exists. Although inexperienced drivers were more likely to follow the advice being given, they also reported being less likely to purchase an information device. This may be the result of less frequent drivers feeling that the savings gained from such a device would not outweigh the costs because of their limited driving. Conversely, more experienced and more frequent drivers perceive a net gain and respond as more likely to purchase a device although they do not follow the advice as often. An ANOVA also revealed that drivers will follow advice to take the freeway more readily than drivers to take the side road and that they are quicker to respond to freeway advise, indicating that a " routestart" exists.

Analysis of the route choice behavior of drivers found that there was a very rapid jump in the decision times over the first 8 of 32 trials and that the times remained relatively constant over the remaining 24 trials. This finding and the fact that average acceptance rates of advice approximated the precision of the system indicate that drivers could sense and adapt quickly to the level of accuracy being provided by the system. Average decision times were the greatest for information provided at 75 percent accuracy. This indicates that subjects were able to identify the level of accuracy for low levels as well as high levels but took a greater amount of time to discern the moderate level of accuracy.

The efforts to develop a model of route choice behavior that incorporates the learning processes of drivers had mixed results. A model was developed that included drivers' updated perceptions of route delay and information accuracy. However, the model was not significantly different from a model that excluded these perceived attributes. The model includes the advantage of a variable attribute since "subjects" followed the advice as readily, the model may simply predict that subjects will select the advised route, therefore predicting about 79 percent accuracy, which is equivalent to the average acceptance rate of advice. More analysis is required using different updating schemes before conclusive results can be made about the effects of experiment on potential future results. Further research efforts will include attempt to formulate more realistic information updating schemes and to extend the research and modeling effort to a more realistic traffic network environment.

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Network Performance Under System Optimal and User Equilibrium Dynamic Assignments: Implications for Advanced Traveler Information Systems

Hani S. Mahmassani and Sririnivas Petti

A comparative assessment was undertaken of network cost and performance under time-dependent system optimal (SO) and user equilibrium (UE) assignment patterns, with particular reference to the effectiveness of advanced traveler information systems (ATIS). Both SO and UE solutions were found using a new simulation-based algorithm and a time-dependent assignment optimization algorithm. Uniformly, experiments were conducted using a menu (high-speedway) signal control system and using a time-dependent assignment optimization model. A diagnosis of system performance for various intensities under such effects using network-level traffic descripters for both SO and UE assignments. The results affirm the validity of a meaningful decrease between SO and UE assignment solutions in urban traffic networks and provide useful insight for mid-size/medium network-level estimation among traffic descriptors. These results suggest that ATIS information supply strategies based on SO-route guidance could considerably optimize the effectiveness of the assignment and generate considerable network savings, especially at moderate to high congestion levels in the network. The results also illustrate the time-dependent ratios of the gains achieved by an SO assignment from quick UE assignment in a congested traffic network.

Approaches incorporating advanced communication technologies, informatics, information systems, electronics, and automation, broadly labeled as intelligent vehicle highway systems (IVHS), continue to generate considerable interest for their potential in alleviating urban and suburban congestion of traffic systems. Advanced traveler information systems (ATIS) provide travelers with real-time information on existing traffic conditions or instructions on routes to reduce overall system user costs. Recently Mahmassani and Petti (2) proposed a heuristic algorithm to solve the system optimal (SO) dynamic traffic assignment problem for the ATIS context, in which a central controller with known or predicted time-dependent origin-destination (O-D) trip desires over the horizon of interest solves the problem to prescribe to users to attain some systemwide objectives. A comprehensive review and discussion of dynamic assignment and traffic simulation models for ATIS have been developed. Traffic assignment system (ATMS) applications are given by Mahmassani et al. (2).

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time-dependent UE solution in terms of the overall system cost. The second method may be considered as a useful proxy for a favorable scenario of long-term network performance under real-time descriptive inference.

It is known from static network equilibrium theory that, SO and UE lead to identical solutions only for situations in which the shortest paths taken by users simultaneously are the best paths from a system viewpoint. Such situations are observed when networks are relatively uncongested so that latency is unimportant and the path between the limited (limited vehicle interactions). At the other extreme, under heavily congested conditions, system performance is not likely to be markedly different under the two assignment schemes because the opportunities for SO to sufficiently ameliorate the network congestions probably would be limited.

For network conditions between the two extremes, the extent of the differences between SO and UE solutions, par- ticularly to some extent, is in the details that are not known. This is very important for ATIS- because if the two solutions are not perceptibly different, coordinated cooperative SO-routing guidance may not be necessary. The paper of the vehicle (defined as a basic safety and, and descriptive information that is less complicated and simpler to disseminate to noncooperative drivers may be suf- ficient. The similarity of the two solutions would have impor- tant implications for the fact that ATIS information sup- ply strategies should take into account the difference in travel to guide the systems toward UE convergence and away is wide fluctuations. However, if SO indeed holds promise for meaningful gains over UE, then normative route guidance or shortening the delay time on the path SO should be provided. It is also desirable to ascertain network and traffic con- ditions under which differences between SO and UE are meaningful.

In this paper, overall user cost and network performance under time-dependent SO and UE assignment patterns are examined in a series of numerical experiments performed on a network test under various loading levels. The system perfor- mance is measured by the effective traffic flow cost in the average traffic flow performance at the network level that was previously addressed only under steady-state conditions, as discussed herein.

NETWORK TRAFFIC FLOW THEORY

Mahanmood and Pesis (4.5) generalized the definitions of speed, flow, and capacity to the network level and examined their relationship in their model of network traffic perfor- mance. These concepts are extended to the dynamic case in the current analysis to analyze the time-varying network traffic conditions (especially for medium to high network loading levels) during the peak period. Average-speed network travel times are determined from the ratio of total kilometers to total vehicle hours in the network over the duration of interest. The average network congestion K (vehicles per lane) is obtained from the ratio of the average time of the number of vehicles per unit lane length in the system. However, the concentration varies dramatically with time as different sets of vehicles and the additional network congestion is examined by taking 5-min average of the number of vehicles per each link length in the network. The obtained average speeds are used to determine the actual (estimated) trip time by unilaterally changing routes and the one that minimizes total travel time (for all users) is the system that attains the shortest travel times. Two solutions from the standpoints of ATIS effectiveness was dis- cussed in the previous section.

Simulation Assignment Solution Procedure

This section describes briefly the algorithm used to solve for SO and UE assignment. A detailed description of the so- lution procedure by Mahanmood and Pesis (2) consists of a heuristic iterative procedure in which a special-purpose traffic simulation model is used to simulate the network and thereby evaluate the performance of the current network operation. A new network in the second step, the more realistic and, and descriptive information of the appropriate arc costs and the resulting path processing com- ponent of the methodology. The algorithm is first summarized for the SO case, followed by a brief description of the mod- ification for the UE problem.

The use of a traffic simulation model to evaluate the SO objective function and model system performance circum- spect. Large-scale traffic simulation models are not suitable for realistic formulation of the problem by obviating the need for link performance functions and link exit functions. An important aspect of the traffic simulation model in the current network is that it is a sufficiently realistic model for the network. The current network is realistic and can be used in any network, the algorithmic algorithms for UE assignment are virtually identical to those for the SO solution except for the specification of the appropriate arc costs and the resulting path processing com- ponent of the methodology. The algorithm is first summarized for the SO case, followed by a brief description of the mod- ification for the UE problem.

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Transportation Research Record 1409

RESULTS

The results from the various experiments are viewed from two principal perspectives. First, they form the basis for comparison of system performance, particularly user costs under UE and SO assignment schemes, thereby addressing the questions relevant to ATIS information strategies described in the introductory section of this paper. Second, they are used to investigate network-level traffic flow characteristics and relationships using network-wide traffic descriptors. This investigation is conducted primarily for the SO flow pattern. An additional element of the study is the time-dependent assignment analysis of the travel time gang of SO over UE, also of significance to ATIS operation.

The results provide several key insights from both of the above perspectives. They manifest a clear qualitative and quantitative distinction in the solution provided by the SO assignment scheme as opposed to the time-dependent UE assignment procedure–to route-vehicles in a general traffic network. The results also reveal important and robust macroscopic relationships between network-level traffic variables that parallel those for single roadways.

System Performance for SO and UE Assignments

Table 1 reports summary statistics on the system performance for the SO and UE assignments for the various loading factors. As expected, at low levels of network loading, when the network is relatively uncongested, the average travel times of vehicles in the network are relatively close across the various loading levels. As the load is increased, the effects of congestion become more prominent and the average travel times in the UE network (marked UE) increase at a higher rate than the loading factor. At very high loading levels, the marginal effect of additional demand on system performance is very high. The results also indicate that there is only limited variation in the average distance traveled by vehicles under the various network loading levels, implying that greater congestion and longer travel times in the main cause of the higher system-wide trip times (the objective function terms) for minimizing total system travel time only. Nevertheless, the average travel distances do increase with the loading level, reflecting a decreasing percentage (although small in magnitude) of drivers assigned to longer travel routes. The average travel distances under UE for various network loading levels are smaller than the corresponding distances for SO, indicating a smaller percentage of long travel routes under UE. This may be explained by the shorter travel distances assigned to longer routes in SO congestion elsewhere to reduce systemwide travel times.

Figure 3 shows comparatively the average trip times under various network loads for UE and SO assignments. As discussed above, both curves illustrate the increasing marginal effects of additional demand on system trip times. Of more relevance to the central question addressed in this paper, Figure 3 highlights the differences in the quality of the solutions provided by the two assignment rules for time-dependent network flows. Be this further illustrated in Figure 4, it indicates that the percentage improvement in average travel time of SO over UE (as a fraction of the UE travel time) for the various average network concentrations corresponding to the

FIGURE 1 Solution algorithm for the SO dynamic assignment problem.

(Time-dependent) average travel time on links instead of the marginal travel times in the shortest-path calculations. In the above solution procedure, this simplifies Step 3 and modifies Step 4 as indicated.

EXPERIMENTAL DESIGN AND SETUP

Network Configuration and Traffic Characteristics

The test network used in this study, having 50 nodes and 163 links, consists of a freeway with a street network od-bidirectional links, as shown in Figure 2. Nodes within the freeway sections are neither origin nor destination nodes. A total of 38 origin nodes and 38 destination nodes are obtained by excluding freeway nodes (nodes 1 through 25 and 46). Freeway nodes are connected to the street network through entrance and exit ramps. Unless otherwise indicated in Figure 2, all arcs shown are bidirectional. All links are 10 km (6.25 mi) long and have two lanes in each direction, except for the entrance and exit ramps, which are directed arcs with a single lane. The

freeway links have a mean free speed of 91.6 km/hr (55 mph), and the other links have a mean free speed of 50 km/hr (30 mph). In terms of traffic flow characteristics, 25 intersections have pre-timed signal control, 16 have feast and signal control, and the remaining 17 still have no signal control.

Experimental Setup

The comparative assessment of system performance for SO and UE assignments is conducted under various network loading levels, which generate various levels of network congestion. The network loading factor is defined as the ratio of the total number of vehicles generated in the network during the assignment period to a given reference number (19,400) vehicles over a 30-min period in each experiment. Table 1 shows the various loading factors considered in this study and the corresponding number of vehicles generated in the test network during the duration of interest (55 min in cases). In addition, it shows the corresponding number of "tagged" vehicles (vehicles generated for the 30-min duration after the

5-min start-up time) for which relevant performance statistics are accumulated. The loading factors range from 0.6 (very low congestion with 11,616 vehicles) to 2.6 (extremely high congestion with 46,674 vehicles). Under each loading level, the UE and SO solutions are obtained, and the resulting time-dependent link flow patterns are obtained from DYNASMART. The shape of the loading curve for the various network loading levels emulates real-world network loading for the peak period, with an initially increasing generation rate until a peak is reached, followed by a decreasing vehicle generation rate.

In the present study, a start-up time of 5 min is provided in DYNASMART for the network to be reasonably occupied, followed by a 30-min peak period generation of traffic (for which performance statistics are accumulated). Another aspect of the experimental setup that critically influences the system performance is the spatial distribution of the O-D demand pattern. The vehicles generated are about equally distributed spatially in terms of both their origins and destinations, except for Nodes 37 and 44, which generate or attract only about 25 percent of the number of vehicles originating or destined to a typical O-D node (i.e., Nodes 1 through 36).

FIGURE 2 Network structure.
TABLE 1 Summary Statistics for SO and UE Assignments

<table>
<thead>
<tr>
<th>Loading Factor</th>
<th>No. of Composed Veh</th>
<th>No. of Targeted Veh</th>
<th>Average Trip Time</th>
<th>Average Trip Distance</th>
<th>Average Success</th>
<th>Average Failures</th>
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<tbody>
<tr>
<td></td>
<td>(minutes)</td>
<td>(minutes)</td>
<td>(minutes)</td>
<td>(minutes)</td>
<td>(minutes)</td>
<td>(minutes)</td>
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<tr>
<td>0.60</td>
<td>11615</td>
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<td>23976 + 21049</td>
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<td>19.95</td>
<td>5699.4</td>
<td>5.53</td>
<td>166978.3</td>
</tr>
</tbody>
</table>

NOTE: 1 km = 0.6 mile

FIGURE 4 Percentage total trip time savings of SO over UE obtained as a function of total UK trip time for various loading factors versus average network concentration. The number by each plotted point is the corresponding loading factor.

FIGURE 5 depicts the cumulative demand generation as a function of time under the 2.0 loading factor along with the cumulative discharge curves under the SO and UE assignments. The various points on the plot are obtained by accumulating the statistics available for each 5-min interval. The area under the demand curve represents the time savings of SO over UE—this is about 1,483 hr.

The figure illustrates the time-dependent nature of the benefits generated by SO over UE. When the network is in the near stage of loading, (for about the first 20 min), it is not sufficiently congested to produce meaningful differences between SO and UE assignments. Most of the savings of SO are between 30 and 70 min into the peak period. The network is close to peak congestion levels. Beyond 70 min, these appear to be virtually no significant gains of SO over UE, and the network is again relatively uncongested. Thus, the benefit of route guidance based on SO assignment over UE routing are not accumulated uniformly over time—rather they are gained when the network is relatively well congested.

FIGURE 3 Comparison of average trip times (minutes) of SO and UE assignments for various loading factors. The number by each plotted point is the corresponding loading factor.
network loading at an increasing rate until the 2.0 loading factor level and then dip down. This trend illustrates the previously discussed tendency of diminished savings for SO under extremely high-congestion conditions.

**Network Flow Relations**

The second aspect investigated through the experimental results relates to the many-to-one network-level traffic theoretic relationships among network-wide traffic descriptors for dynamic traffic networks under consideration. The pertinent traffic variables and their averages over time and space were defined in the first section of the paper. As noted, although mathematical relationships among traffic flow variables are reasonably well established for arterials and interstates, the intricacies of intersections at the network level, particularly the asymptotic derivability of network-wide traffic relationships from the link-level traffic models. However, the simulation results extend the previous findings of Mahmassani et al. (4,5) that the basic trends captured by the single-vehicle relationships need to also hold at the network level for the dynamic case.

The network level speed–congestion relationship for the SO assignment is shown in Figure 7. Each point on the plot corresponds to a simulation run for the whole assignment period and a particular loading factor. The figure clearly illustrates the exiting average network speeds for both SO network computations, parallel and K-Y relationships for an individual roadway. Note that the plots are of individual network components, corresponding approximately to the 1.2 loading factor. This trend reflects the behavior probability of the relationship between network loading and average speeds for the network-level traffic simulation data.

**CONCLUSIONS**

The experiments performed using the simulation-based algorithms to solve both the SO and UE versions of the time-dependent traffic assignment problem have provided insights of critical importance to the design of ATIS information supply strategy and results of fundamental significance in the application of network-level traffic flow modeling.

"Of these, experimental results from a single-test network preclude definitive generalizations; nevertheless, they offer an illustration of the insights that can be obtained on the basic constitution of the problems being addressed while suggesting directions for future research. The first main conclusion is that the results suggest how traffic load differs in overall system and network performance between time-dependent SO and UE assignments. The second main conclusion is that traffic models under time-dependent traffic flow assumptions have limited terms continue to operate within the envelope of relatively simple network traffic flow relationships that exhibit typical similarities to the traffic models that hold for individual road sections."
If we take the U/E assignment results as somehow indicative of the situation that might be attained over time, in a system in which drivers have access to real-time on-board descriptive information through AITS, the results of our experiments suggest that there is considerable potential for SO, coupled with route guidance, especially in heavily congested (although not oversaturated) networks. These results appear to suggest, at least superficially, that descriptive information would likely perform as well or better than route guidance, because U/E system costs were claimed to be just as low as SO costs. Instead, they strengthen the need for recommendations (e.g., by Mahmassani and Jayakrishnan [9]) that coordinated information is necessary beyond a certain market penetration level.

The results further highlight the dynamic nature of the benefits accumulated by net SO assignments over U/E. They suggest that SO is most effective when the traffic network is moderately to highly congested. In the context of peak period traffic, this implies that most savings through SO assignment would be achieved better at the beginning of the peak period than at the end of the peak period but in a time range in between. When the network is lightly or very highly congested (oversaturated), an SO assignment does not perform significantly better than U/E. For relatively uncongested traffic situations, SO and U/E yield almost identical solutions.

Future research on this topic will investigate the system performance under partial (idle) congestion when users are provided with SO paths, thereby introducing an additional element of user behavior. With regard to the traffic network, flow theoretic aspects, relevant to future efforts in this area include analyzing dynamic traffic networks from the perspective of the two-fluid theory of traffic developed by Herman and Prigogine [10].

In conclusion, it is possible to characterize traffic flow in urban traffic systems using relatively simple macroscopic re-

**FIGURE 5** Normalized network concentration (ospyk concentration) as a function of time for various loading factors.

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