Quantification of Possible Impacts of Capacity Expansion Projects on Transportation Costs via Trip-based Full Marginal Cost Estimation Methodology

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Abstract: 250
Word count: 5255 Text + 5 Tables + 3 Figures = 7255
Resubmission Date: November 15, 2007

ABSTRACT

This paper evaluates the impacts of proposed capacity expansions on the full trip-costs on large transportation networks such as Northern New Jersey. Unlike most previous studies, considering link-based measures only, this study focuses on individual trips to estimate the short-term changes in full marginal costs (FMC). Trips between each origin-destination (O-D) pair are represented as paths determined via a novel constrained $k^{th}$ shortest-path algorithm developed as part of the proposed methodology. Road sections are selected as candidates for capacity expansion based on the FMCs obtained for the whole network, i.e., road sections with highest FMC values are selected. Proposed approach for the before-and-after analysis is illustrated using four road sections (State-Highway (SR) 18, SR-17, SR-3, and Garden State Parkway (GSP)). Transportation costs calculated for before-and-after the capacity expansion and their fitted distributions show that trip-cost between a given O-D pair is not constant; rather it follows a probability distribution whose shape is affected by the road characteristics such as road and area types and number of lanes among other factors. Calculated costs at different probability levels show that highest reductions in the FMC are observed along SR-3 and GSP. Cumulative change in the FMCs of these segments is less than 20% with a probability of 0.95 and less than 15% with a probability of 0.5. This type of analysis gives a different and unique insight to policy planners regarding quantification of transportation costs in worst and best cases, and identification of projects that are most likely to generate highest benefits.
INTRODUCTION

To improve roadways, alleviate congestion and to address future traffic growth issues planners are usually asked to propose capacity investment projects.

Even though most transportation policies are local, their influence often spread out beyond the area of application. Responding to policies, traffic will shift from the impacted part of the network to other areas, and the intensity of the shift will depend on several factors, such as road characteristics, demand structure, and network configuration (1). Thus, quantification of changes in the transportation costs after the capacity expansion is crucial for policy planners to determine the possible benefits from capacity expansion projects, and select the projects that are most likely to generate highest benefits.

Several approaches have been developed by researchers and practitioners to evaluate and compare potential transportation improvement projects. Existing methodologies range from single-criteria benefit-cost analysis (BCA) to multiple criteria and total cost analysis methods.

BCA method is an economic approach that evaluates the benefits and costs of projects in dollar values and compares the benefit/cost ratio (2,3,4,5,6,7). Even though this method has several advantages, BCA has rarely been used by urban transportation decision makers due to decision makers’ unfamiliarity with this concept, and complexity of monetarizing factors such as disruption to people’s lives (8, 9). To address some of these concerns DeCorda-Souza et al. (9) proposed a total cost analysis to compare alternatives across modes, which is more useful for the public and political decision-makers. While performing analysis travel time, vehicle operating and accident costs are included.

Multiple criteria methods developed to select the most beneficial projects include several approaches. First approach, scoring method, ranks projects with respect to different objectives, where each objective is assigned a weight and each project is scored with respect to these objectives. Then the project with highest score is recommended (10,11,12). The main drawbacks of this method are inability to solve problems with resource constraints and compensatory bias (9). Second approach covers mathematical programming models, such as multi-attribute/objective decision making, goal programming and analytical hierarchy process. In this approach, a variety of objectives and resource restrictions are considered simultaneously (9,13,14,15,16). The main discrepancy of this approach is the need for crisp data to get meaningful results. Given the high level of uncertainty associated with transportation projects, usually decision makers refrain from such complex techniques (9). Third approach, Analytical Hierarchy Process, was developed to include criteria that are not measurable in an absolute sense. In this approach, subjective judgments enter into the evaluation process (17,18,19). This approach is most suitable when optimization is not pursued, resources are not restricted, and interdependencies do not exist.

This study proposes an alternate methodology for project selection via quantifying individual trip costs based on full marginal costs (FMC). Calculation of FMC for both original and expanded network conditions, using individual trips rather than link-based measures like vehicle-miles traveled, forms the basis for selecting the possible capacity expansion project.
With the use of trip-based FMC methodology proposed here, this study provides a unified scale for quantification of full transportation costs while considering the distributions of costs and their diversities among different O-D pairs and road sections.

Trip travel times and volumes required for the estimation of the FMCs before-and-after the road capacity expansion projects are obtained from the Northern Jersey Transportation Planning model developed by the regional MPO and its consultants using TP+ software package. Since the study focuses on “the short-term” changes in the social costs due to capacity expansion, same time-dependent (am peak, pm peak, and off-peak) origin-destination (O-D) matrices are assigned onto the original and modified (capacity expanded) networks.

Next section summarizes the methodological steps of the study followed by the trip-based FMC estimation methodology and the GIS-based interactive tool. Then, the Northern NJ network, and network specific cost functions along with the capacity investment locations are presented. Next, before-and-after analysis is conducted to investigate the short-term impacts on the FMC of different trips. Probability distributions of different cost categories are estimated for different road sections in order to observe how the transportation costs vary among different area and road types, and different periods. Finally, possible impacts of road expansion projects are estimated at different probability levels and benefits generated from these projects are calculated for worst and best cases. Last section presents the key findings of our analyses and conclusions.

METHODOLOGY

The methodology presented in this study, investigates the changes in the transportation costs among different trips due to capacity expansion. The trip-based FMC methodology applied to estimate the full costs of transportation allows the researchers to observe the differences in the costs among a set of paths between each O-D pair. The steps of our proposed methodology shown in FIGURE 1 are:

1. Using TP+ transportation planning software, traffic assignment is performed for the original network and O-D demand matrices for different time periods.
2. Road sections with highest FMC values are determined, and for these road sections the capacity is increased by adding an additional lane.
3. The original O-D demand matrices for each time period are reassigned onto the modified network using TP+. The main assumption in this step is that since short-term changes are investigated, demand is considered to remain unchanged.
4. Using the assigned network information obtained from TP+, trip-based FMC for each O-D pair is estimated using the methodology which calculates the trip-based FMC of trips considering a set of feasible paths between each O-D pair, proposed by the authors (20).
5. For each cost category the changes in the mean and standard deviation during am, pm and off peak periods are obtained.
6. The histogram plots and probability distributions of each cost category are generated for both original and modified network conditions, and changes in transportation
costs as a function of different area and road types, and different periods are investigated.

7. The fitted distributions are used to quantify the likelihood of possible impacts of capacity expansion projects on the transportation costs in worst and best cases, and to select the project with the highest probability of reduction in transportation costs.

FIGURE 1 Flowchart of the proposed methodology

TRIP-BASED FULL MARGINAL COST ESTIMATION

In this study, full costs before-and-after the road expansion projects are estimated via the trip-based FMC methodology developed by the authors (20).

At the heart of most policy considerations lies the accurate estimation of FMC of highway travel. This information is essential for allocating resources efficiently, ensuring equity among highway users, and for developing effective pricing mechanisms. 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 a mile). Hence, FMC represents the additional costs that the State should consider to encourage efficient use of transportation assets. When dealing with transportation facilities there is no unique or exact way of representing the output. Berechman et al. (21), define
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 (21)), such as number of trips or number of passengers, are used to analyze the overall effectiveness of the system. Moreover in (1), it is emphasized that marginal cost measured on a single-link is a poor predictor of total costs imposed by travel, and considering network-effects is suggested.

In this study, FMC of highway transportation is estimated based on these final outputs namely, trips. Trip is regarded as the major output measure. FMC is defined and calculated as “cost per trip.”

The methodology considered while estimating the trip-based FMC for different O-D pairs is presented in a previous paper by the authors (20). Since the main purpose of this study is to investigate the impacts of capacity expansions on the full costs of the travelers, only a brief summary of the trip-based FMC methodology is provided here for the completeness of the paper. For a more detailed explanation of the methodology please refer to (20).

The methodology developed to estimate trip-based FMC first determines set of feasible paths between each O-D pair. FMC is then calculated for each of the feasible paths that represent trips between these pairs. The proposed shortest path algorithm determines 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 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:

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

(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 \( A_i = \{a_{i1}, a_{i2}, \ldots, a_{iM} \} \) denote the links of the \( i^{\text{th}} \) candidate path where \( M \) is the number of links of the candidate path, and \( A_1 = \{a_{11}, a_{12}, \ldots, a_{N1} \} \) 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:

\[
\begin{align*}
(i) \quad & s_n = \begin{cases} 0 & \text{if } a_{n1} = a_{mi} \forall n \in N, \forall m \in M \\
1 & \text{otherwise} \end{cases} \\
(ii) \quad & S = \frac{\sum s_n}{N} \\
(iii) \quad & S \geq \delta_{\text{min}}
\end{align*}
\]  

\( \delta_{\text{min}} \) 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.

$$M \leq \theta_{\text{max}} N$$ (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, a $k^{th}$ shortest path is computed based on a modified version of Dijkstra’s algorithm (22). 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 until the maximum number of iterations has been reached. For this study, the 50 iterations are found to be satisfactory to find seven different paths between each O-D pair.

GIS-BASED FMC ESTIMATION TOOL

The developed trip-based FMC methodology is implemented in ArcGIS via C-programming and Visual Basic for Applications (VBA). The interactive 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
   - User defined set of O-D pairs among different Travel analysis zones (TAZ)
   - 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

2. The tool compares two different networks and estimates the short-term impacts of network changes on the FMC of selected trips.

NORTHERN NEW JERSEY NETWORK

The Northern NJ network consists 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 TP+. These input data include: (1) volume and travel time of each link resulting from the assignment of separate O-D demand matrices for am peak, pm peak and off-peak periods; (3) Node and link ID’s, (4) highway and residential area type; (5) length, number of lanes, capacity and free flow travel time of each link.

Cost categories considered in this study are (1) vehicle-operating, (2) travel time and congestion, (3) accident, (4) air-pollution, (5) noise, and (6) maintenance. Each cost category was estimated using the data obtained from New Jersey Department of Transportation (NJDOT) and other state and national sources. It should be noted that data on operating, accident, and infrastructure costs are NJ-specific. STATA software is used to estimate the parameters of each cost function. On the other hand, congestion and environmental costs were adopted from relevant studies in the literature. The parameters of the cost functions were modified to reflect NJ-specific conditions. For illustration purposes, only the final total and marginal cost functions are presented here (TABLE 1). The detailed derivation of each cost category can be found in the study performed by the authors (23).
### TABLE 1 Marginal Cost Functions, (23)

<table>
<thead>
<tr>
<th>Cost</th>
<th>Total &amp; Marginal Cost Function</th>
<th>Variable Definition</th>
<th>Data Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle Operating</td>
<td>$C_{opr} = 7208.73 + 0.12(m/a) + 2783.3a + 0.143m$</td>
<td>a: Vehicle age (years)</td>
<td>AAA(24), USDOT (25), KBB (26)</td>
</tr>
<tr>
<td></td>
<td>$MC_{opr} = 0.143 + \left(\frac{0.12}{a}\right)$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| Congestion                    | $C_{cong} = \begin{cases} \frac{dP}{dV} \left(1 + 0.11 \left(\frac{Q}{C}\right)^{0.5}\right) VOT & \text{if } Q \leq C \\
\frac{dP}{dV} \left(1 + 0.11 \left(\frac{Q}{C}\right)^{0.5}\right) VOT + \frac{dQ}{dV} \left(\frac{Q}{C} - 1\right) VOT & \text{if } Q > C \end{cases}$ | $Q = \text{Volume (veh/hr)}$
|                               |                               | $d = \text{Distance (mile)}$
|                               |                               | $C = \text{Capacity (veh/hr)}$
|                               |                               | $VOT = \text{Value of time } (\$/hr)$
|                               |                               | $V_o = \text{Free flow speed } (mph)$ | Mun (27)
|                               |                               |                       | Small and Chu (28) |
| Category 1: freeway, expressway, interstate highway | $C_{avg} = 127.5Q^{0.37} M^{0.76} L^{0.33}$
|                               | $+ 114.75Q^{0.05} M^{0.35} L^{0.49}$
|                               | $+ 198.90Q^{0.17} M^{0.42} L^{0.45}$
|                               | $MC_{avg} = 98.175Q^{0.23} M^{0.76} L^{-0.33}$
|                               | $+ 97.53Q^{0.15} M^{0.35} L^{0.49}$
|                               | $+ 33.813Q^{0.83} M^{0.32} L^{0.45}$ | $Q = \text{Volume (veh/day)}$
|                               |                               | $M = \text{Path length (miles)}$
|                               |                               | $L = \text{no of lanes}$ | NJDOT (30)
| Category 2: principal arterial | $C_{avg} = 178.5Q^{0.37} M^{0.35} L^{0.43}$
|                               | $+ 18.359Q^{0.05} M^{0.35} L^{0.37}$
|                               | $MC_{avg} = 103.5Q^{0.42} M^{0.39} L^{0.43}$
|                               | $+ 8261.5Q^{0.35} M^{0.65} L^{0.47}$ |                       | FHWA (29) |
| Category 3: arterial-collector-local road | $C_{avg} = 229.5Q^{0.37} M^{0.37} L^{0.37}$
|                               | $+ 9179.96Q^{0.24} M^{0.31} L^{0.35}$
|                               | $MC_{avg} = 133.11Q^{0.42} M^{0.37} L^{0.37}$
|                               | $+ 6793.17Q^{0.26} M^{0.31} L^{0.35}$ | $\text{Fuel consumption at cruising speed } (\text{g/l/mile})$
|                               |                               | $V = \text{Average speed (mph)}$
|                               |                               | $Q = \text{Volume (veh/hr)}$ | EPA (31) |
| Air pollution                 | $TC_{air} = Q(0.01094 + 0.2155F)$
|                               | $MC_{air} = 0.01094 + 0.2155 \left(F + \frac{DE}{Q}\right)$ where; | $F = \text{Fuel consumption at cruising speed } (\text{g/l/mile})$
|                               | $F = 0.0723 - 0.00312V^2 + 5.403x10^{-5}V^2$ | $V = \text{Average speed (mph)}$
|                               |                               | $Q = \text{Volume (veh/hr)}$ |                       |
| Noise                         | $C_{noise} = 2 \int_{r_0 = 50}^{r_f} \left(r - 50\right) D W_{avg} \frac{RD}{5280} dr$ where; | $D = \% \text{discount}$
|                               | $W = \text{Housing value } (\text{S})$
|                               | $RD = \text{Residential density}$
|                               | $r = \text{Distance to highway (mile)}$
|                               | $K = \text{Noise-energy emis.}$
|                               | $K_{car} = \text{Auto emission}$
|                               | $K_{truck} = \text{Truck emission}$
|                               | $F_c = \% \text{of autos}$
|                               | $F_t = \% \text{of trucks}$
|                               | $F_{car} = \% \text{const. speed autos}$
|                               | $F_{truck} = \% \text{const. speed tr.}$
|                               | $V_c = \text{Auto Speed } (\text{mph})$
|                               | $V_t = \text{Truck Speed } (\text{mph})$ | Delucchi and Hsu (32) |
|                               | $L_{eq} = 10 \log(Q) + 10 \log(K) - 10 \log(F) + 1.14$ |                       |                       |
| Maint.                        | $C_M = \frac{796.32(M)^{0.40}(L)^{0.39}}{P}$
|                               | $MC_M = \frac{796.32(M)^{0.40}(L)^{0.39}}{P \times 365.24}$ | $Q = \text{Volume (veh/day)}$
|                               |                               | $L = \text{no of lanes}$ | Ozbay et al. (23) |
|                               |                               | $P = \text{time-period}$
|                               |                               | $t = \text{trip duration } (\text{hr})$ |                       |
STUDY OF THE ASSESSMENT OF IMPACTS OF ROAD EXPANSIONS

In this section, impacts of real-world capacity investments on several route sections are investigated. The specific road sections to be expanded are determined based on the FMC values obtained for the overall network. Specifically, road sections with highest FMC values are selected and the number of lanes of these road sections is increased (one lane is added to each road section). Top four road sections obtained as a result of FMC based ranking are sections of State Highway (SR) 18, SR-17, SR-3, and Garden State Parkway (GSP). TABLE 2 summarizes the lengths of these road sections, road and area types, truck allowance rules, and the changes in the number of lanes. According to NJDOT classification, SR-3 and GSP are urban freeways, while SR-17 and SR-18 are suburban expressways with similar number of lanes. Trucks restrictions are only valid for the GSP. FIGURE 2 shows the location of the road sections for which the possible impacts of capacity investment are assessed using the proposed methodology. Since the number of lanes on each road section changes among different links the average number of links on the road sections is calculated as follows:

\[
\text{Avg number of lanes} = \frac{\sum \text{number of lanes}_i \times \text{length of the link}_i}{\text{total length of the road section}}
\]

<table>
<thead>
<tr>
<th>Road</th>
<th>Length</th>
<th>Area Type</th>
<th>Road Type</th>
<th>Trucks Allowed</th>
<th>Avg # Lanes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Orig.</td>
</tr>
<tr>
<td>SR-3</td>
<td>3.33</td>
<td>Urban</td>
<td>Freeway</td>
<td>Yes</td>
<td>3</td>
</tr>
<tr>
<td>SR-17</td>
<td>10.8</td>
<td>Suburban</td>
<td>Expressway</td>
<td>Yes</td>
<td>2.4</td>
</tr>
<tr>
<td>SR-18</td>
<td>6.11</td>
<td>Suburban</td>
<td>Expressway</td>
<td>Yes</td>
<td>2.63</td>
</tr>
<tr>
<td>GSP</td>
<td>6.27</td>
<td>Urban</td>
<td>Freeway</td>
<td>No</td>
<td>3.8</td>
</tr>
</tbody>
</table>

After increasing the capacity of these road sections, using the same O-D demand matrices, traffic is reassigned onto the modified network, and the output information obtained from the traffic assignment is used for comparison of before-after costs. It should be noted that impacts of each capacity investment is investigated separately, i.e. four different modified networks are created for four different capacity investments. To focus on multiple O-D pairs, TAZs in the vicinity of the improved road sections are selected, and the changes in trip-based FMCs are calculated using the developed GIS tool. 20 different O-D pairs are analyzed to investigate short-term impacts of the proposed policy implications on the FMC trips.

Short-term Impacts of Capacity Expansion Projects

Next, short-term impacts of capacity expansion on the full transportation cost among different O-D pairs are investigated. TABLE 3 summarizes before-and-after trip-based FMCs for all the road section and periods. For all O-D pairs in the vicinity of the studied road sections and for each time period, different cost categories are evaluated. For all trips, am peak period produce the highest range of FMC values followed by pm peak and off-peak periods. During am and pm peak periods the dominant cost categories are travel time, external time and queue costs, followed by vehicle operating, accident and air pollution costs. Noise and maintenance costs are
the least impacted cost categories among all. During off-peak period, since the volume on the links does not exceed the link capacity, queue cost is zero for all trips. Highest portion of the trip FMC is covered by travel time and vehicle operating costs; followed by external time, accident, and air pollution costs. Similar to the peak periods, lowest share of the trip FMC are formed by noise and maintenance costs. For each cost category highest values are observed for SR-18 followed by SR-17 and GSP, while SR-3 has the lowest cost values in each category. The analysis results claim that for all O-D pairs and periods the trip-based FMC values have been reduced. This reduction is as low as 2% for some trips, while as high as 35% for other trips. The highest reduction in the cost values is observed for travel time, external time and queue costs followed by environmental, accident, maintenance and vehicle operating costs. Furthermore, it is observed that road sections SR-3 and GSP would experience the highest reduction in cost values, if the capacity expansion projects were to be assessed in these roadways.

FIGURE 2 Locations of road expansion projects
<table>
<thead>
<tr>
<th>Road</th>
<th>MCopr ($/trip)</th>
<th>MCtime ($/trip)</th>
<th>MCext ($/trip)</th>
<th>MCqueue ($/trip)</th>
<th>MCacc ($/trip)</th>
<th>MCair ($/trip)</th>
<th>MNoise ($/trip)</th>
<th>MCmaint ($/trip)</th>
<th>FMCsum* ($/trip)</th>
<th>FMCsum** ($/trip)</th>
</tr>
</thead>
</table>
Statistical Distributions of Trip-based Full Marginal Costs

Based on the calculated transportation costs before-and-after the capacity expansion, probability distribution of each cost category is generated for each time period and road section. Fitting distributions to different road sections at different periods, allow the researchers and policy planners to observe not only the average transportation costs but their distributions as a function of different area types (urban vs. suburban), road types (freeway vs. expressway), number of lanes, and different periods (peak vs. off-peak). This way, planners can have a better idea about the transportation costs in different regions while studying the implications of various highway investment strategies. The summary of the fitted distributions and their parameters are shown in TABLE 4. For illustration purposes only histograms for SR-3 for different periods are given in FIGURE 3a, FIGURE 3b and FIGURE 3c. The histograms regarding different cost categories and periods depict that FMC shows differences for different O-D pairs located in the vicinity of the same road section.

Fitted distributions of operating, accident, and maintenance costs shown in TABLE 4 are found to follow a Weibull distribution for both SR-17 and SR-18; while external time, queue and trip-based FMCs follow lognormal distribution, and travel time, air pollution and FMC calculated via excluding queue costs follow normal distribution. On the other hand, for SR-3 and GSP, all cost categories follow normal distribution apart from operating and maintenance costs which follow lognormal and Weibull distributions, respectively.

Standard deviations of the fitted distributions state that the highest variance in the cost values is observed for SR-18 and SR-3 followed by SR-17 and GSP road sections. A possible explanation for lower variances on road sections SR-17 and GSP can be the insufficient route availability around these road sections. Moreover, after the capacity expansion, the variance of the transportation costs would be reduced, indicating that the probability of observing very high or very low cost values would be reduced.

These unique differences among the road sections show that road specific characteristics like road and area types and number of lanes affect the shape of the probability distribution of the cost functions. Moreover, when the availability of different routes around the areas located within a region is insufficient compared with other regions (GSP and SR-17), most of the trips between O-D pairs create similar cost values, while for other road sections the O-D demand behavior and volumes are more heterogeneous. After the capacity expansion histograms for each cost category shift to the left, keeping their shape almost the same. This result is expected, since apart from the capacity expansion for these road sections, everything else in the network including the O-D demand matrix was kept unchanged to mimic short-term network conditions after the implementation of these infrastructure improvement projects.
<table>
<thead>
<tr>
<th>Road Period</th>
<th>MCopr</th>
<th>MCtime</th>
<th>MCext</th>
<th>MCqueue</th>
<th>MCacc</th>
<th>MCair</th>
<th>MCmaint</th>
<th>FMC*</th>
<th>FMC**</th>
</tr>
</thead>
<tbody>
<tr>
<td>SR-3 am peak</td>
<td>org.</td>
<td>LN(0.49,0.49)</td>
<td>N(3.61,1.48)</td>
<td>N(1.97,1.91)</td>
<td>N(36.37,16.03)</td>
<td>N(0.34,0.07)</td>
<td>N(0.43,0.13)</td>
<td>W(5.59,0.6)</td>
<td>N(7.42,2.46)</td>
</tr>
<tr>
<td>SR-3 pm peak</td>
<td>mod.</td>
<td>LN(0.16,0.36)</td>
<td>N(3.28,1.19)</td>
<td>N(1.75,0.99)</td>
<td>N(28.33,13.91)</td>
<td>N(0.29,0.06)</td>
<td>N(0.41,0.12)</td>
<td>W(4.38,0.4)</td>
<td>N(6.77,2.15)</td>
</tr>
<tr>
<td>SR-3 off peak</td>
<td>org.</td>
<td>LN(0.12,0.27)</td>
<td>N(3.41,0.89)</td>
<td>N(1.12,0.59)</td>
<td>N(18.61,10.81)</td>
<td>N(0.38,0.1)</td>
<td>N(0.41,0.08)</td>
<td>W(6.87,0.57)</td>
<td>N(6.39,1.78)</td>
</tr>
<tr>
<td>SR-17 am peak</td>
<td>org.</td>
<td>W(8.31,2.47)</td>
<td>N(7.01,0.94)</td>
<td>LN(1.35,0.23)</td>
<td>N(3.96,0.21)</td>
<td>W(10.63,0.53)</td>
<td>N(0.68,0.11)</td>
<td>W(25.85,0.12)</td>
<td>N(14.5,2.01)</td>
</tr>
<tr>
<td>SR-17 pm peak</td>
<td>mod.</td>
<td>W(8.41,2.41)</td>
<td>N(6.34,0.96)</td>
<td>LN(0.85,0.13)</td>
<td>N(3.91,0.19)</td>
<td>W(10.11,0.51)</td>
<td>N(0.64,0.10)</td>
<td>W(26.35,0.11)</td>
<td>N(10.9,1.69)</td>
</tr>
<tr>
<td>SR-17 off peak</td>
<td>org.</td>
<td>W(9.03,2.32)</td>
<td>N(6.80,0.85)</td>
<td>LN(1.43,0.17)</td>
<td>N(4.05,0.13)</td>
<td>W(5.87,0.65)</td>
<td>N(0.61,0.09)</td>
<td>W(20.21,0.15)</td>
<td>N(14.6,1.57)</td>
</tr>
<tr>
<td>SR-18 am peak</td>
<td>org.</td>
<td>W(4.93,2.23)</td>
<td>N(7.85,1.49)</td>
<td>LN(2.27,0.38)</td>
<td>N(4.08,0.23)</td>
<td>W(6.69,0.75)</td>
<td>N(0.51,0.14)</td>
<td>W(10.10,0.11)</td>
<td>N(21.63,5.34)</td>
</tr>
<tr>
<td>SR-18 pm peak</td>
<td>mod.</td>
<td>W(4.86,2.15)</td>
<td>N(7.44,1.47)</td>
<td>LN(2.04,0.39)</td>
<td>N(4.01,0.25)</td>
<td>W(4.96,0.71)</td>
<td>N(0.49,0.13)</td>
<td>W(13.48,0.09)</td>
<td>N(19.4,3.32)</td>
</tr>
<tr>
<td>SR-18 off peak</td>
<td>org.</td>
<td>W(4.19,2.27)</td>
<td>N(7.51,2.36)</td>
<td>LN(1.66,0.35)</td>
<td>N(3.47,0.22)</td>
<td>W(5.53,0.78)</td>
<td>N(0.44,0.10)</td>
<td>W(6.19,0.09)</td>
<td>N(16.4,3.88)</td>
</tr>
<tr>
<td>GSP am peak</td>
<td>org.</td>
<td>W(4.24,2.15)</td>
<td>N(6.94,1.48)</td>
<td>LN(1.58,0.41)</td>
<td>N(3.63,0.28)</td>
<td>W(4.48,0.72)</td>
<td>N(0.43,0.11)</td>
<td>W(6.83,0.08)</td>
<td>N(15.4,3.54)</td>
</tr>
<tr>
<td>GSP pm peak</td>
<td>mod.</td>
<td>W(3.87,2.08)</td>
<td>N(5.79,1.54)</td>
<td>LN(0.39,0.47)</td>
<td>-</td>
<td>W(6.32,0.37)</td>
<td>N(0.44,0.12)</td>
<td>W(3.3,0.04)</td>
<td>N(10.7,2.79)</td>
</tr>
<tr>
<td>GSP off peak</td>
<td>org.</td>
<td>W(4.38,2.00)</td>
<td>N(5.25,1.41)</td>
<td>LN(0.15,0.46)</td>
<td>-</td>
<td>W(4.95,0.83)</td>
<td>N(0.41,0.11)</td>
<td>W(3.12,2.42)</td>
<td>N(9.6,2.42)</td>
</tr>
</tbody>
</table>

(1) *: Full marginal cost values excluding the queue costs, (2) **: Full marginal cost values including the queue costs, (3) LN: Lognormal, (4) N: Normal, (5) W: Weibull
FIGURE 3a Impacts of SR-3 capacity expansion on marginal costs, am peak period
*: Full marginal cost values excluding the queue costs
**: Full marginal cost values including the queue costs

FIGURE 3b Impacts of SR-3 capacity expansion on marginal costs, pm peak period
SELECTION OF PROJECTS FOR CAPACITY EXPANSION

Transportation agencies are faced with the problem of efficiently selecting a subset of transportation projects for implementation. One of the major difficulties in project selection is the quantification of the values of measures such as value of time, value of human life, and environmental impacts (9). With the use of trip-based FMC methodology proposed here, this study provides a unified scale for quantification of all transportation costs while considering the distributions and diversification of costs with respect to different O-D pairs and road sections.

Based on the fitted distributions of trip-based FMCs for different road sections, it is possible to calculate the transportation costs for original and modified network conditions at different probability levels. Considering probability of occurrence of different cost values instead of constant transportation costs for different road sections, allows policy planners to acquire information regarding the likelihood of expected cost impacts of different capacity expansion projects.

TABLE 5 summarizes the results of FMC values excluding and including the queue costs for original and modified network conditions calculated at different probability levels (p=0.1, 0.25, 0.5, 0.75, and 0.95).
The values in TABLE 5 show the FMC values and the changes in the FMC values after the capacity expansion. For instance, the first entry shows that with a probability of 0.10, the FMC values (excluding the queue costs) on the SR-3 during the am peak period would be less than 4.27$/trip. Similarly, when the road capacity is expanded, the reduction in the cost value would be less than 5.92% with a probability of 0.1.
Capacity expansions in the am-peak period do not generate improvements of more than 10% to 15% in the transportation costs with a probability of 0.95. The highest improvement in the FMCs is observed for GSP with less than 14% reduction in the transportation cost with a probability of 0.50, followed by SR-18, SR-3 and SR-17. When queue costs are included in the calculation, relative range of improvements has been increased. Since capacity expansions directly affect time and queue costs, this result is expected. The highest improvement is observed for SR-18, for which the FMC values would be reduced by less than 20% with a probability of 0.95.

For pm peak period, it is observed that capacity expansions would have a similar impact on the transportation costs. For most road sections the reduction in the cost values is higher compared with the am peak period. With a probability of 0.5, the improvement would be less than 15% for GSP and less than 10% for other road sections (when queue costs are excluded). If the queue costs are included in the calculation, reduction in the FMCs increases around 20% for most road sections.

The reduction in the cost values is lower during off-peak periods compared with peak periods. Since during off-peak hours traffic demand is lower than the capacity, adding more capacity to the road sections would not reduce the transportation costs as much as the peak periods.

The overall transportation cost comparison using different probability levels show that the highest benefit from capacity expansion projects would be experienced during peak periods with a reduction of 20% per trip in the FMC values. The road section for which the most improvement observed is SR-3 and GSP followed by SR-17 and SR-18 road sections.

This probabilistic analysis of transportation costs among different O-D pairs and road sections, give an insight to the policy planners regarding the diversity of the trip-based FMCs in a transportation network. This new way of looking at the result allows the planners to better identify road sections that are likely to provide the highest benefit when capacity improvements are implemented. With this information, transportation agencies may quantify the benefits of different projects in worst and best cases and make more informed decisions while selecting transportation improvement projects.

**CONCLUSIONS**

The purpose of this paper is threefold: (1) Investigate the impacts of capacity expansion on the transportation costs of different regions of Northern NJ, (2) Estimate the probability distributions of each cost category for both original and modified network conditions, in order to observe transportation costs vary among different area and road types, and different periods, (3) Using the fitted distributions to quantify the transportation costs at different probability levels, to determine the level of improvements generated from different capacity expansion projects and to select the project that is most likely to generate the highest benefits.

Unlike other studies that employ link-based measures, this study focuses on individual trips to estimate the short-term changes in the transportation network where the possible impacts of capacity expansions are assessed. Trip travel times and volumes required for the estimation of the FMCs before-and-after the road capacity expansion projects are obtained from the Northern Jersey Transportation Planning model developed by the regional MPO and its consultants using TP++.
The trip-based FMC approach used to determine the impacts of the capacity expansion projects is developed by the authors (1). Trip-based FMC value between each O-D pair is calculated by finding a specialized constrained k-shortest path between that specific O-D pair, and calculating the transportation costs along these feasible paths that represent trips.

The specific road sections to be expanded are determined based on the FMC values obtained for the overall network. Specifically, road sections with highest FMC values are selected and number of lanes of these road sections is increased. These road sections are SR-18, SR-17, SR-3, and GSP.

Transportation costs before-and-after the capacity expansion case studies and their fitted distributions show that FMC between a given O-D pair is not constant; rather it follows a probability distribution whose shape is affected from road specific characteristics like road and area type and number of lanes among other factors. Moreover, when the availability of different routes around the areas located within a region is insufficient compared with other regions, most of the trips between O-D pairs produce similar costs, while for other road sections the O-D demand behavior and volumes are more heterogeneous. After the capacity expansion, for each cost category, histograms shift to the left while keeping their shape almost the same.

Information obtained from the distribution of transportation costs and the diversity among different road sections and O-D pairs, is then used to quantify the possible benefits of capacity expansion projects, and to select the most beneficial project.

Transportation costs calculated at different probability levels for both original and modified network conditions show that the highest benefits are experienced during pm peak followed by am peak and off-peak. Moreover, the highest reduction in the transportation costs is observed for SR-3 and GSP followed by SR-17 and SR-18. The cumulative change in the costs are quantified as less than 15% with a probability of 0.95 and less than 15% with a probability of 0.5.

This probabilistic analysis of transportation costs among different O-D pairs and road sections, give an insight to the policy planners regarding the diversity of the trip-based FMCs in a transportation network, and identifying the road sections that are most likely to generate highest benefits when capacity improvements are implemented. With this information, transportation agencies may quantify the benefits of different projects for worst and best cases and make more informed project selection decisions.

ACKNOWLEDGEMENTS

This project was sponsored by a grant from the University Transportation Research Center at City College of New York. Additional support was provided by NJDOT. We would like to thank Professor Joseph Berechman for providing invaluable comments on an earlier version of a research report that contained some of the information presented in this paper. We would also like to thank Mr. Robert Diogo from North Jersey Transportation Planning Authority for providing the test network and some of the data used in the paper, and Mr. Abbas Hiry for his useful comments and suggestions. The opinions and conclusions presented are the sole responsibility of the authors and do not reflect the views of sponsors or other participating agencies.
REFERENCES


