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Article

Development and Evaluation of an Economic-Driving Assistance Program for Transit Vehicles

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Abstract: This paper focuses on development and evaluation of an economic-driving assistance program for transit vehicles (EDTV) which can minimize energy consumption, air pollution emission of buses, and improve the level of service of transit system as well. Taking advantage of the latest advances in information and communication technologies, the EDTV system can provide bus drivers with optimal recommended bus holding times at near-side bus stops and dynamic bus speed to adapt to the real-time traffic control plan at downstream intersections. In order to address the impacts of the stochastic variation of bus dwell time, the total link between adjacent intersections is divided into three parts: upstream of bus stop part; bus stop part; and downstream of bus stop part. The methods for calculating recommended parameters, including bus holding time and bus speed in each of the three parts are proposed based on real-time bus status and signal status at downstream intersections. A VISSIM-based simulation platform was designed and used for simulating and evaluating the proposed EDTV system. Extensive experimental analyses have shown that the proposed EDTV system can improve the performance of a transit system in terms of reducing fuel consumption, air pollution emissions and level of service of the transit system.

Keywords: economic-driving; energy efficiency; bus signal priority; speed adjustment

1. Introduction

The transportation system is one of most significant users of energy. Encouragement of transit system usage is one known strategy for reducing traffic that some suggest is second only to a complete driving ban in its potential for reducing energy use [1]. Especially, with the blooming of the Chinese economy in recent years, the traffic volume in Chinese cities has increased rapidly. Traffic congestion, accompanied by large amounts of fuel consumption appear nearly everywhere, more seriously in major cities such as Beijing and Shanghai. Giving transit priority is a worthy societal objective. With the enlargement of transit networks, an increasing number of literatures have focused on techniques to improve the service quality of transit systems.

The quality of transit bus service concerns both operators and users. Bus routes may have many stops and signals which affect bus movements and operational efficiency. The need to control bus movements along bus routes arises because their headways are unstable. As a result, lots of research has focused on bus operation control techniques. Using empirical data Abkowitz and Engelstein examined transit running times at various times of the day, in different directions of travel, and at different points along routes in Cincinnati (OH, USA). They found that transit running times are highest and most variable during the afternoon peak period. Regardless of time period, it is apparent that variation in running times increases with distance from route origin so that service deteriorates as the vehicle proceeds downstream [2]. An analysis of bus travel times and speeds was conducted in a cross section of U.S. cities by Levinson in 1983 [3]. Three basic analyses were conducted: (a) bus and car speeds were compared; (b) bus travel times and delays were estimated from various field studies; and (c) bus travel times were derived based on dwell time, traffic congestion, actual acceleration and deceleration rates, and distance between stops.

In order to decrease bus delay at intersections and improve reliability of transit system, a handful of studies have proposed transit signal priority (TSP) strategies and documented the benefits of TSP implementations [4–6]. These studies on signal priority strategies can be broadly divided into three categories: passive priority strategy; active priority strategy and real-time priority strategy; and various methodologies including experimental, simulation-based or theoretical analysis methods. Many traffic signal control systems have bus priority logic embedded in their software. Such systems provide signal priority at the local or the system level. The SCATS system [7] transit priority logic includes green extension, special phase sequences, and compensation to the non-transit phases. The SCOOT system [8] grants priority to buses (phase extension and recall) on the basis of user-specified intersection degree of saturation to avoid excessive delays to the rest of the traffic. Field evaluations in London showed bus delay savings ranging from 5 to 10 s per signal with no disadvantage to the rest of the traffic [9]. The UTOPIA system in Turin, Italy [10], is an adaptive control system that provides absolute priority to transit by continually optimizing the signal settings over a short time interval (rolling horizon). Reported benefits include a 20% increase in the average bus speeds without disadvantages to the rest of the traffic.

Most previous work has focused merely on optimizing signal timings or operation control strategies independently and treated bus speed as an exogenous input that was quantified by roadway speed limit or some constant values determined by local practices. In reality, real time bus speed is a function of several factors, including bus driver behavior, bus characteristics, and impacts of upstream signals and traffic conditions, even with an exclusive bus lane. The departure of the constant speed values used in these algorithms from real bus speeds may consequently result in low TSP efficiency or even TSP system failure. Bus speed determines the time duration of a bus traveling the distance between the upstream intersection (and bus detectors) and the downstream intersection. The time duration is a critical component of TSP strategy optimization algorithms. Therefore, different real bus speeds would require different transit priority signal timings, even under the same traffic conditions. Besides bus speed and bus dwell time at near side bus stop, the bus holding time at near side bus stop also have significant impacts on bus arrival time at downstream intersections.

Although speed is very important both for efficiency and safety of all traffic systems, including transit systems, and the potential benefit of integrated optimization of speed and signal plan were revealed [11,12], technical difficulties in reliable bus speed detection and real time communications between buses and traffic controllers may have been obstacles to the use of time-dependent changeable bus speeds in transit signal prioritization. As technologies continue to mature, Connected Vehicle systems have progressed significantly and changed the way we design transit signal priority systems, including traffic sensing and traffic signal operations design [13]. While traditional video and in-pavement detectors can generally provide information about vehicle presence, Connected Vehicle technologies allow vehicles to transmit a much broader range of information to controllers, such as real time vehicle locations, bus schedule deviations and speeds, and the control parameters can also be transmitted back to buses. This capability in turn makes it feasible to vary bus speed based on the needs of transit system optimization.

Moreover, very limited literatures have addressed the problem about how to decrease bus fuel consumption and air pollution emissions using either bus operation control strategies or transit signal priority control strategies. However, the fuel consumption of bus systems is a very important part of total fuel consumption of the transportation system. The speed and stops of vehicles are both critical factors which affect bus fuel consumption and air pollution emission [14]. Stops per distance (stops per mile) is also a very important metrics to estimate fuel consumption and emission. Evaluation of speed control system also validated that the fuel consumption and emissions can be decreased by proper speed guidance, and the fuel consumption decreases with the decrease of number of stops per distance [15]. To address the issues proposed above, this research focuses on developing an economic-driving assistance system for transit vehicles (EDTV) which can minimize energy consumption, air pollution emission of buses, and improve the level of service of the transit system as well. Taking advantage of the latest advances in information and communication technologies, EDTV integrates two bus operation control strategies, holding control at bus stop and dynamic speed control and provides bus drivers with optimal recommended bus holding times at near-side bus stop and dynamic bus speeds to adapt the real-time traffic control plan of downstream intersections. The developed system can:

(1) Minimize fuel consumption of transit vehicles while improving the level of service of transit systems;
(2) Capture explicitly the dynamic interaction between bus speed, bus holding time, bus dwell time and signal timings at downstream intersections; and

(3) Optimize bus holding times and recommend bus speed dynamically with respect to real time signal status and bus arrivals.

The paper is organized as follows: the basic structure of the proposed approach is presented in the next section. The logic designed for integrated optimization of dynamic bus speed and holding time at near side bus stop is outlined in Section 3. A case study is described in Section 4 to demonstrate the effectiveness of the proposed EDTV system and perform sensitivity analysis on critical factors that may affect model performance. Conclusions and recommendations are given at the end of the paper.

2. Basic Concept and Framework of EDTV

The key feature of the control concept of this paper is integrated optimization of bus speed and bus holding time at near side bus stops. Bus speed and bus holding time at near side bus stops determines the time when the bus arrive at the stop line of an intersection after being detected. This time element is a critical factor which decides whether a bus should stop at the stop line of a downstream intersection after passing a near side bus stop. Hence, different speeds and different bus holding times would result in different fuel consumption status for the same bus and the same background signal timings.

Figure 1. Interaction of bus speed and bus holding time.

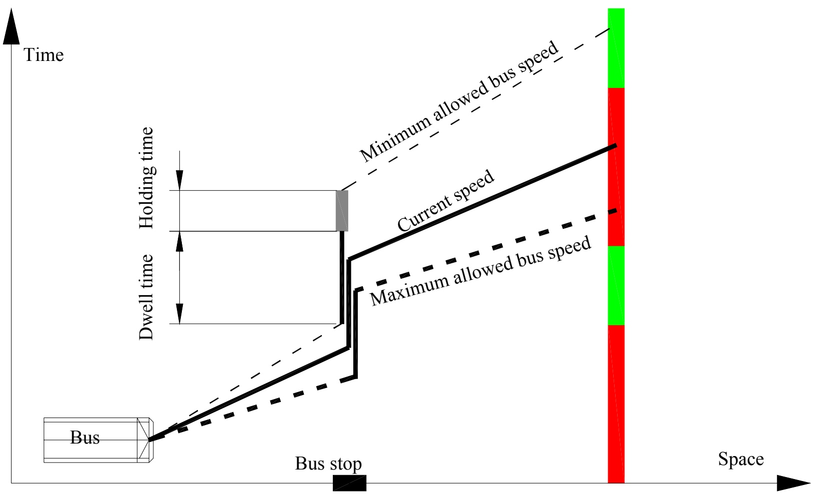
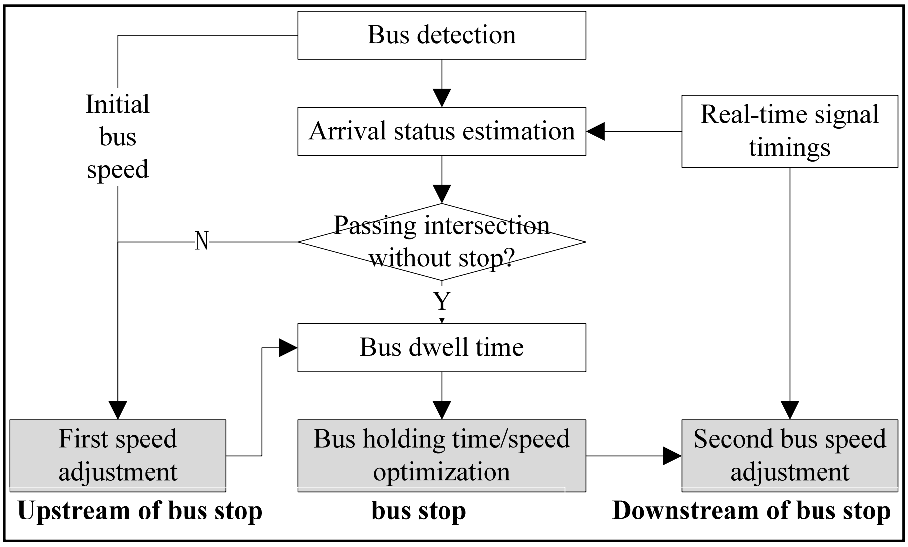


Figure 1 illustrates the basic concept of the proposed EDTV system. With the help of real-time communication between buses and traffic controller (e.g., through Connected Vehicle) technologies, current bus speed and background signal timings can be collected and sent to the EDTV as soon as a bus enters into the link between the two adjacent intersections. As shown in Figure 1, changes of either bus speed or bus holding time at the near side bus stop or both of them can change the bus arrival status at the downstream stop line, e.g., stopping or passing.

Besides bus speed and bus holding time, bus dwell time is another factor which affects the arrival time of bus at downstream intersections as shown in Figure 1. The dwell time is usually determined by the number of passengers which usually is a random number. In order to take the stochastic feature of bus dwell time into consideration, the total link between adjacent intersections is divided into three parts: upstream part; bus stop part; and downstream part, and the EDTV system consists of three methods accordingly: bus speed optimization model upstream of the bus stop; holding time optimization model at the bus stop; and bus speed adjustment model downstream of the bus stop. The structure of the EDTV system is shown in Figure 2. As shown in this figure, the bus status as well as real-time signal timings will be sent to the EDTV system as long as it is detected, e.g., it appears in the link to the target intersection.

Figure 2. Framework of the EDTV system.



There are three steps for the optimization of dynamic bus speed and bus holding time for every detected bus. The functions of the three parts are introduced as follows:

(1) *First speed adjustment*: generate the first recommended speed which can be used by a detected bus to travel the distance between bus detector location and the bus stop.
(2) *Holding time/speed optimization*: provide a recommended holding time at the bus stop after the bus door has closed and a recommended speed for a bus traveling the distance between the bus stop and the stop line at a downstream intersection.
(3) *Second speed adjustment*: monitoring changes of real-time signal timings and bus speed, and generating real-time recommended bus speeds.

3. Optimization Methods for Adjustment of Bus Speed and Holding Time

3.1. Assumptions

To yield tractable solutions for the proposed approach with realistic constraints, this study has employed the following assumptions.

(1) The bus detection and communication system can provide real-time two-way communications between buses and traffic controllers and support the real time optimization of bus speed and transit signal priority; and
(2) There is an exclusive bus lane in the studied approaches, and all buses will accept the recommended speed and holding time immediately and accurately.

3.2. Notations

To facilitate the model presentation, the key parameters used hereafter are summarized in Table 1.

Table 1. Notations and Parameters.

v_0	The current real time bus speed (m/s)
v_{max}	The maximum allowed bus speed (m/s)
v_{min}	The minimum allowed bus speed (m/s)
T_0	The time when bus reaches the intersection with current speed (s)
C	The cycle length (s)
g_s	The starting time of bus phase (s)
g_e	The ending time of bus phase (s)
w_s^a	The starting time of bus-arriving-window (s)
w_e^a	The ending time of bus-arriving-window (s)
L	The length of distance between bus detector and bus stop (m)
$L^{'}$	The length of distance between bus stop and the stop line (m)
α	Time headway for safety parking (s)
v	The recommended speed for the bus at upstream of bus stop (m/s)
v'	The recommended speed for the bus at downstream of bus stop (m/s)
v^*	The real-time bus speed (m/s)
h	Bus holding time at bus stop (s)
h_{max}	Maximum bus holding time at bus stop (s)
n	Positive integer, number of cycles

In the following parts of this section, the method for optimization of bus speed as well as bus holding time used at each steps are introduced. The optimization logics are designed based on the analysis of interaction of bus speed, bus holding time, bus dwell time, real-time signal timings and bus arrival time at stop lines.

3.3. Logic 1: First Speed Adjustment Logic

Once a bus comes into the detecting area, the decision of whether or not and how to consider the impacts of the nearest preceding bus that has not passed the stop line can be directly made by logic 1. Logic 1 is composed by the following seven sub-logics:

Logic 1.1: If there is no preceding bus, go to Logic 2 directly.
Logic 1.2: Average bus dwell time is used to calculate bus arrival time at the downstream intersection, and bus holding time at the bus stop is assumed equal to 0;
Logic 1.3: If the arrival time of the preceding bus is earlier than the planned arrival time of the current bus, the preceding bus has no impact on the current bus and goes to Logic 1.5, otherwise, goes to logic 1.4.
Logic 1.4: If the arrival time of the preceding bus is later than the planned arrival time of the preceding bus, the passing time of the current bus is related with that of the preceding bus and it is of no use to adjust the current bus speed, then, goes to Logic 2.

Logic 1.5: In order to minimize bus travel time, if the current bus can arrive at the stop line within the green time of a bus signal at a higher speed value within the allowed speed range, the highest feasible speed can be selected. Therefore the recommend bus speed can be computed with the following equation, and goes to Subset 2; otherwise, goes to Logic 1.6.

$$v = \max\left[\frac{L+L^{'}}{g_s+nC-T_0^{'}}, v_{max}\right] \tag{1}$$

Logic 1.6: If the arrival time of the bus driving with the current speed is within the range of the green time of the bus phase, the current bus speed should not be changed, goes to Logic 2;

Logic 1.7: If the slowest bus arriving time (traveling with the slowest speed) is within the bus green time, the recommended speed can be computed with the following equation; otherwise, the bus cannot pass the intersection by changing speed, and the recommended speed is set to equal the current bus speed.

$$v = (L + L^{'})/(w_s^p + nC - T_0) \tag{2}$$

3.4. Logic 2: Integrated Optimization of Bus Holding Time and Bus Speed

The bus holding time should be determined after the doors of the bus are closed. The decision of whether to hold the bus at bus stop and the holding time can be made by Logic 2. Logic 2 is composed by the following five sub-logics:

Logic 2.1: Estimate the arrival time of the bus at the stop line with the speed recommended by Logic 1 under no holding situation. The holding time should be as short as possible to decrease bus travel time. Therefore, if the bus arrives at intersection during the green time, the original recommended speed should be adopted as recommended speed again, the holding time is equal to 0; otherwise, goes to Logic 2.2;

$$v' = v \tag{3}$$

$$h = 0 \tag{4}$$

Logic 2.2: If the bus can arrives at an intersection with the highest speed during green time, the highest speed should be adopted as the recommended speed to minimize bus travel time, the holding time is equal to 0 accordingly;

$$v' = v_{max} \tag{5}$$

$$h = 0 \tag{6}$$

Logic 2.3: If the bus can arrive at an intersection with the lowest speed during green time, there is no need to hold the bus at the bus stop to avoid potential confusion of passengers. The recommended speed should be the highest speed with which bus can pass the intersection without stopping. Therefore, the bus speed can be calculated by Equation (7), and holding time should be 0 as shown in Equation (8).

$$v' = L/(nC - T_0 + g_e) \tag{7}$$

$$h = 0 \tag{8}$$

Logic 2.4: Let t represent the signal status which is the length of passing red time of bus signals when a bus arrives at the stop line using the lowest speed. If $t < h_{max}$, it means the bus can pass the intersection without stopping by adjustment of holding time. In order to minimize holding time, the recommended speed should be the minimum speed and the holding time can be calculated based on the recommended speed as shown in Equation (10). Otherwise, it means bus still has to stop at the intersection even if the maximum holding time is used, goes to Logic 2.5.

$$v' = v_{min} \tag{9}$$

$$h = \left(\frac{L}{v_{min}}\right) mod\ C \tag{10}$$

Logic 2.5: The bus cannot avoid stopping again at the downstream intersection by adjust holding time and speed, therefore, the holding time and speed can be can be calculated by the following equations:

$$v' = v \tag{11}$$

$$h = 0 \tag{12}$$

3.5. Logic 3: Second Speed Adjustment

Logic 3 is designed to avoid the real time bus speed from deviating from the recommended bus speed due to stochastic impacts of the environment or bus driver behavior. It is composed of two sub-logics:

Logic 3.1: If v^* is not equal with v', and bus can pass the stop line without stopping according to Logic 2, the v^* should be updated by the following equation:

$$v^* = v' \tag{13}$$

Logic 3.1: If a bus has to stop at the stop line according to Logic 2, there is no need to monitor the value of v^*.

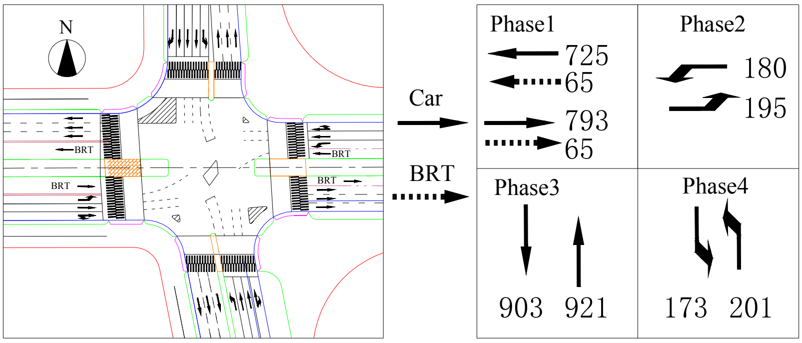
4. Evaluation and Analysis

4.1. Experiment Design

To illustrate and evaluate the applicability and efficiency of the proposed method, this study uses an intersection on Beiyuan Road, a main BRT (Bus Rapid Transit) corridor of Jinan, for a case study. There are exclusive bus lanes operating at the intersecting streets of Beiyuan Road. The basic layout of the intersection, the phase design and the traffic volume are given in Figure 3.

The model is evaluated at three levels of transit demand (vehicles per hour): low (Demand Level I)—0.7 times of the basic volume as shown in Figure 4, moderate (Demand Level II)—basic volume as shown in Figure 4 (the number near the arrow), and heavy (Demand Level III)—traffic conditions (1.3 times the basic volume).

Figure 3. Basic parameters of the intersection used in the case study. (**A**) Layout of the intersection; (**B**) Phase sequence and traffic volume.



(**A**) (**B**)

VISSIM simulation software is used to evaluate the proposed methods [16]. VISSIM is a microscopic, time step and behavior based simulation model developed to model urban traffic and public transit operations. The program can analyze traffic and transit operations under constraints such as lane configuration, traffic composition, traffic signals, transit stops, *etc*., thus making it a useful tool for the evaluation of various alternatives based on transportation engineering and planning measures of effectiveness. The process starts with VISSIM's Component Object Model (VISSIM -COM) interface. This is an external module enabling communication and dynamic object creation between the simulation environment and external processes, and the proposed method can be connected with VISSIM exactly. Measures of effectiveness including travel time, speed, fuel consumption, and emissions can be obtained from VISSIM. Each simulation runs for one hour; to overcome the stochastic nature of simulation results, an average of 10 simulation runs has been used.

4.2. Experimental Results and Analyses

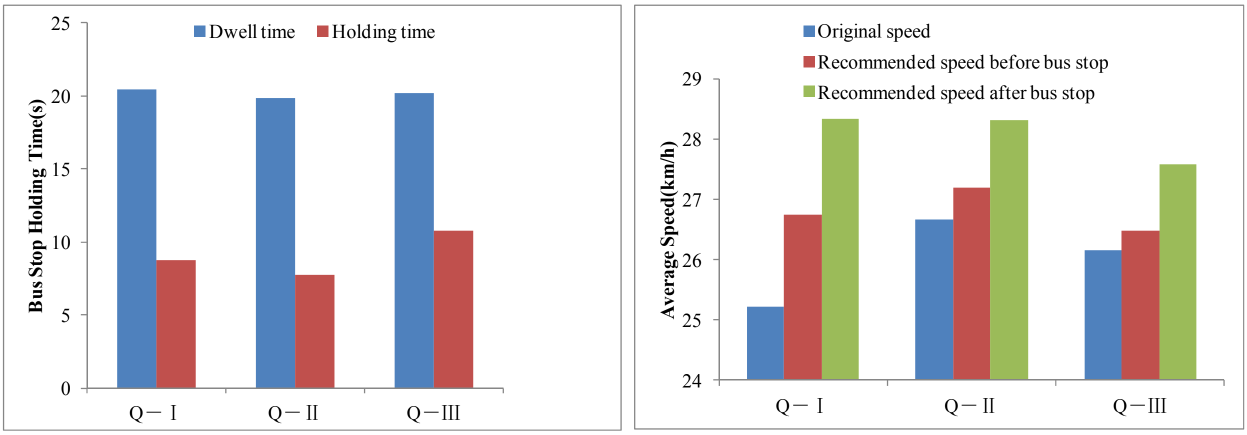
To evaluate the performance of the proposed model, we have developed and compared the following signal control scenarios:

- *No EDTV* (NEDTV): implements fixed signal timing plans optimized offline using Synchro 6 without EDTV.
- *EDTV*: implements the same signal plans as the No EDTV scenario, and recommended bus speed, and holding time generated by the proposed EDTV method.

Figure 4 shows the average optimization results of EDTV under different traffic demand scenarios, Figures 5–7 show the comparison results from the proposed EDTV system and the traditional NEDTV scenario under different levels of demand as defined above.

As shown in Figure 4, the proposed EDTV can generate recommended holding times and bus speeds efficiently. The average bus holding time and bus speed are different under different traffic demand levels. The recommended bus speed for a bus to travel the distance between detection location and bus stop is different with that for bus to travel the distance between bus stop and the downstream intersection. These results validate the effectiveness of the proposed EDTV method. Figure 4 also shows that it is necessary to re-calculated the recommended bus speed after the bus passes the bus stop.

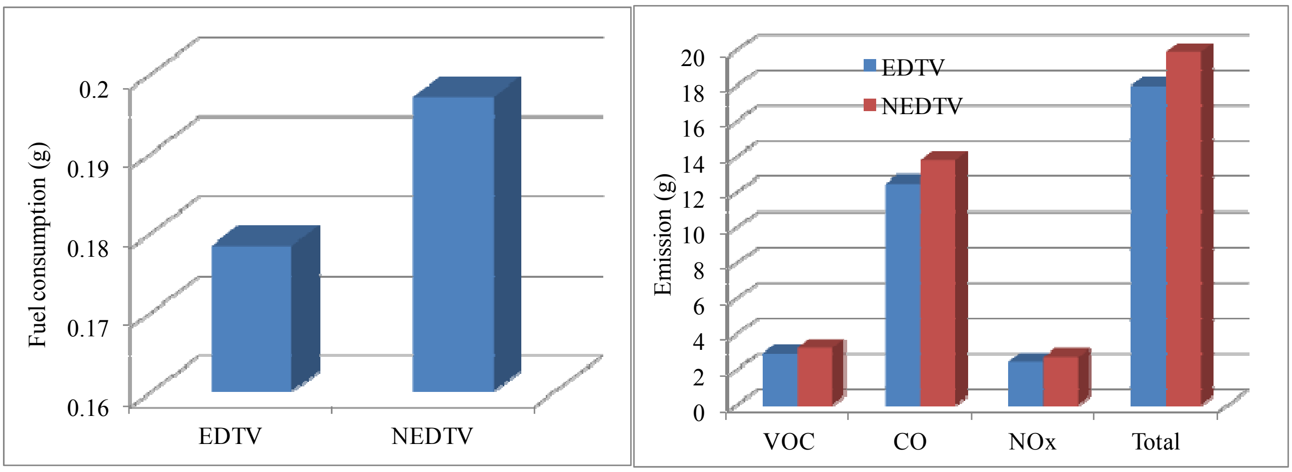
Figure 4. Average recommended holding time and bus speed.



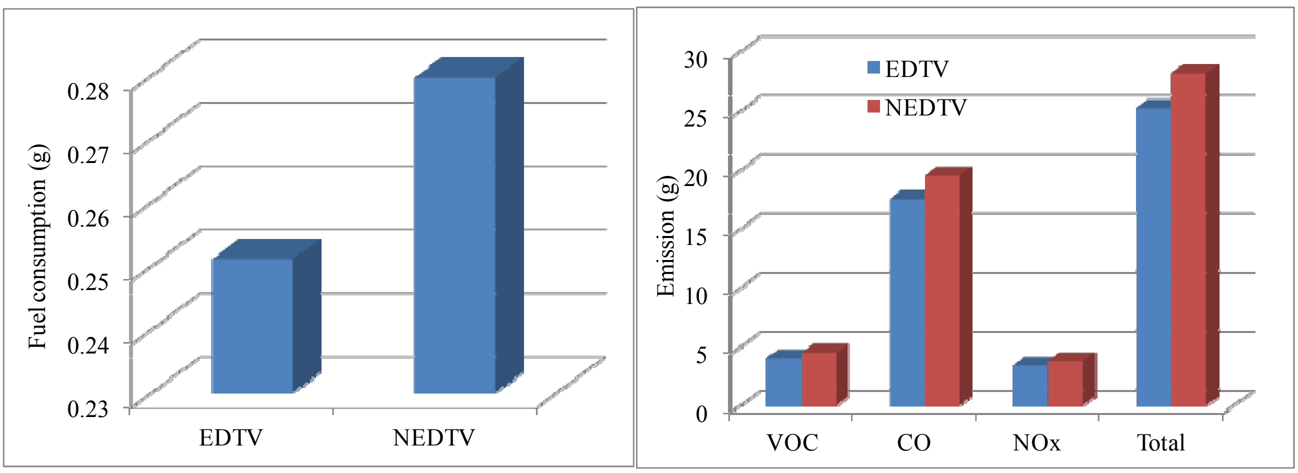
(**A**) Bus holding time. (**B**) Bus speed.

To investigate the performance of the bus speed and holding time generated by the proposed EDTV system, this study has compared the fuel consumption and air pollution emission of buses under different demand levels.

Figure 5. Bus fuel consumption and pollution emission under different traffic demand.

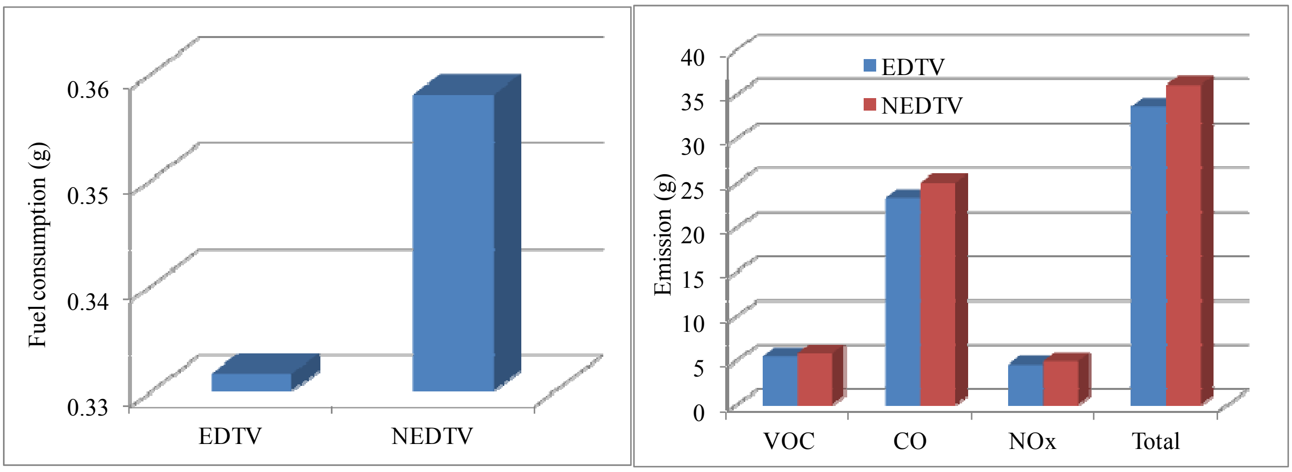


(**A**) Demand Level I.



(**B**) Demand Level II.

Figure 5. *Cont.*



(**C**) Demand Level III.

As indicated in Figure 5, one can reach the following findings:

(1) The proposed EDTV outperforms NEDTV in all demand scenarios in terms of reduction in bus fuel consumption (7.3%–9.5% savings over NEDTV). Such results clearly demonstrate the advantages of the proposed model in saving energy.

(2) Recommended bus speed and holding time plans generated by the proposed EDTV will also contribute a significant decrease of air pollution emission of buses. Compared with NEDTV, the decrease in average is about 3.7%–10%.

Beside fuel consumption and air pollution emission, the impact of EDTV system on transit system efficiency and travel time was also investigated. As shown in Figure 6, although the level of demand has impacts on the performance of EDTV, the total travel time of buses can be significantly reduced by EDTV compared with NEDTV (ranging from 5.6% to 10%). Based on the results of Figure 5 and Figure 6, it can be found that improvements have been achieved by the EDTV system in terms of enhancing economic driving and improving level of service of transit system simultaneously.

Figure 6. Travel time analysis.

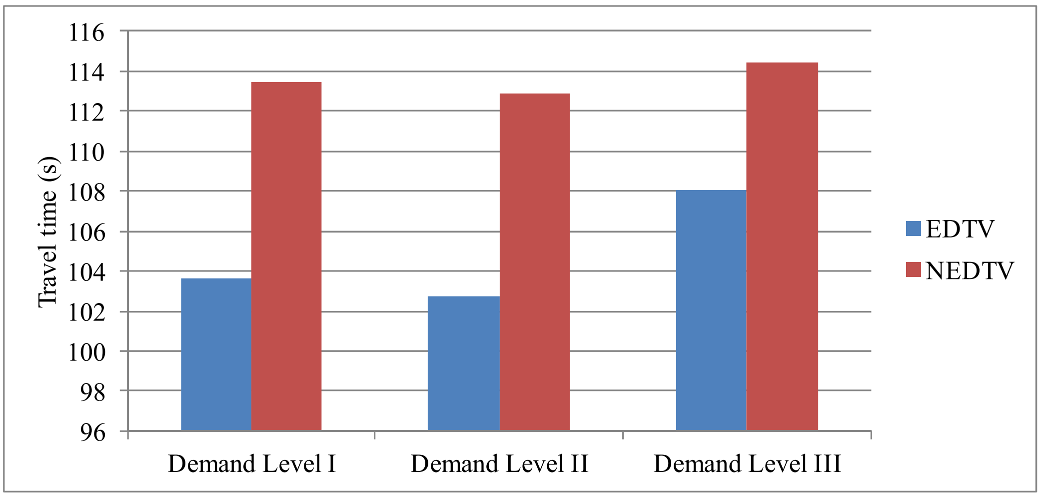
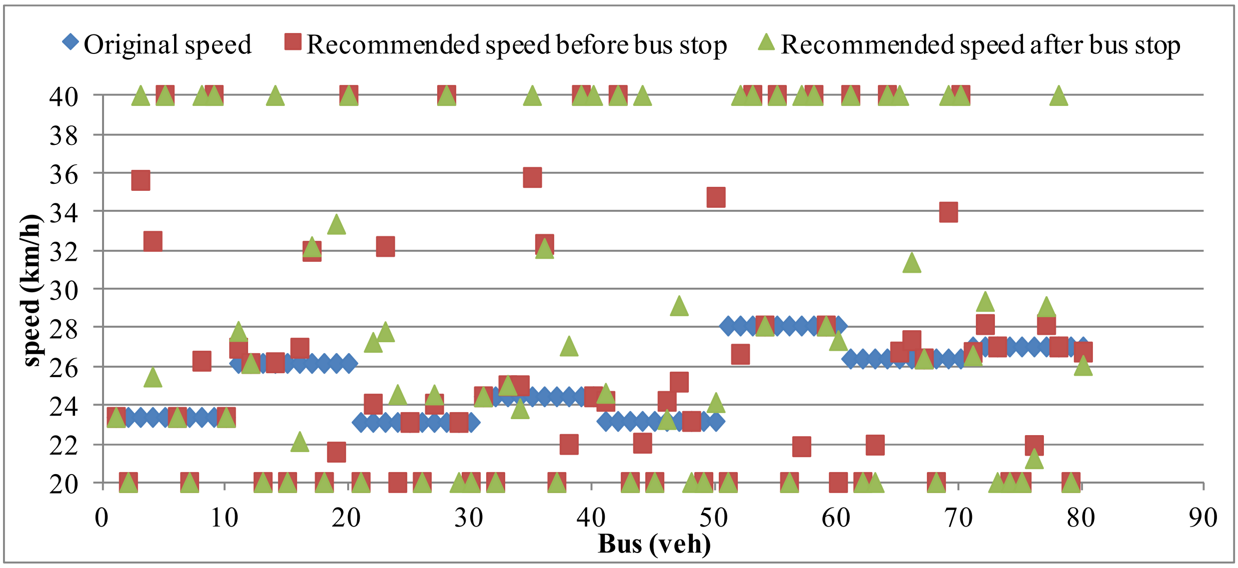
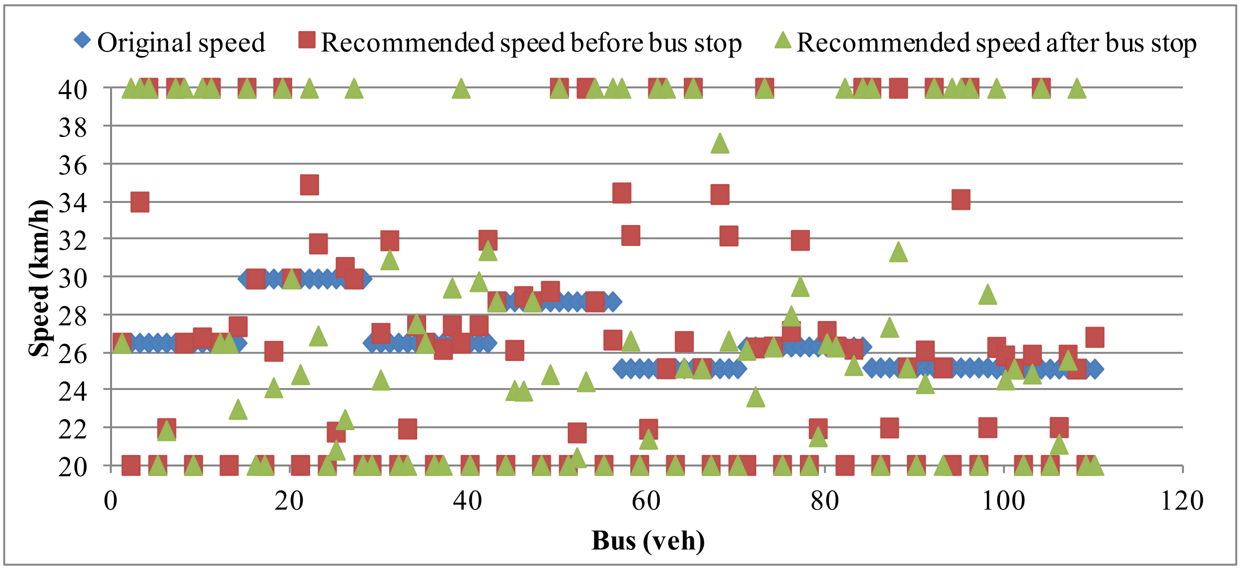


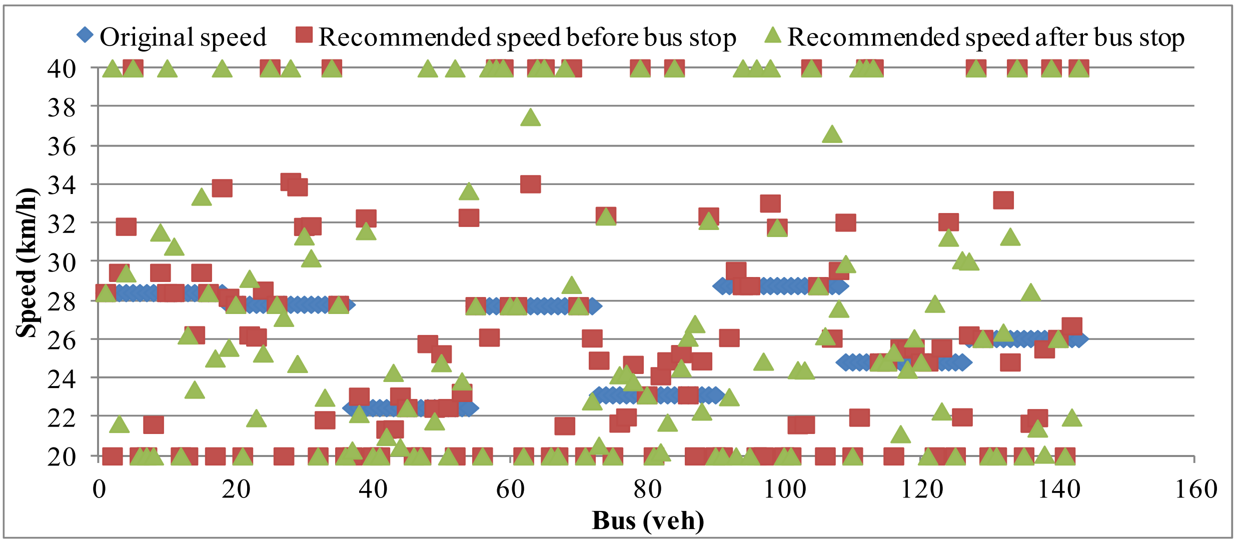
Figure 7. Comparison of recommended bus speed.



(**A**) Demand Level I.

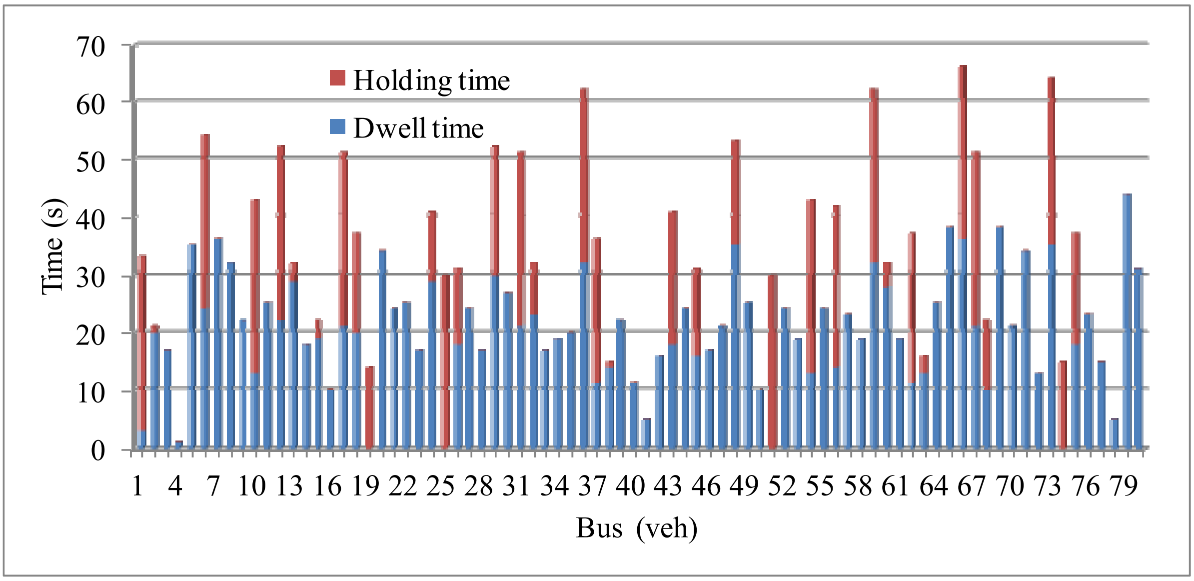


(**B**) Demand Level II.

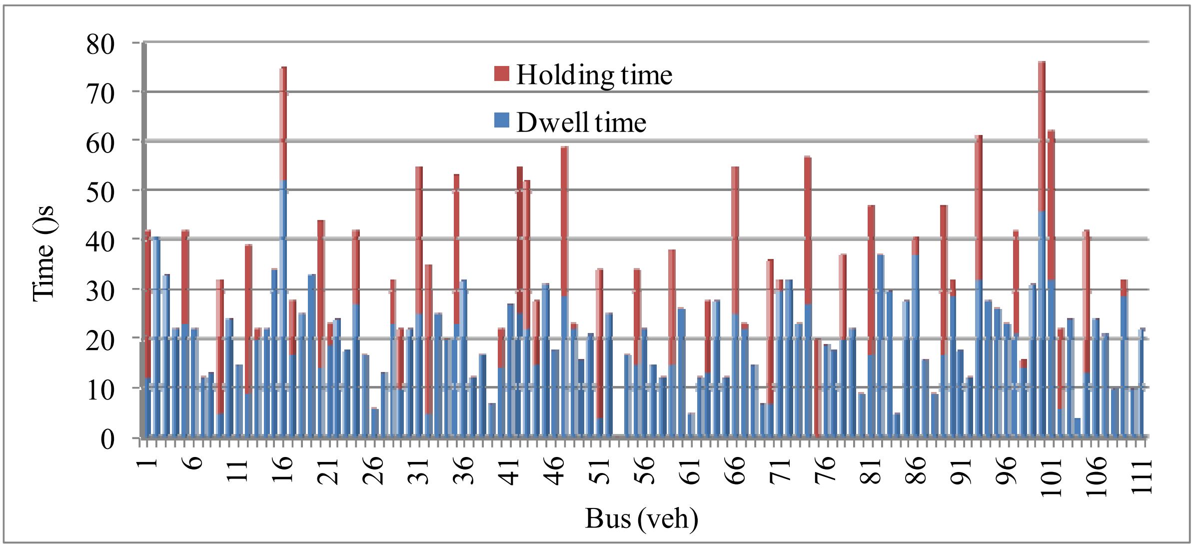


(**C**) Demand Level III.

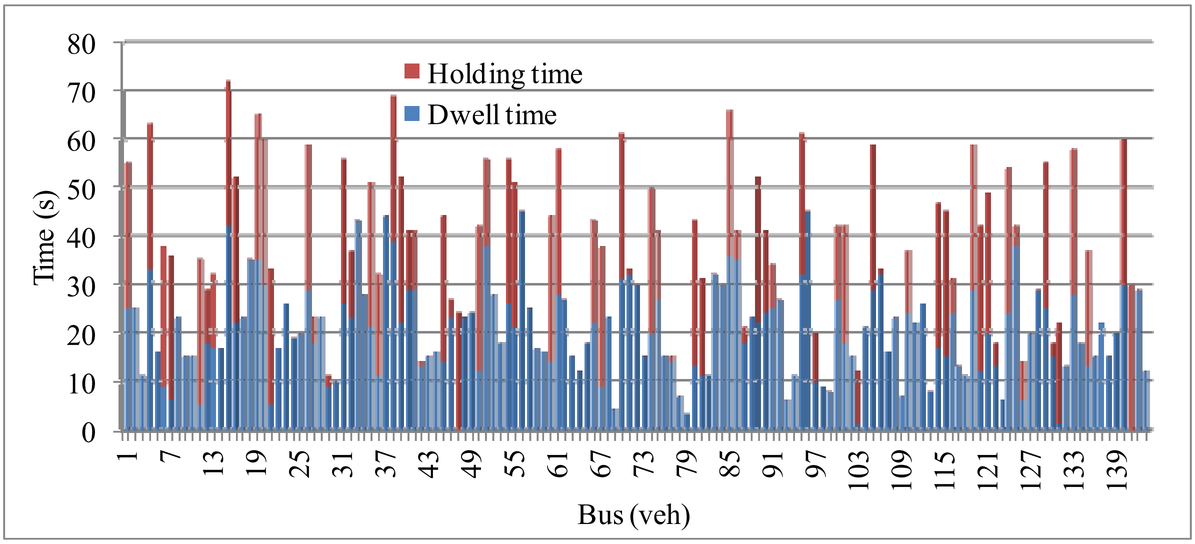
Figure 8. Comparison of recommended bus holding time.



(**A**) Demand Level I.



(**B**) Demand Level II.



(**C**) Demand Level III.

To assist traffic engineers in best understanding the results and the application feasibility of the proposed EDTV, this section describes further investigations of the details of bus speed and bus holding time at near side bus stop recommended by the proposed EDTV.

In Figure 7, the original speed, recommended speed before arriving at bus stop and recommended speed after passing bus stop of every bus are presented. As indicated in Figure 7 and Figure 8, one can reach the following conclusions:

(1) The proposed EDTV system can generate a recommended bus speed and bus holding time at near side bus stops for all buses. Moreover, the recommended bus speed upstream of the bus stop and downstream of the bus stop (Figure 7) is different among different vehicles, as is the recommended holding time (Figure 8);
(2) The stochastic variety (Figure 8) of bus dwell time may be the main reason for the differences in recommended bus speed upstream of the bus stop and downstream of the bus stop (Figure 7);
(3) Since the recommended bus speed and bus holding time should satisfy the constraints of minimum and maximum bus speed and maximum holding time, respectively, these constraints are very important factors which have significant impacts on the performance of the proposed EDTV method.

5. Conclusions

This study has presented an economic-driving assistance system for transit vehicles (EDTV) which can adapt bus operation status with signal timings at downstream intersections when real-time adjustment of bus speed and holding time is available. Aiming at minimizing fuel consumption and air pollution emissions, EDTV can provide bus drivers with optimal recommended bus holding times at near-side bus stops and dynamic bus speeds to avoid bus stops at intersection again after passing near side bus stops. In order to take the stochastic feature of bus dwell time into consideration, the total link between adjacent intersections is divided into three parts: upstream part; bus stop part; and downstream part. The methods for calculating the recommended parameters, including bus holding time and bus speed at each of three parts are proposed based on real-time bus status and signal status at downstream intersections. A VISSIM-based simulation platform was designed and used for simulating and evaluating the proposed EDTV method. Extensive experimental analyses shown that the proposed EDTV system can improve the performances of transit system in terms of reducing fuel consumption, air pollution emissions and level of service of the transit system.

Note that this paper has presented preliminary evaluation results for the proposed system. More extensive theoretical analysis and numerical experiments or field tests will be conducted to assess the effectiveness of the proposed model under various traffic and transit demand patterns. Another possible extension to this study is to take the impacts of general traffic into the consideration and optimize signal timings and bus operation control strategies together since both of them have impacts on bus operation status, including fuel consumption, air pollution emission and bus travel time.

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