model developed is really a composite model in which equations for each of five functional classifications estimate the distribution of trip ends among stations. The initial groupings by functional classification and O-D reports used in this analysis are given in Table 2. The independent variables that proved to be significant were ADT at the destination station, percentage of trucks excluding panel and pickups at the destination, percentage of through trips at the destination, and route continuity as a dummy variable.
The data base was 7.1 percent. It appeared that the question, the average percentage of trucks of the constant was indeed invalid?

On a 1965 basis, both Ahoskie and Wilson conducted in Elizabeth City during two time periods, had more than 11 percent trucks in the traffic stream crossing the cordon, whereas the average percentage of trucks in the traffic stream to the production of through trips was changing over time. A summary of the pertinent analysis data is given in Table 5. The models recommended in this paper performed better when compared with the 1973 O-D data than when compared with the 1958 data. This result tends to confirm the hypothesis that through-trip production models have been dynamic during the past two decades and that periodic reevaluation of the models is required in order to maintain their maximum efficiency.

Table 3. External-external trip distribution models.

<table>
<thead>
<tr>
<th>Functional Classification of Origin Station</th>
<th>Distribution Equation</th>
<th>( r^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interstate</td>
<td>( Y = -2.70 + 0.21 \cdot \text{PTTDES} + 67.96 \cdot \text{RTECON} ) (5.48) (22.28)</td>
<td>0.96</td>
</tr>
<tr>
<td>Principal arterial</td>
<td>( Y = -7.40 + 0.55 \cdot \text{PTTDES} + 24.68 \cdot \text{RTECON} ) (6.22) (9.09)</td>
<td>0.87</td>
</tr>
<tr>
<td>Principal arterial</td>
<td>( + 45.62 \cdot \text{ADT}/\text{CD} ) (2.66)</td>
<td></td>
</tr>
<tr>
<td>Minor arterial</td>
<td>( Y = -0.63 + 86.68 \cdot \text{ADT}/\text{CD} + 30.04 \cdot \text{RTECON} ) (8.18) (11.38)</td>
<td>0.86</td>
</tr>
<tr>
<td>Minor arterial</td>
<td>( Y = -1.08 + 0.00079 \cdot \text{DESADT} + 0.47 \cdot \text{PTKDES} ) (4.21) (2.43)</td>
<td>0.69</td>
</tr>
<tr>
<td>Minor arterial</td>
<td>( + 31.78 \cdot \text{ADT}/\text{CD} ) (3.45)</td>
<td></td>
</tr>
<tr>
<td>Major collector</td>
<td>( Y = -0.80 + 109.42 \cdot \text{ADT}/\text{CD} ) (15.37)</td>
<td>0.73</td>
</tr>
</tbody>
</table>

Note: \( Y \) = percentage distribution of through-trip ends from an origin station to a destination station, PTTDES = percentage of estimated through-trip ends at destination station, RTECON = route continuity \( 1 = \text{yes}, 0 = \text{no} \), ADT/CD = ADT at destination station divided by the sum of ADT at all stations, DESADT = ADT at destination station, PTKDES = percentage trucks excluding panels and pickups at the destination station, and \( t \) = t-value for the coefficient.

Table 4. Statistical results for models.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Total Observations</th>
<th>Mean of Dependent Variable</th>
<th>Mean of Independent Variable ( r^2 )</th>
<th>Standard Error</th>
<th>Coefficient of Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage through-trip ends</td>
<td>134</td>
<td>5.22</td>
<td>0.92</td>
<td>5.36</td>
<td>103</td>
</tr>
<tr>
<td>in distribution of through-trip ends</td>
<td>179</td>
<td>8.95</td>
<td>0.76</td>
<td>9.35</td>
<td>104</td>
</tr>
<tr>
<td>Minor arterial</td>
<td>85</td>
<td>8.24</td>
<td>0.74</td>
<td>6.63</td>
<td>80</td>
</tr>
<tr>
<td>Major collector</td>
<td>166</td>
<td>7.22</td>
<td>0.48</td>
<td>7.74</td>
<td>107</td>
</tr>
<tr>
<td>Minor collector and local</td>
<td>204</td>
<td>6.46</td>
<td>0.53</td>
<td>6.83</td>
<td>106</td>
</tr>
</tbody>
</table>

Table 5. Analysis of stability of through-trip-end estimation model.

<table>
<thead>
<tr>
<th>Item</th>
<th>1958</th>
<th>1973</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cordon ADT</td>
<td>22798</td>
<td>29790</td>
</tr>
<tr>
<td>Number of trucks excluding panels and pickups</td>
<td>2705</td>
<td>2407</td>
</tr>
<tr>
<td>Percentage of trucks</td>
<td>11.87</td>
<td>8.08</td>
</tr>
<tr>
<td>Through-trip ends</td>
<td>6676</td>
<td>6566</td>
</tr>
<tr>
<td>RMSE for trip-end-estimation model performance (%)</td>
<td>29.28</td>
<td>22.11</td>
</tr>
</tbody>
</table>

Constant was indeed invalid?

As a beginning point in attempting to answer this question, the average percentage of trucks of the station volumes for the 1965 and 1975 periods was analyzed. On a 1965 basis, both Ahoskie and Wilson had more than 11 percent trucks in the traffic stream crossing the cordon, whereas the average percentage of trucks crossing the cordon in the 1975 data base was 7.1 percent. It appeared that the composition of the traffic stream had indeed changed over time and that a performance comparison that used the old test data to compare the new models with those previously reported would be invalid.

Fortunately, external O-D surveys had been conducted in Elizabeth City during two time periods, 1958 and 1973. The availability of these data provided the opportunity to test in a limited manner the hypothesis that the relation of percentage of trucks in the traffic stream to the production of through trips was changing over time. A summary of the pertinent analysis data is given in Table 5. The models recommended in this paper performed better when compared with the 1973 O-D data than when compared with the 1958 data. This result tends to confirm the hypothesis that through-trip production models have been dynamic during the past two decades and that periodic reevaluation of the models is required in order to maintain their maximum efficiency.

Now that there was an explanation for the adverse comparison of the old versus new models utilizing the 1965 vintage O-D data, a test of the new through-trip estimation model was performed on 1975 O-D data for Laurinburg, North Carolina, a city with an urban area population of 22,500 and 20 external cordon stations. The model performed extremely well, yielding an RMSE of 7.6 percent. One station, Secondary Road 1601, had an extraordinarily high proportion of trucks, 18.3 percent, compared with the station volume of 240 vehicles/day. Removing this station from the analysis yielded an RMSE of 6.3 percent.

The next test was that of the distribution models. Again, the new distribution models were tested against those previously reported by using the 1965 Ahoskie O-D data. The old distribution models had previously given an RMSE of 87.8 trips; in comparison with the same data, the new models gave an RMSE of 88.1 trips. Given that the basis for the distribution was the trip ends estimated by the generation model, it can be concluded that the new distribution models are superior to the old ones. This statement is derived from the fact that the through-trip ends estimated by the new generation model based on the 1965 Ahoskie test data had an RMSE of 13.6 percent compared with that of 11.5 percent for the old models. Therefore, the starting point for the new distribution models had 18 percent more error than the old models. The new models not only are much simpler but also produce a better distribution.

A problem discovered in applying the old through-trip distribution models was the poor performance of the models in handling the case of the intersection of two major facilities—e.g., I-40 and I-77 in Statesville, North Carolina. This situation was tested with the new models, and the results are shown in Figure 1. For route continuity, the paired stations are 1 and 9 and 3 and 17. The results are much better than those for the old distribution models.
EXAMPLE APPLICATION OF MODELS

A short example is offered to demonstrate the ease with which the recommended models can be applied and to illustrate some of the mathematical detail in developing the estimated through-trip table. The input data required are given in Table 6.

Estimates of the percentage of through-trip ends at each external station are developed by using the major-collector equation given in Table 3. Then each percentage is multiplied by the corresponding station ADT to produce an estimate of the number of through-trip ends passing the station. These trip ends will be used in the distribution phase. The results for the example are given below (total trips = 3575):

<table>
<thead>
<tr>
<th>Station No.</th>
<th>Through-Trip Ends</th>
<th>Calculated Percentage</th>
<th>Adjusted Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>19.71</td>
<td>306</td>
<td>306</td>
</tr>
<tr>
<td>2</td>
<td>23.76</td>
<td>523</td>
<td>523</td>
</tr>
<tr>
<td>3</td>
<td>19.29</td>
<td>301</td>
<td>301</td>
</tr>
<tr>
<td>4</td>
<td>42.75</td>
<td>1872</td>
<td>1872</td>
</tr>
<tr>
<td>5</td>
<td>29.74</td>
<td>931</td>
<td>931</td>
</tr>
<tr>
<td>6</td>
<td>45.05</td>
<td>2397</td>
<td>2397</td>
</tr>
<tr>
<td>7</td>
<td>34.69</td>
<td>819</td>
<td>819</td>
</tr>
<tr>
<td>Total</td>
<td>7149</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The next step is to match each station, according to its functional classification, with the proper equation as given in Table 3. The correct equation for each distribution is chosen according to the station from which the trip ends are to be distributed, the origin station. For example, from station 1, major collector, to all other stations, one would choose Equation 4 from Table 3.

In applying any of the distribution equations, the resulting sum of the estimated percentages from one station to all others does not generally add up to 100 percent. The percentages should simply be factored so that their resulting sum is 100 percent. The results of the distribution phase for this example are given in Table 7 for stations 1, 4, and 5.

In applying the proper distribution equation at each station, the estimated two-way trip interchange between a particular origin station and all other destination stations is generated. Two-way trips are distributed because the dependent variable initially estimated was trip ends. The distribution procedure, when completed, results in two estimates of two-way trip interchange for every pair of stations, each having acted as an origin station once. The value used for this triangular trip matrix is taken as the average of the two values.

After the estimated trip interchanges are averaged and the trip matrix is summed, the total number of trip ends at individual stations will vary from the values predicted by the initial equation. This results because of the averaging procedure. A FRATAR factor is determined, and the trip table is balanced and adjusted to the initial predicted number of through-trip ends at each station. Figures 2 and 3 present the results of the above procedures for the example problem.
SUMMARY AND CONCLUSIONS

The purpose of the research discussed in this paper was to try to improve the methodology for synthesizing a through-trip table for small urban areas. New parameters were introduced in an attempt to alleviate problems discovered in using previously developed models. The new variables that proved to be significant, both in leading to simpler models and avoiding old problems, were route continuity as a dummy variable and station ADT developed as an attraction factor.

Both models continue to reflect the importance of trucks in the estimation and distribution of through trips. The importance of this factor has varied since the mid-1960s. During the mid-1970s, the increased availability of the automobile and an expanded standard of living diminished the correlation between trucks and through trips. The important point is that, as relations among the independent parameters change, the models, to remain valid, must be updated.

Overall, the models presented are adequate for long-range planning purposes. They are extremely easy to apply and produce results that are reasonable and sufficiently accurate for planning purposes.

REFERENCES