Bridge User Cost Estimation – A Synthesis of Existing Methods and Addressing the Issues of Multiple Counting, Workzones, and Traffic Capacity Limitation

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ABSTRACT
Efforts to incorporate the concerns of bridge users in project and program evaluation are often stymied by lack of a comprehensive and consistent framework for assessing the different user cost types and components. There is a need to synthesize and update existing user cost estimation techniques so that the process of incorporating user costs in bridge investment evaluation can be more consistent and streamlined. Secondly, user costs during bridge workzones have rarely been considered in the literature. Thirdly, there is a need to recognize that a bridge detour may occur for more than one reason, thus there is a danger of multiple counting and this could translate into overestimation of user cost. To address these issues, this paper presents a framework for comprehensive estimation of user costs for bridge management, a methodology for bridge workzone user cost estimation, and an approach to address the issue of multiple counting. Furthermore, the paper develops a method to estimate the bridge user delay cost due to traffic capacity limitation. The methodologies are demonstrated using a case study.
INTRODUCTION

Background Information and Problem Statement

Comprehensive evaluations of bridge investments need to incorporate explicitly the concerns of major stakeholders including bridge users (1-6). Bridge user cost is caused mostly by functional deficiencies of a bridge (7) such as limitations of load capacity or vertical clearance. These limitations cause vehicles to detour, hence increasing the cost of vehicle operations and travel time. User costs are also incurred in the case of moveable bridge openings, where bridge users are delayed as the bridge opens up to enable ships to pass through (8).

The existing literature contains a fairly extensive amount of past research on the subject of bridge user cost estimation. In North Carolina and Indiana, user cost was first implemented in the state bridge management systems in the 1980s (1,7). In bridge management software such as PONTIS and the Indiana Bridge Management System IBMS, bridge user costs are considered in calculation of project benefits as a reduction in user cost due to bridge actions (3, 4, 9). Johnston et al. (2) developed user cost estimation methods that considered accident and detour user costs, duly recognizing that accident user cost is higher where there is narrow deck width, poor alignment, or impaired vertical clearance, and that detour cost is a function of load capacity and vertical clearance limits. Similarly, Son and Sinha (3), in their life-cycle user cost estimation methodology for IBMS, considered detour cost due to load capacity and vertical clearance limits and also considered the travel time cost of speed reduction due to narrow lane width. Thompson et al. (4-6) in developing a Pontis user cost model for Florida DOT, incorporated bridge width, approach alignment, vertical clearance, and operating rating in user cost estimation.

In presenting the different cost components of bridge user cost estimation, past studies focused on the costs during the period of normal operations of the bridge with little or no explicit inclusion of costs incurred during preservation workzone periods. Also, in calculating bridge user costs due to detours, most past studies did not comprehensively account for the possibility that a vehicle may detour for more than one reason; as such separate calculations for each of the multiple reasons for detouring may yield overestimates of total user cost. Furthermore, even though some studies considered user cost due to narrow bridges (3,4), their calculation structure either calculates bridge widening benefit as accident cost reduction or only presents bridge widening benefit in the form of congestion delay reduction under the situation of bridge widening without adding lanes. Thus, the estimation of bridge widening benefits due to lane addition improvements was not addressed. Last but not least, the poor condition of the bridge wearing surface can also cause additional Vehicle Operating Cost (VOC) but is not sufficiently addressed in the literature.

In recognizing the above shortcomings of the existing methodologies for bridge user cost calculation, this paper presents an updated and comprehensive framework for user cost calculation. This is largely based on methods presented in the existing literature but includes refinements that consider all components of user cost in the bridge life-cycle horizon including normal operations periods and workzone periods. The refinements include methodologies to reliably calculate detour user costs to avoid the problem of multiple counting in the calculation of user benefit for all types of bridge actions, and in the calculation of user cost due to inadequate bridge traffic capacity and poor condition of
the wearing surface. A case study is presented to demonstrate the applicability of the suggested framework and the new refinements.

**Incorporating Calculated User Costs in Bridge Life-cycle Cost Analysis**

Life-cycle cost analysis is a widely-used technique for amalgamating the costs and benefits of bridge investments that are accrued to the bridge agency, users, and the affected community over the long term \((3, 10)\). The accumulation of bridge user costs over time is best appreciated in a life-cycle context. A typical life-cycle profile for a steel bridge is shown in FIGURE 1 \((11)\). In evaluation of bridge investment alternatives, the user costs corresponding to each alternative can be first estimated in undiscounted dollars, and then brought to their present worth or equivalent uniform annual amounts for purposes of comparison \((11)\).

There are two distinct periods during the bridge life-cycle that influence the components of user cost that need to be considered: the normal operations period where the bridge is being used by traffic and there is no repair activity on the bridge; and the workzone period where there is a repair action on the bridge that may impede traffic flow. Compared to former, the workzone period has short duration but may have considerable user cost impacts, often due to reduced bridge width, lower speed limit, or even complete bridge closure. The estimation of bridge user costs should be carried out for the entire bridge life cycle, and thus should consider the various dimensions of user cost incurrence: normal operations and workzone periods; road users on the highway located over the bridge or/and under the bridge; and the key components of user costs, namely: detour, accident, and delay costs.

**TRAFFIC FLOW CONTEXTS, SERVICE FEATURES, AND ASSOCIATED BRIDGE USER COSTS**

For purposes of user cost computation, we herein describe two contexts of traffic flow on the road of interest relative to the bridge (FIGURE 2).

**Road Traffic Flow over the Bridge**

In this case, the road is over the bridge (FIGURE 2(a)). The bridge passes over a water body, railway, another road, wildlife crossing, etc. Limitations in bridge width and load capacity produce road user costs. Relatively unusual is the situation where a bridge has vertical clearance limitations over the bridge: such instances include roadway on a through-trusses (where clearance is impaired by sway bracing); roadways that, at the location of the bridge in question, also pass beneath older railroad bridges; and the even more rare case of 3-level interchanges where the middle-level bridge may have vertical...
clearance limitations over the bridge. If the facility under the bridge is non-transportation related, then user cost computation is applicable only to users of the road. However, if the service feature is a secondary road, or transporting water body, then user costs should be calculated for two classes of users: users of the road (over the bridge); and users of the facility (road, water vessels) passing beneath the bridge.

**Road Traffic Flow under the Bridge**

In this case, the road is under the bridge (FIGURE 2(b)). The facility over the bridge could be a pedestrian crossing, wildlife crossing, or another road.

![FIGURE 2 Traffic Flow Contexts](image)

(a) Road Traffic is over Bridge  (b) Road Traffic is under Bridge

**TABLE 1 presents the factors to be taken into consideration in calculating bridge user cost for the different contexts of traffic flow.** It is seen that a bridge deficiency may incur more than one of the three cost components, namely, detour, accident, and delay. Besides the causes listed in Table 1, special events, such as incidents, also cause bridge user cost. For example, after an accident, the bridge may be partially or fully closed thus causing vehicles to slow down or detour; leading to user costs of detour or delay. It is important to note that in certain cases of bridge replacement or rehabilitation, there will be little or no detour (and its associated costs) because the agency provides an alternative temporary bridge structure in close proximity to the original structure. It is also important to note that immediately after a bridge accident, user costs could be incurred due to the subsequent delay (due to accident clearance time) and even to secondary accidents such as rear-end crashes.

**TABLE 1 Major User Cost Components**

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<tbody>
<tr>
<td>Users of the road over the bridge</td>
<td><strong>Operating Periods</strong>&lt;br&gt; Inadequate load capacity&lt;br&gt; Inadequate vertical clearance over bridge&lt;br&gt; Inadequate horizontal clearance over bridge&lt;br&gt; Poor alignment&lt;br&gt; Inadequate traffic capacity&lt;br&gt; Wearing surface condition</td>
<td>Yes&lt;br&gt; Yes&lt;br&gt; Yes&lt;br&gt; Yes&lt;br&gt; Yes</td>
<td>Yes&lt;br&gt; Yes&lt;br&gt; Yes&lt;br&gt; Yes&lt;br&gt; Yes</td>
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<tr>
<td>Users of the road under the bridge</td>
<td><strong>Workzone Periods</strong>&lt;br&gt; Workzone-related activities</td>
<td>Yes</td>
<td>Yes</td>
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<td></td>
<td><strong>Operating Periods</strong>&lt;br&gt; Inadequate vertical clearance under bridge&lt;br&gt; Inadequate horizontal clearance under bridge</td>
<td>Yes</td>
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<td><strong>Workzone Periods</strong>&lt;br&gt; Workzone-related activities</td>
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COMPUTATIONS FOR BRIDGE USER COST COMPONENTS

Bridge users incur costs during the normal operations period or during workzone periods. During each of these periods, the specific components, or circumstances in which the cost is incurred, include the delay and safety due to restricted bridge operating conditions or detours, as indicated in TABLE 1. The derivations of the expressions for the different user cost components share some similarities. In the ensuing sections of this paper, we explain the user costs due to detour, delay, accidents, and wearing surface condition.

Bridge User Cost Due to Detour

The cost incurred by bridge users due to detour continues to be a dominant component of bridge user cost (2, 3, 9). In spite of earnest efforts toward bridge improvement, there still exists a large number of bridges with deficiencies that cause vehicles to detour. For instance, 47% bridges on Indiana’s interstate system have inventory rating under 40 tons and 1.5% have operating rating under 40 tons. Trucks of 40 tons are allowed on the Interstate Highway System according to the federal commercial vehicle standards (12). With regard to vertical clearance, for about 1,705 bridges, the feature intersected by the bridge is another highway. Of these, 4% have vertical clearance under 14 ft. There is no federal vehicle height limit, but state maximums of vehicle height range from 13.6 to 14.6 ft.

As stated in earlier sections of this paper, most detours are due to inadequacies during normal operations (such as limitations on bridge load capacity, and vertical or horizontal clearance) or operational restrictions during workzone periods. Detours cause an increase in travel distance and time for road users, resulting in additional vehicle operating and travel time costs. The list below presents the expressions for calculating bridge detour costs, due to the indicated deficiencies.

Load capacity limit:

Vehicle Operating Cost = \[ \sum_{i=1}^{m} U_{VOC}(i) \times DL \times N_{L}(i) \]

Travel Time Cost = \[ \sum_{i=1}^{m} U_{TTC}(i) \times DL \times N_{T}(i) \]

Vertical clearance limit (over or under):

Vehicle Operating Cost = \[ \sum_{i=1}^{m} U_{VOC}(i) \times DL \times N_{V}(i) \]

Travel Time Cost = \[ \sum_{i=1}^{m} U_{TTC}(i) \times DL \times N_{T}(i) \]

Horizontal clearance (over or under):

Vehicle Operating Cost = \[ \sum_{i=1}^{m} U_{VOC}(i) \times DL \times N_{H}(i) \]

Travel Time Cost = \[ \sum_{i=1}^{m} U_{TTC}(i) \times DL \times N_{T}(i) \]

Poor alignment:

Vehicle Operating Cost = \[ \sum_{i=1}^{m} U_{VOC}(i) \times DL \times N_{P}(i) \]

Travel Time Cost = \[ \sum_{i=1}^{m} U_{TTC}(i) \times DL \times N_{T}(i) \]

Traffic flow limitations due to workzone:

Vehicle Operating Cost = \[ \sum_{i=1}^{m} U_{VOC}(i) \times DL \times N_{W}(i) \]

Travel Time Cost = \[ \sum_{i=1}^{m} U_{TTC}(i) \times DL \times N_{T}(i) \]

Where: \( DL \) = detour length (miles); \( m \) = number of vehicle classes;

\( U_{VOC}(i) \) = unit vehicle operating cost of vehicle class \( i \) (dollars/mile);

\( U_{TTC}(i) \) = unit travel time cost of vehicle class \( i \) (dollars/hour);

\( SP(i) \) = average speed of vehicle class \( i \) on detour (miles/hour); and
\[ N_L^a(i) = N_L(i) \times (1 - PV_L) \]

where \( N_L(i) \) is the theoretical number of class \( i \) vehicles that must detour due to load limit, and \( PV_L \) is the percentage of load limit violators (vehicles that actually do not detour even though they exceed the load limit).

Similarly, \( N_V^a(i) = N_V(i) \times (1 - PV_V), \) \( N_H^a(i) = N_H(i) \times (1 - PV_H), \) \( N_P^a(i) = N_P(i) \times (1 - PV_P), \) and \( N_W^a(i) = N_W(i) \times (1 - PV_W), \) where the symbols and subscripts are defined similarly as done for load limit.

In these expressions, the unit vehicle operating cost \( U_{VOC} \) and unit travel time cost \( U_{TTC} \) can vary significantly depending on prevailing circumstances. Derivations of \( U_{VOC} \) and \( U_{TTC} \) are well addressed in the literature (2, 3, 9). Rather, what is worth addressing in this paper is the determination of the number of vehicles that detour, considering possible multiple-counting issue. Subsequent sections of this paper describe in detail each reason for detouring and derive the expressions for estimating the number of detouring vehicles.

### Detour Due to Inadequate Load Capacity

Vehicles with weight exceeding the posted load limit need to detour. In a deterministic scenario, each vehicle weight is known, thus the number of detouring vehicles can be determined easily. In reality, however, it is nearly impossible to know a-priori the individual weights of the vehicles. Therefore, a probabilistic approach is appropriate. If the vehicle weight distribution is known, the probability that the bridge user detours is determined as the shaded area under the probability density function (FIGURE 3). The percentage of vehicles that detour is represented by the probability that a vehicle weight exceeds the posted load limit.

\[ N_L(i) = \frac{ADT \times \text{Percentage}(i) \times ADT}{\text{Percentage}(i)} \]

For the vehicle type \( i \), the number of detouring vehicles that detour is calculated as:

\[ N_L(i) = P_L \text{ Percentage}(i) \times ADT \]  

where \( ADT \) = average daily traffic on the bridge; \( \text{Percentage}(i) \) = percentage of vehicle type \( i \); \( P_L \) is the probability that a vehicle weight exceeds the posted load limit, and is equal to \( \int_{W_{MIN}}^{W_{MAX}} f(w)dw \), where \( W_{MAX} \) is the maximum weight of type \( i \) vehicle and \( f(w) \) is the probability density function for weights, \( w \), of vehicle class \( i \).
Other variables have the same meanings as presented earlier.

Finally, in calculating the number of vehicles that detour due to inadequate load
capacity, it is important to recognize that the load capacity itself does not remain constant
over time. The combined and accumulated effects of truck loading, climate, and aging
culminate in deterioration, weakening, and consequently, reduction of bridge load
capacity in the long term. The load capacity of a bridge at any point in time within its life
could be determined mostly using deterioration models that predict load capacity at a
future year. In rare and specific instances, field tests have been used to determine load
capacity. Chen et al. (1) presented results of research on bridge load capacity
deterioration. Bridge load capacity can also be determined using structural analysis
software such as AASHTO’s Virtis (13), in conformance with AASHTO standards. The
current standard is AASHTO’s Load and Resistance Factor Rating Specifications (14). In
addition, it is important to note that the posted load limit during the workzone period may
be lower than that posted during the period of normal operations.

As may be recognized in the preceding section, estimating the number of
detouring vehicles (Equation (1)) hinges on the integrity of the vehicle weight
distribution function, \( f(w) \). Fekpe and Clayton (15) developed a model to predict the
heavy-vehicle weight distributions. Sobanjo and Thompson (8) analyzed the distribution
of truck weights at interstate and non-interstate highways in Florida and recognized that
the truck weight distributions differ from year-to-year and from place-to-place. FHWA’s
Office of Highway Policy Information maintains a Vehicle Travel Information System
(VTRIS) which contains data from weigh stations in 16 states and generates vehicle
weight distributions in different highway classes. For analyzing user costs at a given
bridge, a common vehicle weight distribution generated using data from a bridge with
similar traffic characteristics could be used for the analysis. However, the ideal situation
is to collect vehicle weight data at the bridge of interest and then develop a weight
distribution function specifically for that bridge.

**Detour Due to Inadequate Vertical Clearance**

Users of a highway passing on a bridge need to detour if their vehicle height exceeds the
vertical clearance limit, if any, over the bridge. Typically, this is limited to only a few
specific designed types or highway interchanges. Similarly, users on a highway passing
under a bridge need to detour if their vehicle height exceeds the vertical clearance limit
under the bridge. Additional information on bridge vertical clearance inadequacies are
found in the descriptions for Items 53 and 54 of the Recording & Coding Guide (16).

The number of vehicles that need to detour can be calculated as:

\[
N_{V}(i) = P_{V} \times \text{Percentage}(i) \times \text{ADT}
\]

where \( P_{V} \) is the percentage of vehicles whose height exceeds the bridge vertical
clearance, or the probability that the height of a prospective bridge user vehicle exceeds
the vertical clearance; other variables have the same meanings as presented in Eqn (1).

Similar to the case for load-related detours, not all trucks, trailers, and tractors are
affected by the vertical clearance limit: only a fraction of them typically need to detour
due to height limitations. The federal law does not set a height limit for trucks. However,
typical state standards for truck height limit range from 13.6 ft to 14.6 ft (12). There
seems to be no truck height data at the national level. However, at the state level, Sobanjo
and Thompson developed truck height distribution functions for Florida’s interstate and non-interstate highways (8).

**Detour Due to Inadequacies in Horizontal Clearance**

For users passing over or under a bridge, detour due to horizontal clearance limitations may be necessary (i) during normal operations if the bridge is narrow and (ii) during workzone periods when the operating traffic lanes on the bridge are narrowed to allow repair work to be carried out on the bridge. In both cases, if the available width of the bridge is smaller than the vehicle width, the vehicle detours. The number of detouring vehicles, which depends on the posted horizontal clearance and distribution of vehicle widths, can be calculated as follows:

\[
N_H(i) = P_H \times Percentage(i) \times ADT
\]

where \(P_H\) = the probability that the width of a road user’s vehicle exceeds the posted horizontal clearance or the percentage of vehicles whose width exceeds the posted horizontal clearance; other variables have the same meanings as in Equation (1).

**Detour Due to Poor Alignment**

In certain situations, large vehicle might not be able to maneuver safely in crossing a bridge. This typically occurs on bridge with poor approach alignment. In such cases, the highway agency often specifies the maximum length of vehicles that can use the bridge. Vehicles whose lengths exceed this limit will need to detour. For a given bridge, the number of vehicles that need to detour due to poor alignment can be calculated as:

\[
N_P(i) = P_P \times Percentage(i) \times ADT
\]

where \(P_P\) = the probability that the length of a prospective bridge user vehicle exceeds the vehicle length limit of the bridge or the percentage of vehicles whose length exceeds the vehicle length limit; other variables have the same meanings as presented in Equation (1).

**Detour Due to Workzone**

Due to repair activities associated with a bridge workzone, a bridge may have reduced load capacity and/or vertical clearance over or under the bridge compared to the normal operation period. Also, during workzones, the highway agency often imposes limitations on the length and width of vehicles that can use the bridge. In these situations, vehicles that do not meet these standards must detour. For calculating workzone user cost incurred by detouring vehicles due to each of these detour reasons, the procedure is similar to that presented in previous sections for normal operations. In the case where there is a bridge closure during the workzone, all vehicles need to detour. Even though the workzone period is of relatively short duration compared to normal operations of the bridge, detour costs at such periods can be critical in investment evaluation because large numbers of detouring vehicles at a workzone typically culminate in significant overall user cost.

**The Issue of Multiple-Counting in Detour Computations**

In practice, a vehicle may have excessive weight and height that violate the posted weight and height limits. Such vehicles will need to detour for these two reasons simultaneously. In estimating of the benefit of bridge replacement, Golabi et al. (9) considered the possible double-counting problem but did not do so for other improvement actions. In
most other studies, the user costs of detouring vehicles were calculated separately for
excess weight and for excess height, and summed to yield the total detour cost. In reality,
however, one detour may be due to both height and weight restrictions, causing double
counting. Similarly, when there are more than two reasons for detouring, there is a
possibility of multiple counting.

To illustrate our argument about the possibility of multiple counting and to avoid
consequent overestimation of user cost, we consider the following situations:

(a) Vehicles at a bridge detour for at least one of only two reasons: weight ($D_1$) and
height ($D_2$).

Traditional calculation: From FIGURE 4(a), 75 vehicles detour due to weight and
68 vehicles detour due to height. So overall, the traditional method, which does
not consider the double counting issue, suggests that 143 vehicles detour.

Proposed calculation: Noticing that 65 vehicles detour due to both reasons and
should not be double counted as done in the traditional calculation, it can be seen
that only 78 vehicles detour, overall.

Thus, failure to consider the issue of double counting in this example problem
leads to a significant number of vehicles being counted twice, resulting in a 120%
overestimation of the nr. of detouring vehicles and thus, of user cost.

(b) In this case, vehicles require a detour for at least one of three reasons: weight ($D_1$),
height ($D_2$) and width ($D_3$).

Traditional calculation: From FIGURE 4(b), 191 vehicles detour due to weight,
212 vehicles detour due to height, and 199 vehicles detour due to width. So, the
traditional method, which does not consider the triple and double counting issues
in this problem, suggests that 602 vehicles detour overall.

Proposed calculation: It can be noticed that 161 ($42+51+68$) vehicles detour due
to two reasons and should not be double counted as done in the traditional
calculation. Also, 71 vehicles detour due to three reasons simultaneously and
should not be triple counted as done in the traditional calculation. The figure
shows that only 299 vehicles actually detour.

Thus, failure to consider the issue of triple counting and double counting in this
example problem leads to a significant number of vehicles being counted twice or
thrice, resulting in 262% overestimation of the number of detouring vehicles and
thus, of user cost.

Where there are over three reasons for detouring, it is difficult to visualize
the problem and we herein use set theory to address this.

FIGURE 4 Multiple-counting illustration.
We now present a generalized approach to calculate the number of detouring vehicles while duly accounting for the issue of multiple counting. Based on the set theory (17), the number of detouring vehicles due to any one or more of \( n \) detour reasons can be derived as follows:

\[
N(D_1 \cup D_2 \cup \cdots \cup D_n) = \sum_{j=1}^{n} N(D_j) - \sum_{j<k}^{n} N(D_j \cap D_k) + \sum_{j<k<l}^{n} N(D_j \cap D_k \cap D_l) - \cdots + (-1)^n N(D_1 \cap D_2 \cap \cdots \cap D_n)
\]  

(5)

where \( N(D_j) \) is the number of detour due to reason \( D_j \).

\[
N(D_1 \cup D_2 \cup \cdots \cup D_n) = P(D_1 \cup D_2 \cup \cdots \cup D_n) * ADT
\]  

(6)

where \( P(D_1 \cup D_2 \cup \cdots \cup D_n) = \) the probability that a vehicle detours due to any one or more of \( D_1 \) to \( D_n \) factors. Equation (7), which is based on set theory, can be used to calculate the total percentage of vehicles that detour:

\[
P(D_1 \cup D_2 \cup \cdots \cup D_n) = \sum_{j=1}^{n} P(D_j) - \sum_{j<k}^{n} P(D_j \cap D_k) + \sum_{j<k<l}^{n} P(D_j \cap D_k \cap D_l) - \cdots + (-1)^n P(D_1 \cap D_2 \cap \cdots \cap D_n)
\]  

(7)

\( P(D_j) \) is the probability that a vehicle detours due to reason \( D_j \). \( P(D_1 \cap D_2 \cap \cdots \cap D_n) \) represents the probability that the vehicle detours due to all \( n \) reasons simultaneously. For example, if there are only two reasons for detouring (load capacity and vertical clearance), then

\[
P((w > PL) \cup (V > VC)) = P(w > PL) + P(V > VC) - P((w > PL) \cap (V > VC))
\]  

(8)

where the \( PL \) is the posted load limit and \( VC \) is the vertical clearance limit. The rest of the variables have the same meanings as presented for Equations (1) to (4).

Conditional probability theory is helpful for calculating \( P(D_1 \cap D_2 \cap \cdots \cap D_n) \).

For example, for the case where there are two reasons for detouring, the percentage of detouring vehicles, for vehicle type \( j \), is calculated as follows

\[
P((w > PL) \cap (V > VC)) = P(V > VC) - P((w > PL) \cap (V > VC))
\]  

(9)

or

\[
P((w > PL) \cap (V > VC)) = P(V > VC) - P((w > PL) \cap (w > PL))
\]  

(10)

Each variable has the same meanings as in Equation (8).

**Bridge User Delay Cost Due to Traffic Capacity Limitation**

Users of narrow bridges reduce speed at such facilities (4). As such, a narrow bridge can cause additional user cost due to speed reduction (and thus, increased travel time) during normal operations of the bridge (3). Also, during periods of bridge workzone, partial lane closure at the workzone location may reduce the bridge’s traffic capacity and incur extra travel time. Improvements such as bridge widening may increase the lane width or add lanes (18) and thus increase bridge traffic capacity. For a given traffic volume, when road capacity increases, the travel speed also increases (19). Thus, the user cost due to traffic capacity limitation can be expressed as the additional travel time cost due to speed reduction compared to a baseline or free-flow travel speed:
\[ TTC_{CL} = \sum_{i=1}^{m} \left( \sum_{k=1}^{24} \text{AddedTime}(k) \times ADT(k) \right) \times U_{TTC}(i) \] (11)

Where: \( U_{TTC}(i) \) is the unit travel time cost of vehicle class \( i \); \( ADT(k) \) is the traffic volume in the \( k^{th} \) hour; \( \text{AddedTime}(k) \), the added travel time during \( k^{th} \) hour (hours/vehicle), is calculated as follows:

\[ \text{AddedTime}(k) = BridgeLength \times \frac{\text{Speed}_{FreeFlow}(k)}{\text{Speed}_{Actual}(k)} \times \frac{\text{Speed}_{Actual}(k)}{\text{Speed}_{FreeFlow}(k)} \] (12)

Where: \( \text{Speed}_{FreeFlow} = \) free flow travel speed;
\( \text{Speed}_{Actual}(k) = \) actual travel speed in the \( k^{th} \) hour.

The actual travel speed can be derived from the Bureau of Public Roads function (19) as follows:

\[ \text{Speed}_{Actual}(k) = \frac{\text{Speed}_{FreeFlow}}{1 + a(V/C)^b} \] (13)

Where: \( a, b \) are parameters representing different highway classes and different speed limits (19); and \( V/C \) is the volume/capacity ratio for the \( k^{th} \) hour.

**Bridge User Cost due to Accidents**

The user cost due to accidents is calculated as the product of the expected number of accidents due to bridge deficiencies or workzone and the unit monetary cost of each accident. This, which can be done for each accident type, is consistent with the North Carolina Bridge Management System procedure (2, 9). Thompson et al. (6) also developed an enhanced bridge accident model that estimates annual accident rate as a function of number of bridge lanes, bridge length, road width, approaching alignment rating, deck rating, and traffic volume.

**Bridge User Cost due to Wearing Surface Roughness**

The condition of the bridge wearing surface can affect maintenance, repair, and depreciation cost of vehicles in the form of VOC. The bridge user cost due to wearing surface condition can be calculated as:

\[ U_{\text{Roughness}} = \sum_{i=1}^{m} \Delta U_{\text{Voc}(i)} * BridgeLength * ADT(i) * 365 \] (14)

Where: \( \Delta U_{\text{Voc}(i)} \) is the additional VOC due to wearing surface roughness for type \( i \) vehicle; \( ADT(i) = \) average daily traffic of type \( i \) vehicle.

For calculating additional VOC due to surface roughness, Barnes and Langworthy (21) developed a relationship between additional VOC and International Roughness Index (IRI) and suggested that

\[ \Delta U_{\text{Voc}(i)} = \begin{cases} 0 & \text{when } IRI < 80 \text{ in/mile;} \\ 0.05 U_{\text{Voc}(i)} & \text{when } 80 \text{ in/mile} \leq IRI < 105 \text{ in/mile;} \\ 0.15 U_{\text{Voc}(i)} & \text{when } 105 \text{ in/mile} \leq IRI < 140 \text{ in/mile;} \\ 0.25 U_{\text{Voc}(i)} & \text{when } IRI \geq 140 \text{ in/mile.} \end{cases} \]

where \( U_{\text{Voc}(i)} \) is the unit VOC cost of type \( i \) vehicle.
CASE STUDY

The applicability of the framework is demonstrated using a case study involving a steel bridge in the middle level of a three-level interchange. This is a one-way Interstate bridge ramp with 2 lanes, reconstructed in 1993. It is 21.3 m long, has 13.4 ft vertical clearance over the bridge and has a load capacity of 35.1 tons. Under the bridge, there is a 2-lane highway with vertical clearance of 14.1 ft. The detour length for the roadway over and under the bridge is 1 km. The 2004 ADTs over and under the bridge are 19,265 and 23,160 respectively.

To demonstrate the user cost calculation over the lifecycle, we assume that the bridge long-term preservation strategy follows a standard lifecycle profile in IBMS (11): deck replacement in the 20th year, 35th year, and 55th year; bridge replacement in the 70th year. Besides deck replacement in the 35th year, bridge widening and bridge raising are also performed (FIGURE 1). The bridge widening adds one lane and the bridge raising increases the vertical clearance under the bridge from 14.1m to 16.4m. During the rehabilitation in the 20th and the 55th years, the workzone is assumed to narrow the operational bridge width to one lane for a 3-month period. During the rehabilitation at the 35th year, the bridge is closed for a month and bridge width is reduced to one lane for a 2-month period.

A traffic growth rate of 2% is assumed over bridge life. As such, data on traffic volume and truck weight in Indiana were downloaded from FHWA VTRIS to yield the following distributions: passenger car – 61.22%; bus – 0.2; single unit truck – 24.18%; tractor trailer – 14.4%. In VTRIS, the vehicle weight information only contains weights data for buses and trucks. In this case study, the load capacity of the bridge is 35.1 tons – this is adequate for all automobiles. Thus, the vehicle weight information in VTRIS is enough for this case study to establish the relevant vehicle weight distribution for purposes of user cost estimation. In this case study, we only consider buses, single-unit trucks, and tractor-trailers. Using the EasyFit statistical software package (20), cumulative distributions for the weights of these vehicle classes were established as follows:

\[ F(x) = 1 - \left(1 + \left(\frac{x}{7.9555}\right)^{13.057}\right)^{0.23826} \]

\[ F(x) = 1 - \left(1 + \left(\frac{x}{2.7676}\right)^{3.9359}\right)^{0.23826} \]

\[ F(x) = (0.39985 + 1.34422\ln(x^{\frac{1.2982}{53.007}})) \]

where \( z = \frac{x}{53.007} \) and where \( \Phi \) is the Laplace integral.

For the vehicle height distribution, the findings of the Sobanjo and Thompson (8) study were used. That study provided height distribution functions for trucks on interstate highways: when the vertical clearance limit is 13–14ft, the percentage of trucks that detour is estimated using the function \((1.10E+56)x^{-48.683}\); when it is 14–16.1 ft, the percentage of trucks that detour is estimated by \(14.567-0.905x\), where \( x \) is the vertical clearance limit in feet. The vertical clearance over/under the bridge is adequate for passenger cars and buses, thus the height distribution of trucks only is considered in the
analysis. Over the bridge, since both the vertical clearance and the load capacity limit may cause detouring of trucks, there is a need to calculate the percentage of double counted trucks. In practice, it is difficult to determine the joint distribution of truck weights and heights. Fortunately, Sobanjo & Thompson (8) carried out a study that included field measurements of truck weights and heights simultaneously using Laser Range Finder and WIM stations in Florida. It is found that for trucks whose weight exceeds 35.1 ton, 18.5% have a height exceeding 13.4 ft. Given this conditional probability, Eqn (10) can be used to calculate the percentage of double-counted trucks.

The bridge load capacity deteriorates with age and the deterioration rate depends on the bridge superstructure/substructure condition (1). The current superstructure and the substructure condition ratings in 2008 are both 7. The IBMS Markov model is used to predict the superstructure and substructure condition ratings; and the load capacity deterioration rates established in part research (1) are used to determine the load capacity in future years. The unit user cost is derived from the Son and Sinha (3) study. In order to be comparable, all user costs in this study are in terms of 2010 US dollars.

The life-cycle bridge detour user cost (due to vertical clearance limit and load capacity limit, not including the detour due to bridge closure) over the bridge are presented in FIGURE 5(a). In the figure, it is seen that all types of detour user costs increase from year to year. This is mainly due to the increasing yearly traffic volumes which increases the number of detouring vehicles. It is also seen that the detour user cost due to the vertical clearance limit exceeds that due to the load capacity limit before year 2039 after which the opposite is the case. This is because the load capacity of the bridge deteriorates every year and thus causes higher percentage of vehicles to detour. However, the vertical clearance never changes, so the percentage of vehicles that have to detour due to vertical clearance does not change. As a result, more vehicles have to detour due to the load capacity limit than due to the vertical clearance limit after Year 2039. For purposes of demonstrating how the problem of multiple counting is addressed, FIGURE 5(a) also presents the double-counted detour user cost that is yielded by the traditional method if the detours due to load capacity and vertical clearance are calculated separately. The amount of double-counted detour user cost is about 18.5% of the detour user cost due to the load capacity limit.

FIGURE 5(b) presents the total detour user costs (due to the vertical clearance limit, load capacity limit, and bridge closure) over the bridge. It is seen that there is a significant gap in user cost between the case with double counting and that without doubling counting. This demonstrates the importance of addressing the double counting issue. It is also seen that while the user cost due to detour keeps increasing annually, there is a very high detour user cost in the 35th year: this is due to the bridge closure as work proceeds to raise and widen the bridge. This spike in user cost demonstrates the importance of considering workzone user cost in bridge investment analysis.

In fact, this case study has an additional detour due only to bridge closure in the workzone. Where the bridge also has a smaller load capacity limit and lower vertical clearance during the workzone period, additional vehicles may detour for those reasons, leading to even higher detour user costs during the workzone period.

FIGURE 5(c) shows that before the bridge raising in the 35th year (2028), the detour user cost due to vertical clearance increases every year (this is due to the
increasing traffic volume); after the vertical clearance under the bridge increases to 16.4ft, detour cost due to the vertical clearance limit under the bridge is eliminated.

The delay user cost due to limited traffic capacity over the bridge life is presented in FIGURE 5(d). It can be observed that the cost due to delay reduces after the bridge widening action in the 35th year (2028). It is also noted that there is a spike in delay user cost in the 20th year (2013), 35th year (2028) and the 55th year (2048). These are due to workzone construction in these years, further demonstrating the need to consider workzone user costs in life-cycle user cost calculations.
Comparing the charts in FIGURE 5(b) and (d), it is seen that the detour user cost is relatively small compared with the delay cost. While the large delay cost may be attributed to the use of the free flow speed as the base line, it is worth noting that the reduction of delay cost is much larger than that of detour user cost in the 35th year. It can be concluded that the bridge widening can yield significantly greater user cost reduction compared with the bridge raising, in this case study.

In presenting the evidence of the importance of considering user delay cost due to traffic capacity limitation, FIGURE 5(e) presents the case where there is no lane addition in the 35th year. It is seen that, the delay costs for both cases are the same before the 35th year. But after the 35th year, without adding one lane, the delay cost increase very rapidly. This is because if the traffic volume increases every year with a constant increase rate, the actual travel speed decreases every year at an increasing rate (can be derived from Equation (13)), thus the additional travel time (Equation (12)) increases at an even faster rate every year. As a result, the delay cost increases very rapidly. Comparing the two cases demonstrates the benefit of adding one more lane in the 35th year. This shows the significance of considering the user delay cost caused by the traffic capacity limitation.

**Conclusion**

This paper established a framework for comprehensive estimation of user cost for bridge investment evaluation by synthesizing existing practice and adding some new considerations. The paper identifies the issue of multiple counting in user cost estimation and provides a method to address this problem. The paper also addresses a gap in the literature by providing a methodology for including workzone consequences in bridge user cost estimation. Furthermore, the paper develops a method to estimate the user delay cost due to bridge traffic capacity limitation, a critical aspect of user cost that enables the estimation of bridge widening (lane-addition) benefits. Using a case study, the applicability of the framework is demonstrated. The results of the case study show that: the multiple counting bias can be addressed effectively; the user cost due to workzone can be significant; and estimating of delay user cost due to traffic capacity is necessary to capture the user benefits of bridge widening.

**REFERENCES**

12. FHWA. *FHWA Bridge Programs NBI Data.*