Policy-Making Tool for Optimization of Transit Priority Lanes in Urban Network

Mahmoud Mesbah, Majid Sarvi, Graham Currie, and Mahmoud Saffarzadeh

Transit improvement is an effective way to relieve traffic congestion and decrease greenhouse gas emissions. Improvement can be in the form of new facilities or giving on-road priority to transit. Although construction of off-road mass transit is not always viable, giving priority to transit can be a low-cost alternative. A framework is introduced for optimization of bus priority at the network level. The framework identifies links on which a bus lane should be located. Allocation of a lane to transit vehicles would increase the utility of transit, although this can be a disadvantage to auto traffic. The approach balances the impact on all stakeholders. Automobile advocates would like to increase traffic road space, and the total travel time of users and total emissions of the network could be reduced by a stronger priority scheme. A bilevel optimization is applied that encompasses an objective function at the upper level and a mode choice, a traffic assignment, and a transit assignment model at the lower level. The proposed optimization helps transport authorities to quantify the outcomes of various strategies of transit priority. A detailed sensitivity analysis is carried out on the relative weight of each factor in the objective function. The proposed framework can also be applied in the context of high-occupancy-vehicle lanes and heavy-vehicle priority lanes.

Many transit priority projects are assessed and implemented each year by road authorities and transport planning departments. Two recent examples in Australia are the Northern Busway in Brisbane (*1*) and the O-Bahn Busway in Adelaide (*2*). Transit priority projects are considered to be an effective solution to traffic congestion and growing greenhouse gas emissions. Having a higher capacity for moving people than do private cars, transit vehicles can increase average network speed by reducing car flow (*3*). Passengers will shift to transit vehicles only if the relative utility of transit compared with private cars is increased. Therefore, it can be desirable to reallocate road space in favor of transit. However, such an allocation would cause a disadvantage to auto users, who may protest prioritization. This trade-off is commonly faced by road authorities in all transit priority projects. This paper presents a mathematical framework for optimizing transit priority at the network level. A detailed objective function is presented that considers the benefit of private and public users as well as measures for emissions. Moreover, the consequence of variation in the relative weight of the terms used in the objective function is investigated. The proposed framework can be used to manage the existing transport network and helps transport authorities to meet the needs of all stakeholders using the network.

Whereas a wide range of studies have recommended criteria for allocation of a lane to bus vehicles, these can be divided into studies with local and network perspectives. Most studies have focused on a link or a corridor basis. Black et al. presented a model to evaluate several alternative road space allocations for a corridor (*4*). The total travel cost of users in the corridor was considered as the performance measure. In another attempt, Jepson and Ferreira assessed various road space priority treatments such as a bus lane and setbacks based on delays in two consecutive links (*5*). By using the concept of intermittent bus lanes (*6*), Eichler and Daganzo suggested an analysis method that is based on kinematic wave theory (*7*). This method can be applied to a long arterial. Currie et al. considered a comprehensive list of impacts of road space allocation (*3*), including travel time, travel time variability, initial costs, and maintenance costs, in a local priority project. Having compared the performance measures in the literature, they proposed an approach with which to evaluate transit priority projects.

These researchers focused on examining bus lane problems at the individual link level. Only a few researchers have considered the problem from a networkwide viewpoint. Waterson et al. represented a macrosimulation approach that evaluates a given priority scenario in the network of Southampton, United Kingdom (*8*). Their approach considered rerouting, retiming, modal change, and trip suppression. A similar evaluation approach was carried out with microsimulation by Liu et al. (*9*). Stirzaker and Dia used another microsimulation approach to evaluate a major bus lane project in Brisbane (*10*).

All these studies assessed a transit priority alternative (TPA). Despite the great level of detail in some studies, the evaluation reveals only whether a TPA (i.e., a set of bus-exclusive lanes) should be implemented. In contrast, Mesbah et al. formulated a bilevel optimization program to find the best alternative of bus lanes in a network (*11*). That method minimized the total travel time in the network for all users. In this paper, that general framework is completed by modification of the objective function to consider wider benefits of the stakeholders and synthesis of the effect of each benefit on the optimal TPA. Furthermore, a heuristic search method based on a genetic algorithm is adopted that enables the method to optimize medium and large-size networks.

The network is evaluated with a macrosimulation approach, which is much faster in analyzing the network than is microsimulation, especially for large-scale networks. This faster analysis time is critical because the network is evaluated several times in the process of optimization. It is impractical to find the optimal TPA in a large-scale network by using microsimulation.

M. Mesbah, M. Sarvi, and G. Currie, Institute of Transport Studies, Department of Civil Engineering, Monash University, Building 60, Clayton Campus, Victoria 3800, Australia. M. Saffarzadeh, Department of Civil Engineering, Tarbiat Modarres University, Jalal Ale Ahmad Highway, P.O. Box 14115-111, Tehran 14397, Iran. Corresponding author: M. Sarvi, majid.sarvi@eng.monash.edu.au.

Transportation Research Record: Journal of the Transportation Research Board, No. 2197, Transportation Research Board of the National Academies, Washington, D.C., 2010, pp. 54–62.
DOI: 10.3141/2197-07

BILEVEL OPTIMIZATION

Two levels of decision making are proposed for finding the optimal TPA. At the upper level, the transport authority would propose a TPA. Given this TPA, at the lower level system users would choose a strategy to maximize their own benefit under the prevailing conditions. Again, the transport authorities would modify the initial TPA on the basis of the behavior of users, and the cycle continues. This problem can be modeled as a Stackelberg competition, in which the transport authority is the leader firm and system users are the follower firms (*12*). The optimal TPA is chosen in equilibrium conditions when neither transport authority nor users can improve their benefits. The Stackelberg competition can thus be modeled as a bilevel optimization problem.

The upper level is articulated in accordance with the transport authority's point of view. Therefore, the system optimum is formulated in this paper for the upper level. For transit priority projects, the London Department for Transport (*13*) collected many of the priority impacts that were implemented by Currie et al. (*3*) to evaluate an exclusive bus lane project. Currie at al. used traffic microsimulation to evaluate a TPA (*3*); however, application of microsimulations are limited for large networks and in optimization. Therefore, a modified objective function is proposed in this study by using the results of a macrosimulation analysis.

The objective function takes into account the total travel time of car and transit users as well as other performance measures of the system, such as travel cost and emissions. There can also be a series of practical constraints for a priority scheme that is formulated in the constraints of the upper level. A comprehensive objective function and associated constraints are defined in the next subsection. The output of the upper level is the set of decision variables that define the location of the exclusive lanes.

User response to the decision made by transport authorities is modeled at the lower level. A macrosimulation model based on the traditional four-step transport planning is used. In this study, it is assumed that the total travel demand in the network is not changed by introduction of a TPA. Nevertheless, the shift of demand from one mode to the other is modeled. It is also assumed that two modes, private car and bus, use the network. Thus, the total demand is split between these modes. In the last step of planning, car and bus demand are assigned to network links. At the lower level for private cars and buses, a traffic assignment model and a transit assignment model are used, respectively. It is important to note that the TPA is determined at the upper level, whereas the objective function can be calculated in the lower level. The formulation of the lower level is discussed in the subsequent sections.

Notation

The following notation is used:

- A = set of all links in the network, $A = A_1 \cup A_2 \cup A_2'$;
- A_1 = set of links in the network where the provision of priority is impossible;
- A_2 = set of links with priority lane (with exclusive lane);
- A_2' = set of conjugate links with mixed traffic (no exclusive lane);
- B = set of links having a bus line, walking links, and transfer links;
- L = set of bus lines;
- I = set of bus stops;
- f_a = sum of frequency of service for all bus lines on link a;
- f_p = frequency of service for bus line p;
- l_a = length of link a;
- s_a = bus service time on link a, which is equal to running time plus dwell time at stops;
- $t_a^{c/b}(x)$ = travel time on link a by car c or bus b, which is a function of flow;
- w_i = total waiting time for users at node i;
- $x_a^{c/b}$ = passenger flow on link a by mode car c or bus b;
- bdg = available budget;
- exc_a = cost of implementation of an exclusive lane on link a;
- $\text{imp}^{c/b}$ = aggregate weight of operation costs of a car c or bus b to the community, including emissions, noise, accident, and reliability impacts;
- occ^c = average occupancy rate for the car mode;
- $\alpha, \beta, \gamma, \eta$ = weighting factors to convert the units and adjust the relative importance of each impact in the objective function, $\alpha, \beta, \gamma, \eta \geq 0$;
- ϕ_a = 1 if there is an exclusive lane on link a, 0 otherwise;
- $B_i^{+/-}$ = set of outgoing or incoming links (incoming with negative sign) from or to node i; and
- q_i^b = passenger demand at node i.

Upper-Level Formulation

The upper-level model is formulated as system optima from the transport authority's perspective. In this study, the objective function of Equation 1 is proposed to consider time and cost of travel by car and bus as well as impact of a TPA on environmental measures of the network. The upper level can be proposed as follows:

$$\min Z = \alpha \sum_{a\in A} x_a^c t_a^c(x) + \beta\left(\sum_{a\in B} x_a^b t_a^b(x) + \sum_{i\in I} w_i\right) + \gamma \sum_{a\in A} \frac{x_a^c}{\text{Occ}^c} l_a \text{imp}^c + \eta \sum_{a\in B} f_a s_a \text{imp}^b \quad (1)$$

subject to

$$\sum_{a\in A_2'} \text{exc}_a \phi_a \leq \text{bdg} \quad (2)$$

$$\phi_a = 0 \text{ or } 1 \qquad \forall a \in A_2 \quad (3)$$

$f_a = \sum_{p\in L} f_p \xi_{p,a}$ where $\xi_{p,a}$ is the bus line–link incident matrix, where ξ is 1 if link a is on bus line p, and $t_a^b(x)$ is the in-vehicle travel time.

The first term of the objective function is the total travel time by car; the second term represents the total travel time by bus, including access time, waiting time, and transfer time. The next two terms correspond to the cost of travel by car and bus. Coefficients $\alpha, \beta, \gamma, \eta$ can reflect different policies in the relative importance of each term. They also convert the units. As Equation 1 shows, the objective function is formed from the transport authority's perspective. The budget constraint is demonstrated in Equation 2.

There are two types of links in the network. The first is links on which no lane can be dedicated to buses. This type includes collector links and links with special considerations. The second type is the links that potentially can have an exclusive lane. In the network model, instead of each link in this type, two links are defined: one with and one without an exclusive bus lane (sets A_2 and A_2'). Decision variables determine which links would be in the real network. Only one of the links can be selected. Based on the set of decision variables in the upper level, flow and travel time are computed at the lower level.

Practical considerations can be embedded to the method as the upper-level constraints. For instance, it may be necessary to have continuity in a proposed bus lane in the network. This could be accounted for by adding a set of constraints to the upper-level formulation. These constraints are in the form of $\phi_2 + \cdots + \phi_n = (n-1)\phi_1$ to ensure that when ϕ_1 is 0, ϕ_2 to ϕ_n are 0 and when ϕ_1 is 1, all ϕ_2 to ϕ_n are 1. Heuristic algorithms are very flexible in solving the problem with complex constraints.

Lower-Level Formulation

Models at the lower level estimate user response to a given TPA. These models in the bilevel structure function as constraints to the optimization programming presented in the upper level. As a result of these models, flow and travel time are obtained.

It is assumed that the total travel demand in the network is not changed by introduction of a TPA. Therefore, the origin–destination (OD) matrix, resulting from the traffic distribution step, can be used in the lower-level models. This demand is divided into car and bus travel by using a mode split model, then car demand and bus demand are assigned to the network with traffic and transit assignment models, respectively.

The modal split model predicts the share of car and bus in travel demand. For this purpose, a logit model is applied (*14*). The model calculates a utility function for each mode of travel from its attributes. Then, the probability of traveling by a mode is found depending on the utility value. Since two modes of travel are available, two utility functions are used. Priority provision can shift the travel demand to use bus. A change in the decision variables changes the attributes of travel by each mode, which in turn can influence the mode share.

$$p^{c/b} = \frac{\exp\left(U^{c/b}\right)}{\exp\left(U^{c}\right) + \exp\left(U^{b}\right)} \tag{4}$$

$$U^{c/b} = a_0 + a_1 * X_1^{c/b} + a_2 * X_2^{c/b} + \cdots + a_n * X_n^{c/b} \tag{5}$$

where X_1, X_2, to X_n are the attributes of modes car c and bus b such as travel time and out-of-pocket costs, and a_0, a_1, to a_n are constant coefficients of the model.

Traffic assignment is the second model at the lower level. Traffic assignment is carried out by using a static user equilibrium (UE) model, which is a conventional model for strategic planning (*15*). This model finds car flow and travel time in the network with an optimization approach. The effect of the decision variables in the flow and travel time cannot explicitly be expressed; this is one of the reasons that a bilevel approach is proposed. The decision variables of the upper-level optimization would appear at the constraints of the UE formulation as follows:

$$\min Y = \sum_{a \in A} \int_0^{x_a^c} t_a^c(x)\,dx \tag{6}$$

subject to

$$\sum_k f_k^{rs} = q_{rs}^c \qquad \forall r, s \tag{7}$$

$$f_k^{rs} \geq 0 \qquad \forall k, r, s \tag{8}$$

$$x_a^c = \sum_{rs}\sum_k f_k^{rs}\delta_{k,a}^{rs} \qquad \forall (i, j) \in A \tag{9}$$

$$x_a^c \leq M\phi_a \qquad \forall (i, j) \in A_2 \tag{10}$$

$$x_a^c \leq M\left(1 - \phi_a\right) \qquad \forall (i, j) \in A_2' \tag{11}$$

where f_k^{rs} is the flow on path k connecting origin node r to destination node s, q_{rs} is the trip rate between r and s, and x_a^c is related to f_k^{rs} by the incident matrix $\delta_{k,a}^{rs}$, where δ is 1 if link a is on path k for any OD pair rs and 0 otherwise; M is a big-enough constant.

The optimization function is demonstrated in Equation 6, and Equations 7 through 11 show the constraints. Of the constraints, the first two are conservation of flow and nonnegativity constraints. The third (Equation 9) defines the relation of paths to links. The next two (Equations 10 and 11) prevent traffic flow on the links that ultimately would not be constructed. The decision variables on the right-hand side of Equations 10 and 11 bind the lower level to the upper-level formulation. Instead of each candidate link, two links are defined. The binding constraints ensure that only one of these coupled links would have a positive flow.

Transit assignment is the third model that assigns the bus demand to the transport network. Transit assignment implicitly expresses the effect of decision variables on transit flow and travel time. All the models proposed in the literature for transit assignment can be applied in this framework. Nevertheless, some binding constraints similar to Equations 10 and 11 should be added to their formulation. In this paper, a model based on that of Spiess and Florian is adapted (*16*).

$$\min W = \sum_{a \in B} x_a^b t_a^b + \sum_{i \in I} w_i \tag{12}$$

subject to

$$\sum_{a \in B_i^+} x_a^b - \sum_{a \in B_i^-} x_a^b = q_i^b \qquad \forall i \in I \tag{13}$$

$$x_a^b \leq f_a w_i \qquad \forall a \in B_i^+ \qquad \forall i \in I \tag{14}$$

$$x_a^b \leq M\phi_a \qquad \forall a \in A_2 \tag{15}$$

$$x_a^b \leq M\left(1 - \phi_a\right) \qquad \forall a \in A_2' \tag{16}$$

$$x_a^b \geq 0 \qquad \forall a \in B \tag{17}$$

To make the demonstration simple, it is assumed that the stops are located on the nodes. The first constraint is conservation of flow, and the second apportions the flow according to the frequency of links. Equations 15 and 16 are the mentioned binding constraints. The last constraint ensures nonnegativity of flow.

SOLUTION ALGORITHM

Bilevel structure even with linear objective functions and constraints at both levels is an NP-hard problem and is difficult to solve. In this study, a heuristic approach based on a genetic algorithm (GA) is

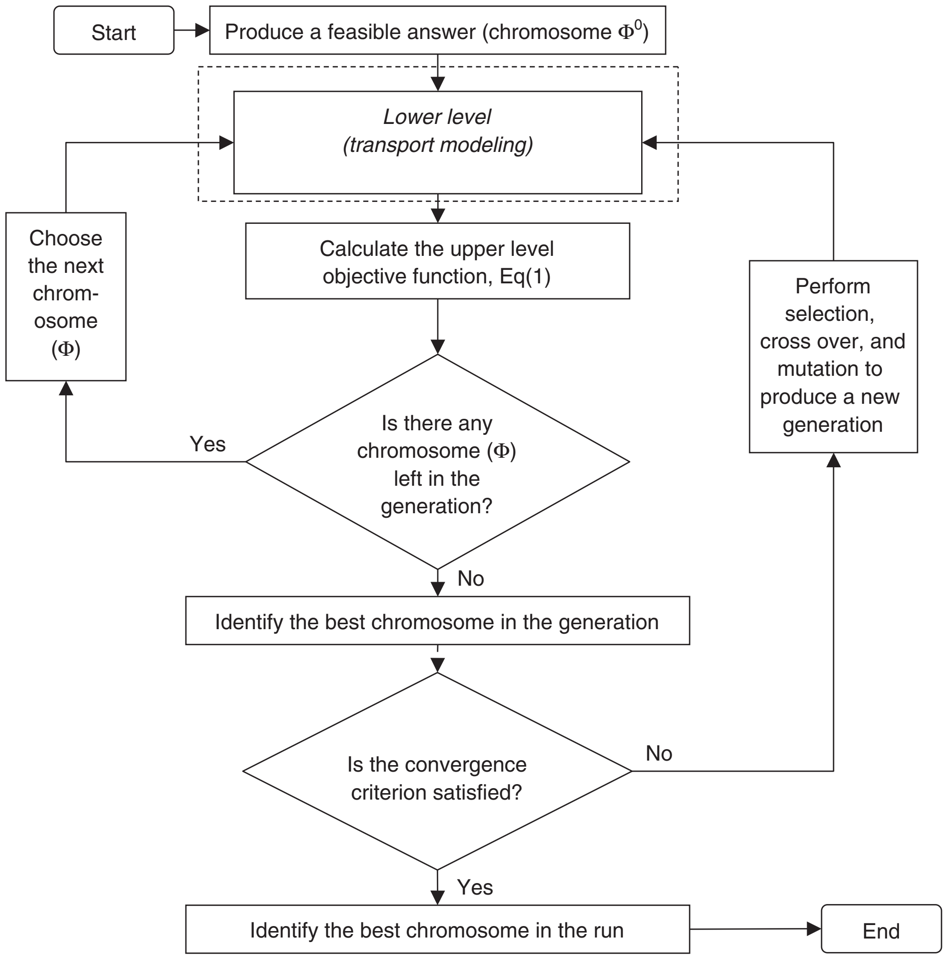

FIGURE 1 GA solution flowchart.

proposed in which the new answers are produced by combining two predecessor answers (*17*). Inspired by evolutionary theory in nature, GA starts with a feasible set of answers called a population (Figure 1). Each individual answer in the population (called a chromosome) is assigned a survival probability based on the value of the objective function. Then, the algorithm selects individual chromosomes based on this probability to breed the next generation of the population. GA uses cross over and mutation operators to breed the next generation, which replaces the predecessor generation. The algorithm is repeated with the new generation until a convergence criterion is satisfied. A number of studies applied GA to transit networks. Two recent examples are a transit network design problem that considers variable demand (*18*) and minimization of transfer time by shifting time tables (*19*).

To adopt GA to the concept of this study, a gene is defined to represent the binary variable ϕ and a chromosome to represent the vector of genes (Φ). A chromosome is equivalent to a TPA. A chromosome (or TPA) contains a feasible combination of links on which an exclusive lane may be introduced (set A_2). Therefore, the length of the chromosome is equal to the size of A_2. The algorithm starts with a feasible initial population. The chromosomes of the initial population are produced randomly. To ensure feasibility, according to the constraint represented in Equation 2, the cost of each chromosome is calculated. If the cost exceeds the budget, one of the genes with a value of 1 is changed to 0, and this continues until the cost becomes less than the budget.

Once a feasible chromosome population is produced, the upper-level objective function for all chromosomes can be determined. Each chromosome identifies the leader's decision vector for the network. It is the users' turn at the lower level to make use of the network. Thus, for each chromosome, the lower-level behavioral models are used, as depicted in Figure 1, which results in flow and travel time. The upper-level objective function for the chromosome is determined with the flow and travel time. The lower-level calculations are repeated for all chromosomes in the population (Figure 1).

The chromosomes with higher values of the objective function are assigned a higher survival probability. Then, GA operators of selection, crossover, and mutation are used to produce the next generation (set of TPAs). Similar to the process in the initial population, this process ensures the feasibility of the new generation. The new generation replaces the previous one and the calculations are repeated. Several tests on GA strategies for this problem revealed that to increase the convergence rate of the algorithm, the best chromosome of the last population should be kept in the chromosome pool. The algorithm stops when either the number of iterations reaches the maximum number of iterations or the best answer does not improve in a certain number of iterations. This cycle is also demonstrated in Figure 1.

NUMERICAL EXAMPLE

In this section, the proposed method is applied to an example network. Figure 2 shows the layout of the network. This grid network consists of 86 nodes and 306 links. All the circumferential nodes together with Centroids 22, 26, 43, 45, 62, and 66 are origin and destination nodes. A flat demand of 30 persons/h is traveling from all origins to all destinations. The total demand for all the 36 origin destinations is 37,800 persons/h. Ten bus lines cover the network, as shown in Figure 2. The frequency of service for all the bus lines is 10 min. The models and parameters used in this example are extracted from those calibrated for the Melbourne integrated transport model by Department of Transport, Victorian government (*20*).

Vertical and horizontal links are 400 m long with two lanes in each direction and a speed limit of 60 km/h. It is assumed that if an exclusive lane is introduced on a link, it would also be introduced in the opposite direction of the link. There is a total of 120 links (60 links, two directional) in the network of Figure 2 on which an exclusive lane can be introduced. These links are shown in bold in Figure 2. The following Akcelik cost function is used for the links cost function (*21*):

$$t_{1,a}^{c} = t_{0,a} + \frac{3{,}600a}{4}\left[\left(\frac{x_a^c}{\mathrm{cap}_{0/1,a}^c}\right) - 1 + \sqrt{\left(\frac{x_a^c}{\mathrm{cap}_{0/1,a}^c} - 1\right)^2 + \frac{8b}{ad}\left(\frac{x_a^c}{\mathrm{cap}_{0/1,a}^c}\right)}\right] \tag{18}$$

where

t_0 = travel time with free-flow speed,
a = length of observation period,
b = constant, and
d = lane capacity.

It is assumed that each link has two lanes and

$$\begin{aligned} v_0 &= 36 \text{ km/h}, \\ a &= 1 \text{ hr}, \\ b &= 1.4, \\ d &= 800 \text{ veh/h}, \\ \mathrm{cap}_{0,a}^c &= 1{,}800 \text{ veh/h, and} \\ \mathrm{cap}_{1,a}^c &= 900 \text{ veh/h}. \end{aligned}$$

(cap is capacity.)

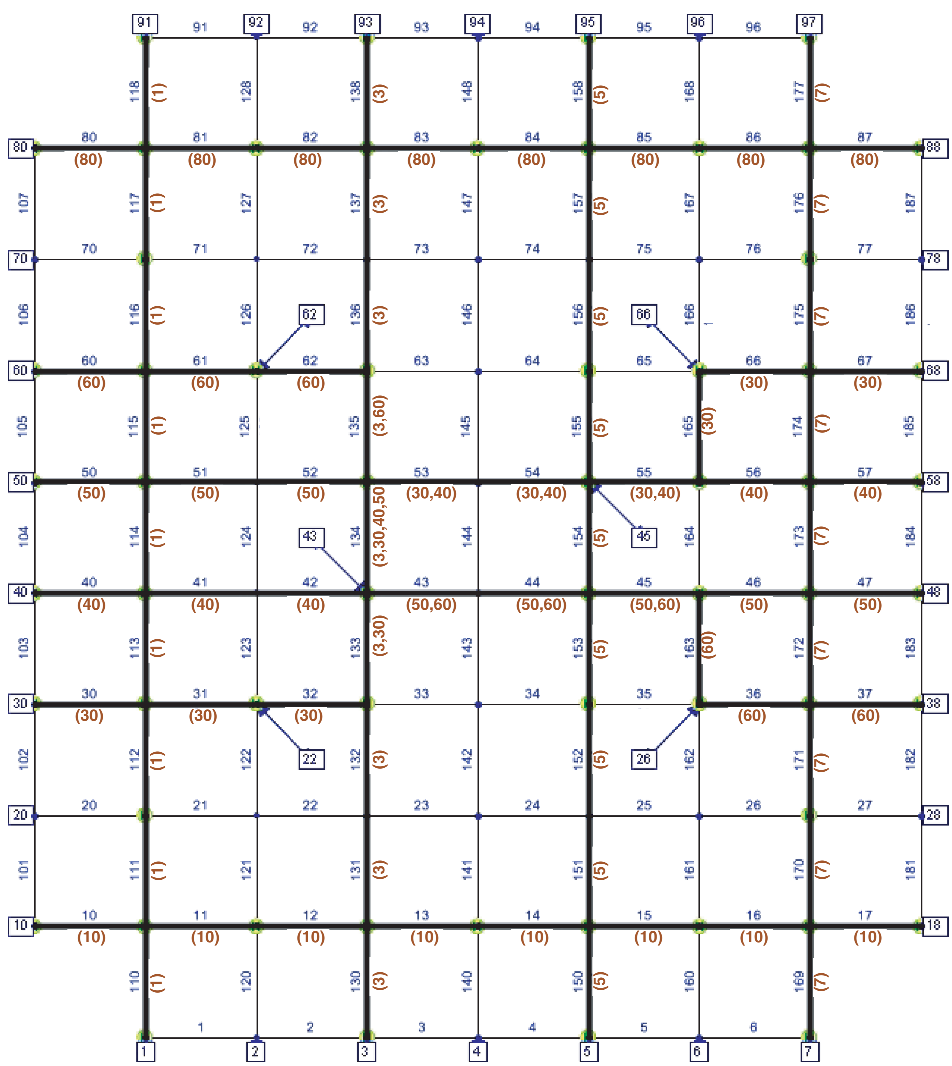

FIGURE 2 Example network (O-D nodes are in boxes; bus lines are in parentheses).

Mode share is determined by using a logit model (Equations 4 and 5). In Equation 5, the average travel time (X_1) and distance (X_2) between OD node pairs are considered for mode attribute. It is also assumed that

$$U^c = -2 - 0.2731 * X_1^c - 0.2235 * X_2^c$$

$$U^b = -3.9 - 0.1300 * X_1^b$$

Once the demand matrices are determined, car demand is assigned with UE and bus demand is assigned with a frequency-based assignment. It is assumed that bus frequencies are fixed in this example. The feedback process from assignment to modal split is performed to adjust the assumed attributes in the modal split. The convergence criterion of the feedback process is set on the difference of the travel time on a link from its travel time in the last iteration. The lower-level transport model is implemented with the VISUM modeling package (*22*).

The upper-level objective function includes total travel time (veh/s) and total vehicle distance (veh/km). The absolute value of the objective function therefore can be very large. To avoid numerical problems, the improvement of each term compared to a base case is considered instead of the absolute value of the term in the objective function. This does not change the optimal answer since a constant is subtracted from the objective function. The base case is assumed to be the case where no link is provided with an exclusive lane ($\Phi = 0$). For constraints, it is assumed that budget allows for all candidate links for the provision of bus priority.

A common stopping criterion for GA is the number of generations. If the objective function does not improve for a considerable number of generations, the calculations are terminated. In this example, the number of generations is increased to 2,000 to investigate an appropriate stopping criterion. This test showed that the objective function did not improve after 800 generations, which is adopted as the stopping criterion for this example. However, a test with this stopping criterion takes more than 3 days to run on a normal desktop computer, which is not practical for performing a sensitivity analysis. A relaxed stopping criterion of 200 iterations reduced the execution time to just over 1 day with less than 5% compromise on the objective function. The TPAs resulted after 200 and 800 iterations are different only in a maximum of three of 60 decision variables. This tolerance is acceptable for studying the sensitivity of the weighting factors of the objective function. Furthermore, values of population size, crossover probability, and mutation probability are found to be 40, 0.98, and 0.05, respectively. The adjustment of these parameters is outside the scope of this paper.

SENSITIVITY ANALYSIS

There are four terms in the upper-level objective function, and a weighting factor is associated with each term, namely, total travel time by car, total travel time by bus, total travel distance by car, and total service time by bus. An increase in α, γ, η or a decrease in β would lead to a stronger priority scheme. Transport authorities can solve the trade-off between the benefits of cars and public transport sectors by tuning these weighting factors. This section demonstrates how sensitive the optimal answers are to the value of the weighting factors.

The starting point is to assume that all the factors are equal. Application of the proposed method to the network of Figure 2 resulted in introduction of an exclusive bus lane on the following 22 links: 31, 32, 36, 41, 43, 44, 45, 53, 54, 55, 56, 61, 62, 66, 131, 132, 133, 134, 135, 136, 137, and 154.

This answer is anticipated since it includes all links on which two or more bus lines were traveling (134, 43, 44, 45, 53, 54, 55, 133, 135). It also includes Links 131 to 136, which make up the busiest north–south bus corridor and exclude outer links with low bus patronage, such as 11 to 16 and 111 to 117. The following subsections discuss the effect of variation of weighting factors.

Variation in Alpha

The effect of variation in the weighting factor of total travel time by car (α) is explored in this section. Figure 3 illustrates the number of links with a bus lane in the optimal answer when alpha is changed from 0.1 to 4. For alpha values of less than 0.7, no exclusive lane should be introduced in the network that shows an immense bias toward car usage. Alpha values larger than 2 would result in the

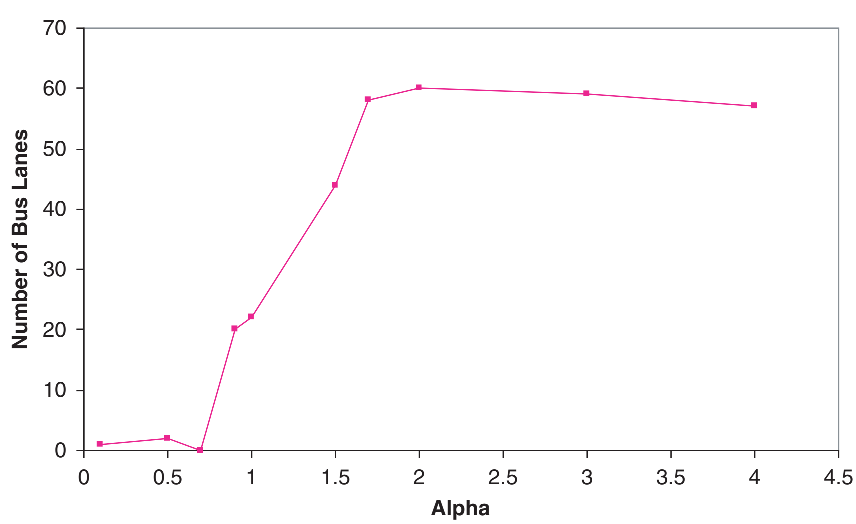

FIGURE 3 Effect of variation in alpha on priority scheme.

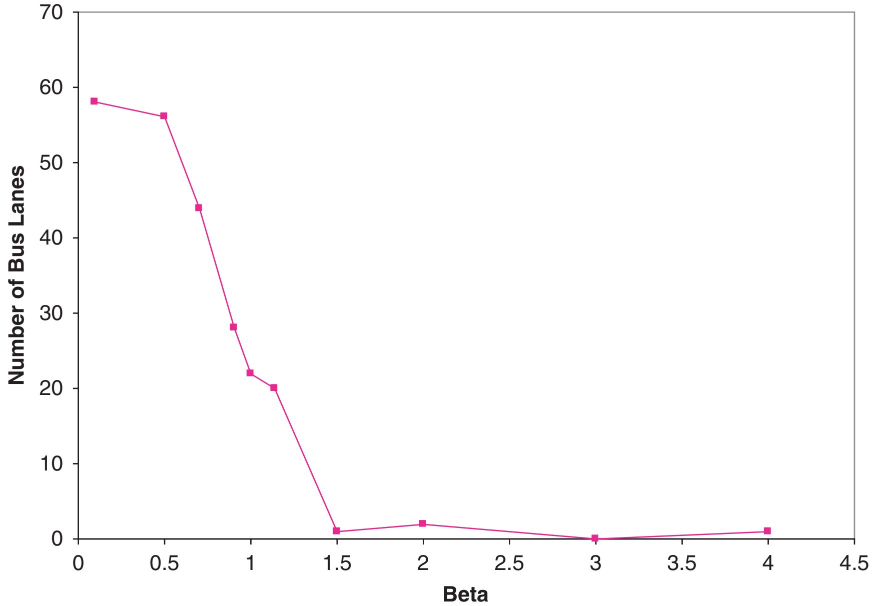

FIGURE 4 Effect of variation in beta on priority scheme.

introduction of a bus lane on every possible link. As mentioned, small fluctuations in the preceding ranges are due to the stopping criterion of 200 iterations. Should the number of iterations be increased to 800, a smoother graph would be obtained.

Variation in Beta

This section investigates the effect of change in the weighting factor for total travel time by bus (β). Figure 4 shows the number of links with a bus lane in the optimal answer when beta is changed from 0.1 to 4. Beta values larger than 1.5 would result in no bus lane in the network; for beta values less than 0.1, all possible links should get a bus lane. A comparison of Figures 3 and 4 confirms that the effect of beta on the results is opposite to the effect of alpha.

Variation in Gamma

The effect of modification of the weighting factor of the total travel distance by car (γ) is studied in this section. Travel distance by car for some users may increase by an increase in the space allocated to buses. This is because car users may shift from a congested route with a bus lane to an alternative route that is less congested. In the UE before provision of bus lane priority, this alternative route was longer and therefore was not originally on the shortest path. Nevertheless, after roadpace reallocation, this alternative route may become attractive. The results of the sensitivity analysis showed that although the travel distance of some users may increase, the total travel distance decreases because the number of users by car is reduced. This secondary effect in the mode shift outweighs the original effect in the route choice by car users. Figure 5 demonstrates the number of links with a bus

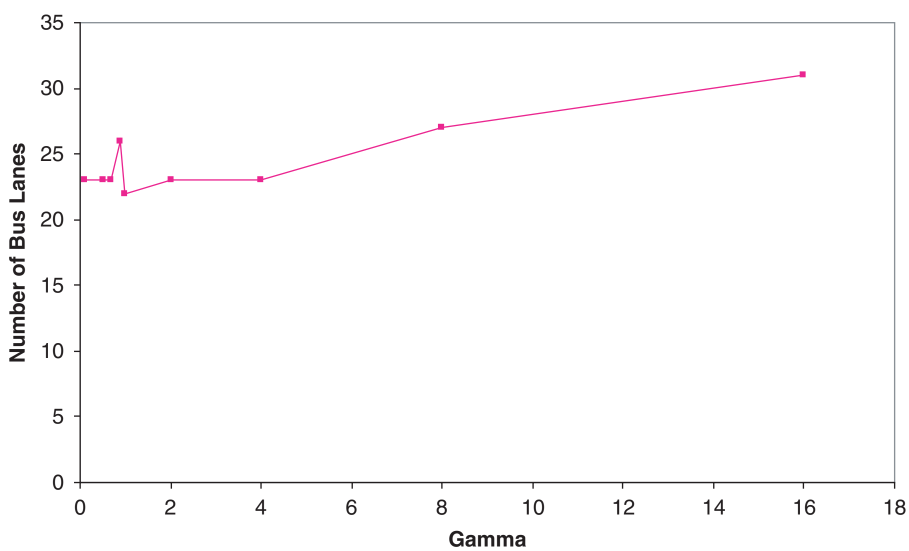

FIGURE 5 Effect of variation in gamma on priority scheme.

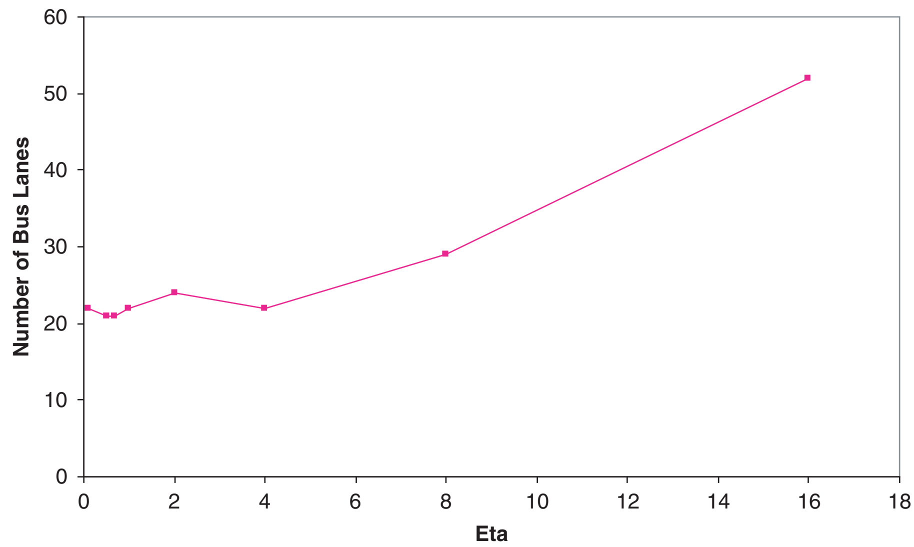

FIGURE 6 Effect of variation in eta on priority scheme.

lane in the optimal answer when gamma is changed from 0.1 to 16. For gamma values less than 4, the distance term does not change the optimal answer. After this point, the number of links with a bus lane in the optimal answer starts to increase.

Variation in Eta

This section discusses the effect of variation in the weighting factor of the total service time by bus (η). Transit operators are interested in reducing this measure because it reduces operating cost and emissions. With a faster service time, a more frequent bus line can be provided that requires the same number of buses and drivers. The more bus lanes, the lower the total service time. Figure 6 depicts the number of links with a bus lane in the optimal answer when eta is changed from 0.1 to 16. Similar to the effect of gamma, only eta values larger than 4 affect the number of bus lanes in the optimal answer. For eta values less than 4, the effect of total travel time is dominant.

Changes in Alpha and Beta Versus Gamma and Eta

This section investigates the combined effect of a change in the weighting factor of the total travel time (α, β) while the weighting factors for total travel distance and total service time (γ, η) are constant and equal to 1. The number of links with a bus lane in the optimal answer when $\alpha = \beta$ is changed from 0.1 to 16 is demonstrated in Figure 7. For $\alpha = \beta > 1$, the effect of the third and fourth terms of the objective function would be negligible. In this case, the optimization is carried out merely based on the total travel time terms. Since the ratio of α/β in all these optimizations is the same, the optimal answer for this category does not vary. However, for $\alpha = \beta > 1$,

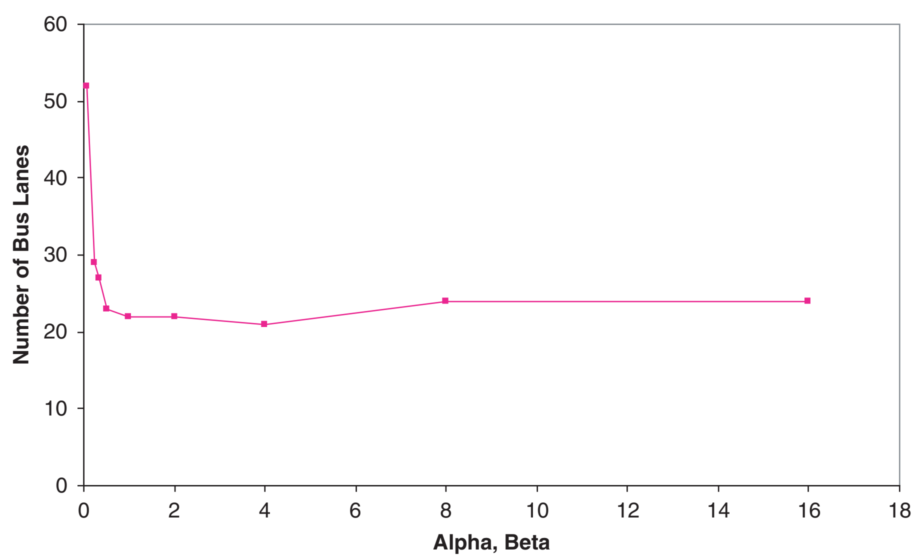

FIGURE 7 Effect of variation in alpha and beta on priority scheme.

the third and fourth terms of the objective function would start to affect the optimal answer. Transport authorities are to decide on the final value of the weighting factors. Should the Department of Transport's vision and the initiatives place high importance on the emissions and operational costs, α and β of 0.5 to 0.2 are recommended. But if users' travel time is the key variable, α and β should be greater than or equal to 1.

CONCLUSION

A bilevel formulation was proposed to optimally reallocate transit priority in a transport network. A method is needed to reflect various policies in transit priority. The upper-level formulation is system optima from the transport authority's perspective along with budget and practical constraints. The detailed objective function consists of total travel time of car and transit users, total distance traveled by cars, and total service time by transit vehicles. The lower level is a modified four-step model for predicting user behavior. It consists of a mode choice, traffic assignment, and transit assignment model. A binary decision variable determines whether a bus lane is introduced on a link. An efficient solution algorithm based on a GA was applied to solve the bilevel optimization. A large-scale network was tested with cars and bus services. This optimization was solved for a wide range of scenarios depending on the transport authority's perspective. The effect of each term of the objective function was elaborated by a sensitivity analysis. The results revealed that if the objective function chosen is total user travel time, a medium transit priority is achieved. Stronger transit priority outcomes result when more terms, such as total travel distance, are taken into account. The approach presented can be used as a tool to help transport managers make transit priority policies while considering a network perspective.

REFERENCES

1. Stewart, D., A. De Aboitiz, and T. Peglas. *Planning and Investigation of the Airport Link Tunnel and Northern Busway, Brisbane.* Australasian Institute of Mining and Metallurgy, Melbourne, Australia, 2008.
2. Rogers, L. H. O-Bahn Busway: Adelaide's Experience. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1791,* Transportation Research Board of the National Academies, Washington, D.C., 2002, pp. 1–5.
3. Currie, G., M. Sarvi, and B. Young. A New Approach to Evaluating On-Road Public Transport Priority Projects: Balancing the Demand for Limited Road-Space. *Transportation,* Vol. 34, No. 4, 2007, pp. 413–428.
4. Black, J. A., P. N. Lim, and G. H. Kim. A Traffic Model for the Optimal Allocation of Arterial Road Space: A Case Study of Seoul's First Experimental Bus Lane. *Transportation Planning and Technology,* Vol. 16, No. 3, 1992, pp. 195–207.
5. Jepson, D., and L. Ferreira. Assessing Travel Time Impacts of Measures to Enhance Bus Operations. Part 2: Study Methodology and Main Findings. *Road and Transport Research,* Vol. 9, No. 1, 2000, pp. 4–19.
6. Viegas, J., and B. Lu. The Intermittent Bus Lane Signals Setting Within an Area. *Transportation Research Part C,* Vol. 12, No. 6, 2004, pp. 453–469.
7. Eichler, M., and C. F. Daganzo. Bus Lanes with Intermittent Priority: Strategy Formulae and an Evaluation. *Transportation Research Part B,* Vol. 40, No. 9, 2006, pp. 731–744.
8. Waterson, B. J., B. Rajbhandari, and N. B. Hounsell. Simulating the Impacts of Strong Bus Priority Measures. *Journal of Transportation Engineering,* Vol. 129, No. 6, 2003, pp. 642–647.
9. Liu, R., D. Van Vliet, and D. Watling. Microsimulation Models Incorporating Both Demand and Supply Dynamics. *Transportation Research Part A,* Vol. 40, No. 2, 2006, pp. 125–150.
10. Stirzaker, C., and H. Dia. Evaluation of Transportation Infrastructure Management Strategies Using Microscopic Traffic Simulation. *Journal of Infrastructure Systems,* Vol. 13, No. 2, 2007, pp. 168–174.
11. Mesbah, M., M. Sarvi, and G. Currie. New Methodology for Optimizing Transit Priority at the Network Level. In *Transportation Research Record: Journal of the Transportation Research Board, No. 2089,* Transportation Research Board of the National Academies, Washington, D.C., 2008, pp. 93–100.
12. Yang, H., and M. G. H. Bell. Models and Algorithms for Road Network Design: A Review and Some New Developments. *Transport Reviews,* No. 18, 1998, pp. 257–278.
13. *Keeping Buses Moving: A Guide to Traffic Management to Assist Buses in Urban Areas.* Department of Environment Transport and the Regions, London, 1997.
14. Ortúzar, J. d. D., and L. G. Willumsen. *Modeling Transport,* 3rd ed. John Wiley and Sons, New York, 2001.
15. Sheffi, Y. *Urban Transportation Networks: Equilibrium Analysis with Mathematical Programming Methods,* Prentice–Hall, Englewood Cliffs, N.J., 1984.
16. Spiess, H., and M. Florian. Optimal Strategies. A New Assignment Model for Transit Networks. *Transportation Research Part B,* Vol. 23, No. 2, 1989, pp. 83–102.
17. Russell, S. J., and P. Norvig. *Artificial Intelligence: A Modern Approach,* 2nd ed. Prentice–Hall, Upper Saddle River, N.J., 2003.
18. Fan, W., and R. B. Machemehl. Optimal Transit Route Network Design Problem with Variable Transit Demand: Genetic Algorithm Approach. *Journal of Transportation Engineering,* Vol. 132, No. 1, 2006, pp. 40–51.
19. Cevallos, F., and F. Zhao. Minimizing Transfer Times in Public Transit Network with Genetic Algorithm. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1971,* Transportation Research Board of the National Academies, Washington, D.C., 2006, pp. 74–79.
20. *Melbourne Multi-Modal Integrated Transport Model (MITM): User Guide.* Department of Infrastructure, Melbourne, Victoria, Australia, 2004.
21. Akcelik, R. Travel Time Functions for Transport Planning Purposes: Davidson's Function, Its Time-Dependent Form and an Alternative Travel Time Function. *Australian Road Research,* Vol. 21, No. 3, 1991, pp. 49–59.
22. *VISUM 11 User Manual.* PTV AG, Karlsruhe, Germany, 2009.

The Transportation Network Modeling Committee peer-reviewed this paper.