Evaluating Highway Capacity Investments using a GIS-based tool – Trip-based Full Marginal Cost Approach

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ABSTRACT

This paper presents a Geographic Information Systems (GIS)-based interactive computer tool, developed for the evaluation and analysis of full marginal costs (FMC) of highway transportation in New Jersey (NJ). The first part of the paper is concerned with the implementation of a trip-based FMC estimation methodology in the GIS environment. We propose a constrained k-shortest path algorithm to estimate the trip-based FMC of a trip along not only the shortest “travel-time” path but a set of feasible paths between each Origin-Destination (O-D) pair that can be attractive to the travelers. The second part of the paper deals with estimation of various transportation cost categories including, vehicle-operating, congestion, accident, air-pollution, noise, and maintenance. This estimation is done using NJ specific data. The methodology is then implemented in ArcGIS, using Visual Basic and C-programming language. The developed GIS-based tool, not only estimates FMC between a selected O-D pair, but also compares complete and partial networks to assess short-term impacts of infrastructure investments on the FMC. The proposed tool will help planners to calculate the true trip costs between different O-D pairs for various user-defined scenarios of various demand/supply changes.
INTRODUCTION

At the heart of most of the policy considerations lies the accurate estimation of full marginal highway travel costs. This information is essential for allocating resources efficiently, for ensuring equity among users of highway users, and for developing effective pricing mechanism. Full Marginal Costs (FMC) means the overall costs accrued to society from servicing an additional unit of user. Estimation of full highway transportation costs has long been one of the major concerns of transportation economists and planners due to its importance in decision-making and policy considerations. The main objective of this interest in FMC estimation is to ensure that prices paid by transportation users reflect the true cost of providing transportation services.

FMC is an effective measure to determine the true cost of transportation. It can be defined as the cost of an additional unit of output. In transportation, FMC measures the actual increase in costs due to an additional unit of travel (a trip or mile). Hence, FMC represents the additional costs that the State should consider to encourage efficient transportation use. The term “output” is defined as the representation and simplification of the overall utilization of product systems by means of selected units. In transportation facilities there is no unique or exact way of representing the output. Berechman et al. (1), define terms intermediate and final outputs for transportation systems. The usage of these outputs in the cost calculation depends on the purpose of the analysis. Intermediate outputs such as vehicle-miles or vehicle-hours are mainly used to evaluate the technical efficiency of a system. On the other hand, final outputs (also called demand oriented measures by Berechman et al. (1)), such as number of trips or number of passengers, are used to analyze the overall efficiency and effectiveness of the system.

Depending on the output definition, two distinct approaches can be followed: (1) distance-based marginal cost estimation, (2) trip-based marginal cost estimation. Distance-based approach considers intermediate outputs, and estimates marginal cost, based on distance, using a cost function specific to a segment of roadway (2, 3, 4, 5, and 6). This approach assumes that each link is loaded with the same amount of unit demand irrespective of its location, origin or destination. However, in reality demand is generated as a result of new trips not individual link volumes (7, 8). Thus, trip is the basic unit of the change in transportation output. In fact, link volumes increase due to the increase in number of trips, and change in link volumes will be different for different links of the network given that spatial characteristics of the capacity and/or supply change as well as trip characteristics between various origins and destinations. Therefore, loading each link of the network with the same amount of demand, and calculating FMC as a response to these changes in demand, will not provide the analyst with useful information in terms of the real effects of these changes. To this extent, distance-based methodology is unable to realistically capture the effect of unit increase in demand required to estimate FMC, and it is not possible “to uncouple the individual effects of changes in one link on the other links by this method” (7). This problem encountered by the distance-based approach has been addressed by Jara-Diaz et al. (8), who proposed the concept of origin-destination (O-D) specific marginal transport cost estimation at a zonal level in a trucking system.
Then, Ozbay et al. (9) proposed a trip-based FMC estimation methodology, where FMC of a trip is calculated along the shortest “travel time” path between each O-D pair.

The motivation of this study lies in the FMC estimation of highway transportation based on final outputs. In this study, trip is regarded as the major output measure. FMC is defined and calculated as “cost per trip.” Although “trip”, as a final output of highway transportation, is not a standard measure as vehicle-miles or vehicle-hours, it has several desirable attributes that will enable us to better understand the policy implications of additional travelers on the roadway network.

This paper proposes a state-of-the-art trip-based FMC estimation methodology, which considers not only the shortest “travel time” path but a set of feasible paths between each O-D pair attractive to the travelers while calculating the FMC. This approach enables the planners to realistically capture the effect of unit increase in demand. This is essential for accurately calculating network-wide marginal costs. The proposed methodology is then implemented using a Geographic Information Systems (GIS)-based interactive computer tool. The proposed tool is used to estimate the FMC with different level of details, and to evaluate the short-term impacts of policy implications on the FMC. For illustration purposes, the developed tool is applied to a well-calibrated real size network, northern New Jersey (NJ) road network, to assess the usefulness of the proposed methodology using real-world case studies.

The next section presents the methodology including the k-shortest path algorithm applied to determine a set of paths between a given pair of O-D nodes, GIS-based tool, and details of the short-term impact analysis. Then, the methodology is applied to northern NJ network after estimating road network specific cost functions. Finally, the last section presents the key findings of our analyses and conclusions.

METHODOLOGY

The methodology presented in this paper proposes a novel approach for calculating network-wide FMC of highway travel. In case of the FMC estimation, the smallest addition to a network is a trip, thus a trip should be considered as the basic decision making quantity, especially in the context of transportation planning (1, 7). To this extent, full cost estimation is trip-based rather than distance-based to realistically capture travelers’ trip making decision process. The following steps are completed:

1. Unlike previous studies, with a novel k-shortest path algorithm, the methodology presented here estimates trip based FMC by considering a set of feasible paths between each O-D pair.
2. The methodology is implemented in GIS using C-programming language and Visual Basic for Applications (VBA), and calculates the FMC of a trip between a selected O-D pair. The user can determine the level of detail, and observe the changes in trip-based FMC among different O-D pairs in a certain area, or throughout the entire network. This makes the FMC estimation model a very useful tool for application in a real-world highway transportation improvement scenario.
3. The developed tool is then used to compare two different networks (before and after scenarios), and to estimate short-term impacts of network changes (lane and/or link additions, etc.) on the FMC of a trip.
For illustration purposes, the methodology is applied to northern NJ road network. Various transportation cost categories including vehicle-operating, congestion, accident, air-pollution, noise, and infrastructure are estimated for this network.

FIGURE 1 summarizes the methodology. The following sections explain the different steps of the methodology in detail.

**CONSTRANGED K-SHORTEST PATH ALGORITHM**

This section focuses on the proposed trip-based FMC estimation methodology. Unlike other previous studies, in this study FMC estimation is done on a trip basis. With a novel methodology, a set of feasible paths between each O-D pair attractive to the travelers is determined while calculating the FMC.

In reality, travel time is not the only factor affecting users’ route choices traveling between different O-D pairs, and consequently the FMC between different O-D pairs. Other factors affect their route decisions, and the FMC resulting from these decisions. Thus, computing a set of feasible paths rather than just the shortest “travel time” paths, allows us to consider factors other than travel time such as trip distance, highway functional types on a route, urbanization degree, and topography.

There are a number of approaches that can be employed to determine multiple paths between O-D pairs, mainly based on the determination of k-shortest paths that satisfy user-defined constraints. In Dial (10) and Sherali et al. (11), a labeling approach was adapted, which included all paths that were optimal with respect to a label, such as...
time, cost, or distance. Alternatively, heuristic methods were adopted by many researchers \((12, 13)\). These methods are mainly based on link elimination and penalty rules, where the network is modified after finding the shortest path.

Existing k-shortest path algorithms may be divided in two categories; algorithms that allow paths to have repeated links \((14, 15)\), and the ones that only consider acyclic paths \((16, 17)\). A comparative study by Brander et al. \((18)\) showed that within the class of algorithms considering only acyclic directed graphs (such as transportation networks), the method proposed by Lawler \((16)\) offered the best performance. Lawler \((16)\) provided an exact algorithm for finding the k-shortest paths between a single origin and a single destination. This algorithm first defines the set of all paths in a network and determines the shortest path of this set. Then the remaining paths are divided into mutually exclusive subsets, and the shortest path for each of these subsets is determined. Later Van der Zijpp et al. \((19)\) extended this approach by adding constraints related to detour and overlap.

The method proposed in this paper provides an alternative to algorithms mentioned above. The main advantage of the proposed method is that it finds the constrained shortest paths directly, instead of selecting the paths from a large set of overall paths. The proposed algorithm finds k-shortest paths that satisfy certain set of constraints in a directed acyclic transportation network. The constraints assure that a set of pre-defined number of the feasible paths that are attractive to the travelers between the selected O-D pair are found. These constraints can be summarized as follows:

**Constraint (1) Travel Time Constraint:** Let \(t_i\) be the travel time of the candidate path \(i\), \(t_1\) be the travel time of the first shortest path. Path \(i\) is feasible if the following condition holds:

\[
t_i \leq \phi_{\text{max}} t_1
\]

Path \(i\) is infeasible if constraint-1 is not satisfied. \(\phi_{\text{max}}\) is a user defined limitation factor on travel time. For illustration purposes a value of \(\phi_{\text{max}} = 1.3\) is selected.

**Constraint (2) Rate of Disjointness Constraint:** Let \(A_i = \{a_{i_1}, a_{i_2}, ..., a_{M_i}\}\) denote the links of the \(i^{th}\) candidate path where \(M\) is the number of links of the candidate path, and \(A_1 = \{a_{1_1}, a_{1_2}, ..., a_{N_1}\}\) denote the links of the first shortest path, where \(N\) is the total number of links of the first shortest path. Then path \(i\) is feasible if a sequence of links within path \(i\) cannot be found for which the following conditions hold:

\[
(i) \quad s_n = \begin{cases} 0 & \text{if } a_{n_1} = a_{m_i} \\ 1 & \text{otherwise} \end{cases} \quad \forall n \in N, \forall m \in M
\]

\[
(ii) \quad S = \frac{\sum s_n}{N}
\]

\[
(iii) \quad S \geq \delta_{\text{min}}
\]

\(\delta_{\text{min}}\) is a user defined limitation factor on disjoint rate. For illustration purposes a value of \(\delta_{\text{min}} = 0.35\) is selected. Path \(i\) is infeasible if constraint (2) does not hold.

**Constraint (3) Link constraint:** Using the variables defined earlier, path \(i\) is feasible if the following condition holds.

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\[ M \leq \theta_{\text{max}} N \] \hspace{1cm} (5)

\( \theta_{\text{max}} \) is a user defined limitation factor on the total number of links. For illustration purposes a value of \( \theta_{\text{max}} = 1.35 \) is selected if \( M \) is larger than 6, and \( \theta_{\text{max}} = 1.5 \) is selected otherwise. Path \( i \) is infeasible if no such constraint is satisfied.

At each iteration, \( K^{th} \) shortest path is computed based on modified Dijkstra’s algorithm (20). The basic idea in Dijkstra’s algorithm is to find the shortest path from one origin to all destinations. However, in this study, the main focus is to find O-D specific shortest paths. Thus, to reduce the complexity of the algorithm, Dijkstra’s approach is modified such that it terminates as soon as the shortest path from the selected origin to the specified destination is found. Once the shortest path between the particular O-D pair, which satisfies all the constraints is found, the network is modified by randomly deleting two links from the shortest path while keeping the network connected. The modified Dijkstra’s algorithm is then reapplied to the modified network to find the next candidate path. The iteration continues until a user defined number of paths has been found, or no more paths which satisfy the required constraints can be found. The pseudo code for the proposed k-shortest path algorithm is shown below.

\[ \begin{align*}
&k = \text{Total number of paths to find, } n = \text{number of paths found so far;} \\
&s = \text{origin, } d = \text{destination; } T = \text{travel time matrix;} \quad \text{TempT = temporary travel time matrix;} \\
&N = \text{total number of links of the first path; } M = \text{total number of links of the candidate path}
\end{align*} \]

\[
\text{begin}
\quad \text{TempT} = T, n = 0, s = S, d = D;
\quad \text{call modified Dijkstra} \hspace{.1cm} (s, d, \text{TempT});
\quad n = 1;
\quad \text{store } A_1 = \{a_{11}, a_{21}, ..., a_{N1}\}; \quad t_1 = \sum_{i,j \in A_1} t_{ij} : N; \quad \text{// link, travel time, number of link information of the } 1^{st} \text{ path}
\quad \text{while } (n < k) \{ \\
\quad \quad w = \text{random } \{1, N\}; \quad y = \text{random } \{1, N\}; \\
\quad \quad \text{TempT} = \text{TempT} \setminus \{a_{w1} \& a_{y2}\} \quad \text{// remove the links } a_{w1} \& a_{y2} \text{ from TempT matrix}
\quad \quad \text{call modified Dijkstra} \hspace{.1cm} (s, d, \text{TempT});
\quad \quad \text{temp store } A_m = \{a_{1m}, a_{2m}, ..., a_{Nm}\}; \quad t_m = \sum_{i,j \in A_m} t_{ij} : M;
\quad \quad \text{if } (\text{Constrain } t - 1 = 1) \& (\text{Constrain } t - 2 = 1) \& (\text{Constrain } t - 3 = 1) \text{ then}
\quad \quad \quad n = n + 1;
\quad \quad \quad \text{store } A_m; t_m; M; \}
\quad \text{TempT} = T; \quad \forall \text{// reinsert the links } a_{w1} \& a_{y2} \text{ to the TempT matrix}
\quad \text{for } (h = 1, h < n, h + 1) \{ \\
\quad \quad w_h = \text{random } \{1, M_h\}; \quad y_h = \text{random } \{1, M_h\}; \\
\quad \quad \text{TempT} = \text{TempT} \setminus \{a_{w_h1} \& a_{y_h2}\};
\quad \}
\}
\end{align*} \]

\text{end}

GIS-BASED FMC ESTIMATION TOOL

This section focuses on the GIS-based FMC estimation tool, which implements the constrained k-shortest path algorithm using C-programming language and VBA, and calculates the FMC of a trip between a selected O-D pair. The proposed tool has several advantages as summarized below.

1. In the developed GIS-based tool, the origin and/or destination of trip can be
   - User-defined single O-D pair (FIGURE 2)
• User defined set of O-D pairs among different TAZs
• User defined set of O-D pairs among different counties
• User defined set of O-D pairs within a county
• User defined set of O-D pairs within the whole network

For county and network level selection, the user does not need to specify the location of O-D pairs. Instead, the program automatically saves the whole origin and destination nodes located within the entire county or network. With the FMC estimation on TAZ and county level, the user can observe the changes in trip-based full marginal costs among different O-D pairs in a certain area. Moreover, network-wide selection helps the user to observe the distribution of trip-based FMC throughout the network.

2. The tool compares two different networks and estimates the short-term impacts of network changes on the FMC of selected trips (FIGURE 3).
During the analysis process, the planner first chooses the network(s) to be analyzed from the scenario selection form (as shown in FIGURE 2). Upon selection of the time period of analysis, level of detail for the analysis area, and the sample size for the O-D pair set, the C code executes the proposed algorithm for each O-D pair. Values of various costs categories are displayed and the selected paths are highlighted after the completion of the program. These costs are the stored for comparison at a later stage. Illustration of a sample network comparison analysis result window, is provided in FIGURE 3. From this window user can either observe the total, marginal, and average cost of each selected trip for each network being compared, or investigate the changes in different cost categories after the network has been modified.

SHORT-TERM IMPACT ANALYSIS

When policy decisions, like capacity investments, are implemented on route sections, three different questions need to be answered:
1. What will be the changes in the O-D demand levels?
2. What will be the economic benefits realized due to the investment?
3. What will be the marginal/average trip cost between a given O-D pair before and after the improvements?

The impacts of capacity investments on a network can be categorized in three different ways: short-term impacts, mid-term impacts, and long-term impacts. Since the focus of this paper is on short-term impacts of policy decisions, only this type of impact analysis is discussed in detail.

In the short-term, travel demand between O-D pairs can be assumed to remain unchanged. This fixed demand will be re-assigned onto the network to analyze the impact of improvements on the system. As shown in FIGURE 4, in the short-term demand function (D) remains the same, whereas supply function shifts from S1 to S2. Therefore, the new equilibrium becomes (P2, V2), i.e. volume increases and cost reduces.

FIGURE 4 Change in equilibrium travel cost and volume from capacity expansion

MODEL APPLICATION

This section presents results of the GIS-based FMC estimation tool applied to northern NJ highway network (FIGURE 5). The network, shown in FIGURE 5, consists

![Diagram](attachment:Figure4.png)
of 5,418 nodes, 1,451 of which are zonal nodes and a total of 15,387 links. The input data required for the estimation process are obtained from transportation planning software, TP+, by the New Jersey Department of Transportation (NJDOT). The input to the developed tool includes; volume, travel time (resulting from the assignment of a specific O-D demand matrix onto the network using TP+), capacity, node and link ID’s, highway type, residential area type, distance, number of lanes, free flow speed, and free flow travel time for each link.

Cost Functions and Data Specification

The cost categories used in this study are (1) vehicle-operating, (2) congestion, (3) accident, (4) air-pollution, (5) noise, and (6) maintenance costs.

Each cost category was estimated using the data obtained from NJDOT and from other sources. It should be noted that data on vehicle operating costs, accident costs, and infrastructure costs are NJ-specific. Whereas, congestion and environmental costs were adopted from relevant studies in the literature, their parameters were modified to fit NJ-specific conditions. For illustration purposes, only the final estimated total and marginal cost functions are presented here (TABLE 1). The detailed derivation of each cost category can be found in a study performed by the authors (30).
### TABLE 1 Marginal Cost Functions (30)

<table>
<thead>
<tr>
<th>Cost</th>
<th>Total &amp; Marginal Cost Function</th>
<th>Variable Definition</th>
<th>Data Sources</th>
</tr>
</thead>
</table>
| Vehicle Operating         | $C_{oper} = 7208.73 + 0.12(mla) + 2783.3a + 0.143m$  
$MC_{oper} = 0.143 + \frac{0.12}{a}$                                      | a: Vehicle age (years)                                                                     | AAA(21), USDOT (22), KBB (23)    |
| Congestion                | $C_{cong} = \begin{cases} 
\frac{d}{V} \left( I + 0.15 \left( \frac{Q}{C} \right) \right)^{VOT} & \text{if } Q \leq C \\
\frac{d}{V} \left( I + 0.15 \left( \frac{Q}{C} \right) \right)^{VOT} + \frac{0.5}{V} \left( \frac{Q}{C} \right)^{VOT} & \text{if } Q > C 
\end{cases}$  
$MC_{cong} = \begin{cases} 
\frac{d}{V} \left( I + 0.15 \left( \frac{Q}{C} \right) \right)^{VOT} & \text{if } Q \leq C \\
\frac{d}{V} \left( I + 0.15 \left( \frac{Q}{C} \right) \right)^{VOT} + \frac{0.5}{V} \left( \frac{Q}{C} \right)^{VOT} & \text{if } Q > C 
\end{cases}$ | $Q =$ Volume (veh/hr)  
$d =$ Distance (mile)  
$C =$ Capacity (veh/hr)  
$VOT =$ Value of time (S/hr)  
$V_o =$ Free flow speed (mph)                                           | Mun (24) Small and Chu (25) |
| Accident(1)               | $C_{acc} = 127.5Q^{0.17}M^{0.09}L^{0.55}$  
+114.75Q^{0.65}M^{0.75}L^{0.49}$  
+198.90Q^{0.17}M^{0.42}L^{0.48}$  
$MC_{acc} = 98.175Q^{0.03}M^{0.86}L^{0.53}$  
+97.53Q^{0.15}M^{0.75}L^{0.49}$  
+33.813Q^{0.42}M^{0.42}L^{0.45}$ | $Q =$ Volume (veh/day)  
$M =$ Path length (miles)  
$L =$ no of lanes                                                         | NIDOT (27) FHWA (26) |
| Category 1: freeway, expressway, interstate highway  
Category 2: principal arterial  
Category 3: arterial-collector-local road | $C_{acc} = 178.5Q^{0.18}M^{0.10}L^{0.49}$  
+18.359Q^{0.64}M^{0.57}L^{0.47}$  
$MC_{acc} = 103.5Q^{0.42}M^{0.69}L^{0.43}$  
+8261.55Q^{0.55}M^{0.63}L^{0.47}$ | $Q =$ Volume (veh/day)  
$M =$ Path length (miles)  
$L =$ no of lanes                                                         | NIDOT (27) FHWA (26) |
| Air pollution             | $TC_{av} = Q(0.0194 + 0.2155F)$  
$MC_{av} = 0.0194 + 0.2155 \left( \frac{F + \frac{\partial F}{\partial Q}}{\partial Q} \right)$ | $F =$ Fuel consumption at cruising speed (gl/mile)  
$V =$ Average speed (mph)  
$Q =$ Volume (veh/hr)                                                           | EPA (28) |
| Noise                    | $C_{noise} = 2 \int_{r_i=50}^{r_{eq}=50} \left( L_{eq} - 50 \right) \frac{RD}{5280} dr$  
$MC_{noise} = \frac{D}{264} \left[ \frac{\partial Q}{\partial Q} \log Q + \log K - \ln r_f - 4.89 \right]$ | $Q =$ Volume (veh/day)  
$r =$ distance to highway  
$K =$ Noise-energy emis.  
$K_{car}$ = Auto emission  
$K_{truck}$ = Truck emission  
$F_c =$ % of autos  
$F_{tr} =$ % of trucks  
$F_{ac} =$ % const. speed autos  
$F_{at} =$ % of const. speed tr  
$V_c =$ Auto Speed (mph)  
$V_{tr} =$ Truck Speed (mph)  
$L_{eq} =$ $Q =$ Volume (veh/day)  
$L =$ no of lanes  
$P =$ time-period  
$t =$ trip duration (hr)                                                 | Delucchi and Hsu (29) |
| Maint.                   | $C_M = \frac{796.32(M)^{0.40}(L)^{0.39}}{P}$  
$MC_M = \frac{796.32(M)^{0.40}(L)^{0.39}}{P3.6524Q}$ | $Q =$ Volume (veh/day)  
$L =$ no of lanes  
$P =$ time-period  
$t =$ trip duration (hr)                                                 | Ozbay et al. (30) |

Note: (1) Accident costs are estimated separately for each road category.
MODEL ILLUSTRATION

In this section, trip-based marginal cost from New Brunswick to Princeton is estimated using the proposed methodology. The shortest path determined by our tool has 53.17 minutes of travel time, with 19.72 miles of distance, and 15,903 veh/hr of traffic volume. The seven different paths found through the k-shortest path algorithm all have travel time and distance values that are close to each other; while total volume shows differences among these different shortest paths. The FMC results estimated considering seven k-shortest paths are shown in TABLE 2. The analysis results indicate that the mean FMC is $67.09/trip when queue costs are included (with standard deviation of $14.09/trip) and $19.78/trip when queue costs are excluded (with standard deviation of $2.20/trip). These findings show that marginal cost values between the selected O-D pair show differences among different paths, indicating that apart from travel time there are other path specific properties such as volume, distance, road and area type, and vehicle speed all affecting the marginal cost between a given O-D pair. Therefore, ignoring other possible paths between O-D pairs may result in under/over estimated cost values. Moreover, comparison of different cost categories show that for a congested area, the major part of the marginal cost comes from queue costs, followed time, operating, and accident costs.

TABLE 2 Marginal cost of each path between New Brunswick and Princeton

<table>
<thead>
<tr>
<th>Path</th>
<th>$MC_{opr}$</th>
<th>$MC_{time}$</th>
<th>$MC_{cong}$</th>
<th>$MC_{acc}$</th>
<th>$MC_{air}$</th>
<th>$MC_{noise}$</th>
<th>$MC_{maint}$</th>
<th>Sum*</th>
<th>Sum**</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.87</td>
<td>7.79</td>
<td>5.42</td>
<td>45.45</td>
<td>0.69</td>
<td>0.45</td>
<td>0.01</td>
<td>0.11</td>
<td>17.34</td>
</tr>
<tr>
<td>2</td>
<td>3.23</td>
<td>8.39</td>
<td>3.96</td>
<td>35.61</td>
<td>1.15</td>
<td>0.48</td>
<td>0.01</td>
<td>0.12</td>
<td>17.34</td>
</tr>
<tr>
<td>3</td>
<td>3.34</td>
<td>9.53</td>
<td>3.84</td>
<td>31.57</td>
<td>1.10</td>
<td>0.46</td>
<td>0.01</td>
<td>0.11</td>
<td>18.39</td>
</tr>
<tr>
<td>4</td>
<td>3.31</td>
<td>10.13</td>
<td>6.87</td>
<td>65.55</td>
<td>0.75</td>
<td>0.60</td>
<td>0.01</td>
<td>0.14</td>
<td>21.81</td>
</tr>
<tr>
<td>5</td>
<td>4.20</td>
<td>10.05</td>
<td>6.35</td>
<td>55.57</td>
<td>0.89</td>
<td>0.57</td>
<td>0.01</td>
<td>0.13</td>
<td>22.20</td>
</tr>
<tr>
<td>6</td>
<td>3.53</td>
<td>10.18</td>
<td>6.93</td>
<td>57.66</td>
<td>0.83</td>
<td>0.45</td>
<td>0.01</td>
<td>0.11</td>
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<tr>
<td>7</td>
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<td>9.88</td>
<td>4.55</td>
<td>39.81</td>
<td>0.79</td>
<td>0.45</td>
<td>0.01</td>
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</tr>
<tr>
<td>Mean</td>
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<td>9.42</td>
<td>5.42</td>
<td>47.32</td>
<td>0.89</td>
<td>0.49</td>
<td>0.01</td>
<td>0.12</td>
<td>19.78</td>
</tr>
<tr>
<td>St dev</td>
<td>0.41</td>
<td>0.95</td>
<td>1.33</td>
<td>12.60</td>
<td>0.18</td>
<td>0.06</td>
<td>0.00</td>
<td>0.01</td>
<td>2.20</td>
</tr>
</tbody>
</table>

IMPACTS OF POLICY IMPLICATIONS ON TRIP-BASED MARGINAL COSTS

In this section, impacts of capacity investments on several route sections namely, State Highway 18, State Highway 17, State Highway 3, and Garden State Parkway are investigated. For each of these highways, the capacities of the road sections with highest FMC values are improved by increasing the number of lanes (one lane is added to each road section). Then, using the same O-D demand matrices, the traffic is reassigned using TP+ for the modified network, and the output obtained from TP+ is used for network comparison. In order to focus on multiple O-D pairs, TAZs around the improved road sections are selected, and the changes in average marginal costs are calculated using the developed GIS tool. For each TAZ pair, 20 different O-D pairs are analyzed, and short-term impacts of policy implications on the FMC of different trips are investigated. TABLE 3 and TABLE 4 present the average marginal cost values for the original network, and the modified network, respectively. Similarly, TABLE 5 shows the percent...
change in the each marginal cost category after the capacity investment. Shaded cells in TABLE 5 refer to the cost categories, which have increased after the capacity is improved.

The results of the analysis show that for all road sections total marginal cost values have reduced after the capacity investment; with the highest reduction in marginal cost is observed at State Highway 3, and the lowest reduction is observed at State Highway 18. This observation could be due to several reasons. First of all, the queue congestion costs observed at State Highway 18 is almost twice larger than the queue congestion costs observed at State Highway 3, since the area around State Highway 18 is much more congested than the area around other routes. Thus, only one lane increase may not be enough for State Highway 18 to satisfy the excess demand in that region. Second, as observed from different paths calculated between different O-D pairs, after the network is improved, the increase in volume in State Highway 18 is higher compared with the increase in volume in other routes, which resulted in overall higher volume compared with capacity investment.

The percentage changes in individual marginal cost categories after the capacity investment show that for all road sections, the highest reduction is observed at congestion related costs. This result indicates that after the network improvements, volume/capacity (v/c) ratios in these regions have been reduced to some extent, which decreased the travel times on these routes and congestion costs.

Overall, even though capacity investments can reduce the marginal cost of users, the amount of savings mainly depends on the characteristics of that region. Particularly, the amount of capacity investment highly depends on the amount of excessive demand that needs to be satisfied, and the reduced congestion delays. In general, the more congested a road, the more traffic is generated by increased demand. Increased capacity on highly congested urban roads generates considerable traffic due to high levels of latent demand (31). Thus, if the road section to be improved is in a very congested area, capacity investments may result in overall higher usage of that road section which would not manage to reduce v/c ratios in that region. Since v/c ratio affects user costs nonlinearly, for the cases when v/c ratio is larger than one, no significant reduction in cost of transportation would be observed.

<table>
<thead>
<tr>
<th>Road</th>
<th>Period</th>
<th>$MC_{opt}$ ($/trip$)</th>
<th>$MC_{time}$ ($/trip$)</th>
<th>$MC_{ext}$ ($/trip$)</th>
<th>$MC_{queue}$ ($/trip$)</th>
<th>$MC_{acc}$ ($/trip$)</th>
<th>$MC_{air}$ ($/trip$)</th>
<th>$MC_{noise}$ ($/trip$)</th>
<th>$MC_{maint}$ ($/trip$)</th>
<th>Sum* ($/trip$)</th>
<th>Sum** ($/trip$)</th>
</tr>
</thead>
<tbody>
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<td>SR 3</td>
<td>a.m.</td>
<td>0.96</td>
<td>3.52</td>
<td>1.94</td>
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<td>0.42</td>
<td>0.05</td>
<td>7.23</td>
<td>43.43</td>
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</tr>
<tr>
<td></td>
<td>p.m.</td>
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<td>3.57</td>
<td>1.09</td>
<td>24.81</td>
<td>0.37</td>
<td>0.39</td>
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<td>6.44</td>
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</tr>
<tr>
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<td>6.82</td>
<td>3.89</td>
<td>51.56</td>
<td>0.49</td>
<td>0.66</td>
<td>0.005</td>
<td>14.30</td>
<td>65.86</td>
<td></td>
</tr>
<tr>
<td></td>
<td>p.m.</td>
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<td>7.00</td>
<td>4.30</td>
<td>57.57</td>
<td>0.57</td>
<td>0.61</td>
<td>0.007</td>
<td>14.90</td>
<td>72.47</td>
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</tr>
<tr>
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<td>61.76</td>
<td>0.69</td>
<td>0.46</td>
<td>0.01</td>
<td>20.07</td>
<td>81.83</td>
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</tr>
<tr>
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<td>41.95</td>
<td>0.75</td>
<td>0.41</td>
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<td>57.44</td>
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<tr>
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<td>5.27</td>
<td>2.43</td>
<td>29.99</td>
<td>0.40</td>
<td>0.65</td>
<td>0.006</td>
<td>10.53</td>
<td>40.52</td>
<td></td>
</tr>
<tr>
<td></td>
<td>p.m.</td>
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<td>0.45</td>
<td>0.59</td>
<td>0.005</td>
<td>10.10</td>
<td>35.94</td>
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</tr>
</tbody>
</table>

*: Marginal Queue cost included. **: Marginal Queue cost excluded
TABLE 4 Marginal cost values for the modified networks

<table>
<thead>
<tr>
<th>Road</th>
<th>Period</th>
<th>$MC_{opr}$</th>
<th>$MC_{time}$</th>
<th>$MC_{ext}$</th>
<th>$MC_{queue}$</th>
<th>$MC_{acc}$</th>
<th>$MC_{air}$</th>
<th>$MC_{noise}$</th>
<th>$MC_{maint}$</th>
<th>Sum*</th>
<th>Sum**</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>($/trip$)</td>
<td>($/trip$)</td>
<td>($/trip$)</td>
<td>($/trip$)</td>
<td>($/trip$)</td>
<td>($/trip$)</td>
<td>($/trip$)</td>
<td>($/trip$)</td>
<td>($/trip$)</td>
<td>($/trip$)</td>
</tr>
<tr>
<td>SR 3</td>
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<td>27.75</td>
<td>0.29</td>
<td>0.39</td>
<td>0.003</td>
<td>0.04</td>
<td>6.75</td>
<td>34.50</td>
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<tr>
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<td>p.m.</td>
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<td>0.90</td>
<td>16.69</td>
<td>0.37</td>
<td>0.36</td>
<td>0.003</td>
<td>0.04</td>
<td>6.00</td>
<td>22.69</td>
</tr>
<tr>
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<td>3.33</td>
<td>50.68</td>
<td>0.48</td>
<td>0.62</td>
<td>0.007</td>
<td>0.1</td>
<td>13.26</td>
<td>63.94</td>
</tr>
<tr>
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<td>3.41</td>
<td>45.48</td>
<td>0.57</td>
<td>0.60</td>
<td>0.006</td>
<td>0.11</td>
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<td>0.08</td>
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<td>0.73</td>
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<td>14.01</td>
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<td>0.006</td>
<td>0.07</td>
<td>9.76</td>
<td>36.14</td>
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<td>p.m.</td>
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<td>0.005</td>
<td>0.07</td>
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<td>30.88</td>
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</tbody>
</table>

TABLE 5 Percent Changes in the marginal cost values

<table>
<thead>
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<th>Road</th>
<th>Period</th>
<th>$MC_{opr}$</th>
<th>$MC_{time}$</th>
<th>$MC_{ext}$</th>
<th>$MC_{queue}$</th>
<th>$MC_{acc}$</th>
<th>$MC_{air}$</th>
<th>$MC_{noise}$</th>
<th>$MC_{maint}$</th>
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<th>Sum**</th>
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<td></td>
<td></td>
<td>($/trip$)</td>
<td>($/trip$)</td>
<td>($/trip$)</td>
<td>($/trip$)</td>
<td>($/trip$)</td>
<td>($/trip$)</td>
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<td>($/trip$)</td>
<td>($/trip$)</td>
<td>($/trip$)</td>
</tr>
<tr>
<td>SR 3</td>
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<td>-3.12</td>
<td>-8.81</td>
<td>-2.58</td>
<td>-23.34</td>
<td>-12.12</td>
<td>-7.14</td>
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<td>-20.00</td>
<td>-6.53</td>
<td>-20.55</td>
</tr>
<tr>
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<td>p.m.</td>
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<td>-5.88</td>
<td>-17.43</td>
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<td>0.00</td>
<td>-7.69</td>
<td>-25.00</td>
<td>-20.00</td>
<td>-6.84</td>
<td>-37.39</td>
</tr>
<tr>
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<td>-1.71</td>
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<td>0.00</td>
<td>9.34</td>
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<tr>
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<td>-4.35</td>
<td>-2.17</td>
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<td>-12.46</td>
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<tr>
<td></td>
<td>p.m.</td>
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<td>0.00</td>
<td>0.00</td>
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</tbody>
</table>

CONCLUSIONS

This paper proposes a state-of-the-art trip-based FMC estimation methodology, which considers not only the shortest “travel time” path but a set of feasible paths between each O-D pair attractive to the travelers while calculating the FMC. This approach enables the planners to realistically capture the effect of unit increase in demand. This is essential for accurately calculating network-wide marginal costs. The proposed methodology is implemented using a GIS-based interactive computer tool. FMC is estimated with different level of details, and the short-term impacts of the policy implications on the marginal costs of different trips are evaluated. For illustration purposes, the developed tool is applied to a well-calibrated real size network, namely northern NJ road network to assess the usefulness of the proposed methodology using real-world case studies.

In the first part of the paper, a constrained k-shortest path algorithm is presented. The user-defined constraints include travel time limitation, minimum partial disjointness rate, and the limitations imposed on the total number of links. The algorithm is coded in C-programming language. GIS-based FMC estimation tool is developed based on Graphical User Interface developed in ArcGIS using VBA. The proposed tool has several advantages. First of all, with different level of details set for the O-D pair selection, the
planner can focus on certain areas or the entire network, and observe the changes in trip-based full marginal costs among different O-D pairs in a certain area. Second, the proposed tool enables planners to investigate the short-term impacts of policy implications on the FMC of different trips.

While dealing with complex transportation networks, it is important to have a user-friendly tool that will enable planners to efficiently identify the areas of interest and to visualize results on the study network. The GIS-based tool developed in this study achieves both these objectives by taking advantage of visualization capabilities of ArcGIS in tandem with the unique, efficient, and versatile algorithm developed by the research team.

In the second part, GIS-based FMC estimation tool is applied to northern NJ highway network. Input data required for the calculation of FMC are obtained from TP+ loaded network output. Vehicle-operating, congestion, accident, air-pollution, noise, and maintenance costs are estimated based on the data obtained from the NJDOT and other sources.

The analyses conducted to observe the short-term impacts of capacity investments on several route sections (State Highway 18, State Highway 17, State Highway 3, and Garden State Highway) demonstrate that even though capacity investments can reduce the marginal cost of users, the amount of savings mainly depends on the characteristics of that region. Particularly, the amount of capacity investments is highly dependent on the amount of excessive demand that needs to be satisfied and the reduced congestion delays. In general, the more congested a road, the more traffic is generated by increased demand. Increased capacity on highly congested urban roads attracts considerable traffic due to high levels of latent demand. Thus, if a road section to be improved is in a very congested area, capacity investments may result in overall higher usage of this same road section which would not necessarily reduce transportation costs.

This GIS-based tool will help planners to estimate the changes in transportation costs due to a particular transportation demand management measure or supply change such as adding new lanes or improving existing lanes. This is a critical component of transportation planning, because demand patterns experience both spatial and temporal variations due to the changes in demand and supply. An accurate cost estimation tool based on the new route flows will help planners to better quantify the effects of these variations and thus to better evaluate current and future transportation investment alternatives. Moreover, transportation planners will be able to study the changes in various components of marginal functions namely operation, environmental, accident, and others and study various options based on the individual cost component of interest to them and other stakeholders.

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