Research Article

Ecodriving for Reduction of Bus Transit Emission with Vehicle's Hybrid Dynamic Model

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This paper formulates a global ecodriving optimal control to advise the green driving speed for bus transit to minimize the exhaust emission using Vehicle-to-Infrastructure (V2I) communication. Assuming communication between vehicles and infrastructure (V2I) and knowledge of traffic signal timings and waiting passengers at stations are known, an optimal driving speed is proposed to minimize the total vehicle emissions of the bus route. The dwell time of the bus transit at each station which includes two parts is proposed. A traffic lights timing model is employed as constraints to control the formation of the green wave band. Vehicle specific power (VSP) model is further applied to evaluate the exhaust emission level linked with the speed and acceleration of the bus transit. An approximate sixteen-kilometer traffic network including fourteen intersections and fifteen stations of Beijing bus transit line 1 in Chaoyang District, Beijing, is chosen to investigate the performance of the developed ecodriving approach.

1. Introduction

Traffic emissions are among the biggest sources of environmental pollution in cities. The emissions of vehicles contain several harmful substances, such as nitrogen oxides (NO_x , i.e., nitrogen monoxide and nitrogen dioxide), hydrocarbons (HC), carbon monoxide (CO), carbon dioxide (CO_2), and fine particulate matter. Around the world, approximately 50% of the NO_x emission and 90% of the CO emission come from traffic [1]. Consequently, traffic emissions, as an environment-oriented traffic control objective, draw more attention [2–7].

Ecodriving in urban traffic networks using traffic signal information is a significant field of intelligent transportation system (ITS). Technology advancement in wireless communication, specifically Vehicle-to-Infrastructure (V2I) and Vehicle-to-Vehicle (V2V) communications, has the potential of data collection (road, vehicle, and passenger) at any space-time position of traffic networks. Knowledge of traffic signal timings has been proven to benefit the energy use of vehicles by reducing the sudden break and idling time at the intersections [3, 8].

Hybrid systems have been an active research topic in the last few years and many results can be found in the control and computer science literature [9]. As a special type of hybrid systems, switched systems have attracted increasing attention [10, 11]. Wei et al. study the problem of traction control, that is, how to stabilize a wheeled mobile robot (WMR) subject to wheel slippage to a desired configuration [12]. Uthachana et al. present a hybrid optimal control solution for the power management problem of a parallel hybrid electric vehicle (PHEV), based on a two-mode operation model of PHEV [13].

The green light optimal speed advisory (GLOSA) [14] can synchronize with green signals without stopping at intersections when vehicles are traveling at an optimal speed. In addition, GLOSA helps vehicles keep a driving speed as much as possible to reduce additional acceleration. In [15], authors provided a fast suboptimal solution that suggests an online speed advisory service to the driver for the energy minimization based on GLOSA system. A framework for vehicle's ecodriving was developed in [16] based on the V2I communication technology to enhance vehicle fuel

FIGURE 1: V2I communication in intelligent transportation systems.

consumption efficiency. In [17], Asadi and Vahidi propose the use of upcoming traffic signal information within the vehicle's adaptive driving control system to reduce stop time at stop lights and fuel consumption. To achieve this goal an optimization-based control algorithm is formulated that uses short range radar and traffic signal information to schedule an optimum velocity trajectory for the vehicle. More extensive discussion about how to find the energy-optimal velocity for a vehicle using V2I and V2V communication in urban traffic networks can be reviewed in the literature [18, 19].

Here we are interested in optimal control of bus transit with minimizing the volume of pollutant of vehicle emissions, such as NO_x , HC, and CO_2 . The vehicle emission model, vehicle specific power (VSP) model [20, 21], is used as performance index to quantify the vehicle emissions, which is closely related to the vehicle dynamics (speed, acceleration) and the road grade. The referred trajectories induced from the traditional "bus priority" and "green wave" schemes of traffic signal timing are tracked by the driver in order to pass through the intersections without stopping. Using V2I communication technology, not only the information of traffic signal planning but also the estimated total delay at each station is transmitted to drivers for decision making. Physical topology graph is shown in Figure 1. Following from our discussion, we also obtain a suboptimal ecodriving trajectory for bus transit to pass through intersections in green light against the dwell time of bus transit at stations.

This paper is organized as follows: Section 2 modeling the vehicle's hybrid dynamic model with switching laws and guard conditions. The traffic signal timing scheme and the global optimal control model for ecodriving are introduced in Sections 3 and 4, respectively. Section 5 describes the iterative optimization method. In Section 6, we select an approximate sixteen-kilometer traffic route of Beijing bus transit line 1 for simulation to verify the validity of the vehicle's hybrid dynamic model through the numerical solution of the simulation. Conclusions and future works are development in Section 7.

2. Vehicle's Hybrid Dynamic Model

The movement of the vehicle is discontinuous, which is interrupted by the passengers regularly getting on and off at the stations by the bus transportation schedule. At the same time, the different vehicle dynamics, such as driving and dwell process, usually lead to the different emission levels of the pollutant. Therefore, it is convenient to build the movement of the vehicle with the hybrid dynamical model. Vehicle's hybrid dynamic model and switching laws among hybrid dynamics are formulated as follows.

Driving Mode. Using the vehicle kinematics, the dynamic of driving mode can be stated as the following equations:

$$\begin{aligned}\dot{x}(t) &= v(t), \\ M\dot{v}(t) &= f_e(t) - f_d(t),\end{aligned}\quad (1)$$

where $x(t)$ is the displacement of vehicle, $v(t)$ is the speed of vehicle, M is the vehicle mass, $f_e(t)$ is traction force of the engine, and $f_d(t)$ means the road forces including aerodynamic drag, rolling resistance, and road grade forces [17].

The road forces $f_d(t)$ can be described in detail as

$$f_d(t) = Mg \sin \theta + MgC_r + \frac{1}{2} \rho_a (v(t))^2 AC_a, \quad (2)$$

where g is the gravitational constant, θ is the road grade angle, C_r is the rolling resistance coefficient, ρ_a is the mass density of air, A is the cross-sectional area, and C_a is the aerodynamic drag coefficient.

When the vehicle dynamics are in the driving mode the vehicle accelerates leaving the station, goes through the intersection with green light, and decelerates into the station. During the driving mode process the vehicle is driving at an expected speed if we neglect the transient acceleration and deceleration process.

Dwell Mode. The location of each station is known, the vehicle dynamics are in the dwell mode when $x(t) = s_j$, where s_j is the location of station Sn_j . The dynamic of dwell mode can be stated as the following equations:

$$\begin{aligned}\dot{x}(t) &= 0, \\ M\dot{v}(t) &= 0, \\ \dot{\tau}(t) &= 1,\end{aligned}\quad (3)$$

where $\tau(t)$ is a timer used to record the vehicle's dwell time. When the vehicle leaves the station, the timer is cleared.

The dwell time of vehicle d_c^j at station Sn_j includes two parts; one is dwell time of passengers regularly getting on and off $d_w^j(t)$; the other one is control quantity δ_j . δ_j is controlled by the driver, meaning the dwell time after all the passengers have regularly finished getting on and off.

The dwell time of passengers regularly getting on and off $d_w^j(t)$ can be estimated with the number of waiting passengers $n_p^j(t)$ at station [23], in which

$$d_w^j(t) = g(n_p^j(t)), \quad (4)$$

where $n_p^j(t)$ is the number of waiting passengers and $g(\cdot)$ is a linear or nonlinear function about the number of passengers.

δ_j is a time independent control variable of vehicle's hybrid dynamic model. The upper bound value of δ_j is $\delta_{\max}^j$, so the dwell time of vehicle d_c^j can be written as the following equation:

$$d_c^j = d_w^j(t) + \delta_j, \quad (5)$$

where $d_c^j \in [d_w^j(t), d_w^j(t) + \delta_{\max}^j]$.

FIGURE 2: Switching laws of vehicle's hybrid dynamic model.

FIGURE 3: Figure of bus transit operation state.

Switching Laws. The vehicle's hybrid dynamic model contains two kinds of switching processes. The one switching process is switching from driving mode to dwell mode; it is autonomous switches; the other switching process is switching from dwell mode to driving mode; it is controlled switches.

Figure 2 describes the switching laws and the guard conditions for the hybrid dynamic model of vehicle. The guard condition from the driving mode to the dwell mode is autonomous as the vehicle arriving stations, while the guard condition from the dwell mode to the driving mode is modeled as control variables of hybrid model such that the timer $\tau(t)$ is equal to the dwell time of vehicle d_c^j .

3. Traffic Signal Timing

Suppose there is an intersection between every two adjacent stations. As it is shown in Figure 3, vehicle leaves from any station Sn_j driving to the downstream adjacent station Sn_{j+1} and goes through the intersection In_j with green light. Going through the intersection with green light can reduce vehicle acceleration and deceleration and vehicle brake numbers as well as vehicle delay and emissions. Therefore it is necessary to know the traffic signal timing of intersection in order to ensure the vehicle without stop at intersection.

In our research, the traffic signal timing at intersections including cycle, split, and offset times is deterministic and given. Under the assumption that the information of signal timing of the traffic lights can be shared with the vehicle via the V2I communication, it is possible to formulate mathematically the state evolution of the traffic lights as follows:

$$L_j = \begin{cases} 1, & rT + t_g^j \leq t_I^j < t_g^j + t_g + rT, \\ 0, & t_g^j + t_g + rT \leq t_I^j < t_g^j + (r+1)T, \end{cases} \quad (6)$$

where L_j is the state of traffic light (red or green) at intersection In_j , t_I^j is the time instant at which the vehicle arrives at the intersection In_j , T is the cycle, t_g^j and t_g are the

start instant and duration of the green phase, respectively, and $r = 1, 2, \dots$ is the number of cycles.

The offset of the neighboring traffic lights is set as

$$t_o^j = t_g^{j+1} - t_g^j = \frac{i_{j+1} - i_j}{\bar{v}}, \quad (7)$$

where $\bar{v}$ is the "green wave" speed, i_j is the position of intersection In_j , and i_{j+1} is the position of upstream intersection In_{j+1} . The "green wave" timing scheme of adjacent traffic lights makes the vehicle pass through the next intersection without stop, which has been extensively studied in the field of traffic engineering to reduce delay.

We restrict the vehicle to pass through the intersections in the driving mode of hybrid model without stop, for intersection In_j , satisfying

$$(x_j(t_I^j) = i_j) \wedge (L_j = 1), \quad (8)$$

where " $\wedge$ " is on behalf of the logic operation "and."

4. Global Optimal Problem

Objective Function. Take the minimum of emissions (NO_x , HC, CO, and CO_2) as the target. The vehicle specific power (VSP) model [20] is used as the performance index to measure the pollutants of vehicle emissions. VSP is a proxy variable for engine load and is defined as the source power per unit mass. The calculation formula of the VSP is as follows:

$$\text{VSP} = v[a \times (1 + \xi_i) + g \times \theta + g \times C_r] + \frac{1}{2} \rho_a \frac{C_a \times A}{M} (v + v_m)^2 \times v, \quad (9)$$

where v is vehicle speed, a is vehicle acceleration, ξ_i is vehicle mass factor, g is acceleration of gravity, θ is vertical rise/slope length, C_r is coefficient of rolling resistance, ρ_a is ambient air density, C_a is drag coefficient, A is frontal area of the vehicle, M is vehicle mass, and v_m is wind speed.

Actually the calculated value of VSP through (9) is dimensionless and has not any actual physical meaning. Table 1 is the VSP modes and the average modal emission rates of each. By querying Table 1, we can obtain the emissions. Emissions can be expressed as

$$E = f(\text{VSP}), \quad (10)$$

where E is the emissions and $f(\cdot)$ is a piecewise function.

Constraint Conditions. Ensuring that the travel time vehicle must arrive at the terminal station Sn_N at the moment $t_f, t_S^N = t_f$. The speed $v_j(t)$, acceleration $a_j(t)$, and traction force of the engine $f_e^j(t)$ values must be in the threshold range, $v_{\min} \leq v_j(t) \leq v_{\max}$, $a_{\min} \leq a_j(t) \leq a_{\max}$, and $f_e^{\min} \leq f_e^j(t) \leq f_e^{\max}$.

Global Optimal Model. Consider the vehicle's hybrid dynamic model of vehicle, the real-time traffic information of the signal planning of intersections, and residence time of stations. Minimizing the emission index of the whole route in the

TABLE 1: VSP modes and the average modal emission rates of each [22].

VSP	VSP mode	CO ₂ (g/s)	CO (g/s)	NO _x (g/s)	HC (g/s)
VSP < -2	1	1.54369	0.01103	0.00101	0.00090
-2 ≤ VSP < 0	2	1.60441	0.00872	0.00104	0.00090
0 ≤ VSP < 1	3	1.13083	0.00468	0.00042	0.00084
1 ≤ VSP < 4	4	2.38626	0.01215	0.00161	0.00103
4 ≤ VSP < 7	5	3.21025	0.01673	0.00264	0.00125
7 ≤ VSP < 10	6	3.95773	0.02327	0.00379	0.00166
10 ≤ VSP < 13	7	4.75201	0.02932	0.00510	0.00209
13 ≤ VSP < 16	8	5.37422	0.03694	0.00637	0.00233
16 ≤ VSP < 19	9	5.94005	0.04951	0.00766	0.00282
19 ≤ VSP < 23	10	6.42751	0.06376	0.00991	0.00299
23 ≤ VSP < 28	11	7.06599	0.10538	0.01269	0.00379
28 ≤ VSP < 33	12	7.61770	0.24781	0.01438	0.00457
33 ≤ VSP < 39	13	8.32244	0.41307	0.01597	0.00570
39 ≤ VSP	14	8.47503	0.62466	0.01672	0.00716

scheduled transportation interval $[0, t_f]$, we can obtain the global optimal control model for ecodriving as follows:

$$\begin{aligned}
 &\text{minimize } J_{\text{total}} = \int_{t=0}^{t=t_f} f(\text{VSP}(v(t), a(t))) dt \\
 &\text{s.t. } \text{vehicle dynamics } (1), (2), (3) \\
 &\quad \text{residence times } (4), (5) \\
 &\quad \text{signal timing } (6), (7), (8),
 \end{aligned} \tag{11}$$

where $t_S^N = t_f$ is the time to arrive at station Sn_N . The constraint condition (8) for the “green wave” of the signal timing represents a set of disjointed time intervals at the same intersection. Therefore, the constraint conditions are nonconvex sets and the solution of the optimal ecodriving of vehicle has to be considered as a suboptimal way.

5. Iterative Optimization Method

Dwell time of passengers getting on and off is a disturbance to the global optimal control. It is difficult to predict the values of $d_w^j(t)$ in advance for each station. In order to solve this problem we should update the dwell time $d_w^j(t)$ through V2I communication at the moment when the vehicle arrives at each station.

Suppose there are N stations and $N - 1$ intersections. The space discretization is carried out according to the position of the station. All optimal solutions can be solved in the iterative optimization; for each step, the vehicle reaches to the next downstream station. Every step there are N_p stations and N_c inputs. N_p means how “far” we wish the future to be predicted for, where $N_p \leq N - 1$ is positive integer. N_c dictates the number of parameters used to capture the future control trajectory, $N_c \leq N_p$. There are $N - N_p + 1$ iterative optimization steps. F_e^k and D_c^k are input vectors,

$F_e^k = [f_e^1(t), \dots, f_e^j(t), \dots, f_e^{N_c}(t)]$, $D_c^k = [d_c^1, \dots, d_c^j, \dots, d_c^{N_c}]$. For k th step $k = 1, 2, \dots, N - N_p + 1$, we have

$$J_t(k) = \min_{D_c^k, F_e^k} \sum_{j=k}^{k-1+N_p} (J_{dr}^j + J_{dw}^j), \tag{12}$$

where $J_t(k)$ is the total emission of k th step iterative optimization and J_{dr}^j and J_{dw}^j are the emissions during the driving mode and dwell mode, respectively.

The performance indexes J_{dr}^j and J_{dw}^j of the vehicle's hybrid dynamics can be described as the following equations, respectively, with more details, for $j = 1, 2, \dots, N - 1$:

$$J_{dr}^j = \int_{t_S^j + d_c^j}^{t_S^{j+1}} f(\text{VSP}(a_j(t), v_j(t))) dt \tag{13}$$

$$J_{dw}^j = \int_{t_S^j}^{t_S^j + d_c^j} f(\text{VSP}(a_j(t), v_j(t))) dt, \tag{14}$$

where t_S^j and t_S^{j+1} are the time instant at which the vehicle arrives at the stations Sn_j , Sn_{j+1} , respectively.

For k th step the dimension of each input vector is N_c . We only implement the first element of these input vectors, that is, $f_e^1(t)$ and d_c^1 , while ignoring the rest of the elements (except the last step). When the next step arrives, the more recent measurement is taken from the state vector for calculation of the new sequence of input vector. This procedure is repeated in real time during the process of iterative optimization. The optimal emission for k th step is $J^*(k)$, $J^*(k) = (J_{dr}^k + J_{st}^k)$.

Notice that when the vehicle arrives at station Sn_{N-N_p+1} , that is, the last step, the number of stations at the downstream remains less than N_p . Then all elements of $F_e^{N-N_p+1}$ and $D_c^{N-N_p+1}$ are effective. The optimal emission of last step is $J^*(N - N_p + 1)$, $J^*(N - N_p + 1) = J_t(N - N_p + 1)$.

FIGURE 4: Bus route of bus transit line one in Beijing city.

TABLE 2: Vehicle performance parameter.

Para.	M (kg)	P (kw)	$f_e^{\min}$ (N)	$f_e^{\max}$ (N)	Physical dimension
Values	17000 (28000)	213	6000	98000	17980 * 2550 * 3100

The total optimal emissions J_{total}^* , $J_{\text{total}}^* = \sum_{k=1}^{N-N_p} J^*(k) + J_t(N - N_p + 1)$.

In the above iterative optimization method process, each step of the iterative optimization is an optimization problem. Main steps are including pruning algorithm, searching feasible path, and optimizing. More detailed steps are as follows.

Step 1. Determine the initial range of state variables.

Step 2. By pruning algorithm calculates feasible regions of each state variable.

Step 3. Determine feasible paths and calculate feasible regions of state variables for each path.

Step 4. Calculate feasible path's optimal solution through nonlinear programming.

Step 5. Repeat Step 4, until every feasible path has been calculated.

Step 6. Search for the optimal feasible path, that is, feasible path corresponding to the minimum value of the optimal index.

Remark 1. The classical model predictive control is a receding horizon optimization process. In our optimization method, the dynamic iterative process is receding along the spatial positions of the stations.

6. Experiments

A segment of bus transportation route of bus transit line 1 in Beijing is chosen as the simulation scene. This transportation route consists of fifteen stations, from the Yuquan Road station to the Ritan Road station, respectively, as seen in

Figure 4, and fourteen traffic intersections with the two-phase signal timing scheme. The spatial displacement of the stations and the traffic intersections are obtained from the Baidu Digital Map.

Bus transit line one is BJ6180C8CTD model of 18-meter LNG (liquefied natural gas) articulated vehicle made by FOTON motor incorporated company. The vehicle performance parameters are shown in Table 2. The unladen mass of vehicle is 17000 kilograms and the total mass is 28000 kilograms. Rated power P of the vehicle is 213 kilowatts. The physical dimension of the vehicle is 17.98-meter long, 2.55-meter wide, and 3.1-meter high. See Table 2 for details.

Parameter values for calculating vehicle drag are shown in Table 3. The slope of the road is zero. The cross section of vehicle A is calculated by the height of the vehicle times the width of the vehicle.

The other model and simulation parameters, such as the station position, intersection position, speed limit of the vehicle, acceleration limit of vehicle, simulation times, and total number of stations are listed in Table 4.

Table 5 lists the parameters of traffic signal timing of the fourteen intersections. The cycle time is 120 seconds; the green time of the vehicle passing phase is 30 seconds. The offset of the neighboring intersections is 113-31-20-90-99-26-10-72-74-12-102-113-8 seconds, respectively. In this simulation, the start time t_g^1 of the green phase of the first intersection is 0.

Simulation results of the total emissions J_{total}^* are 2420 grams. The total delay time at each station d_c , the maximum traction force f_e^m (i.e., the maximum value of each stage in Figure 7), the optimal speeds v^* , the optimal acceleration a^* , the optimal arriving time of each station t_s^{j*} , and the optimal arriving time of each intersection t_l^{j*} are shown in Table 6.

Figure 5 gives the spatiotemporal diagram of optimal driving route for the public transits line one. Vehicle delays at

TABLE 3: Road forces calculation parameters.

Para.	g (m/s ²)	θ (°)	C_r	C_a	ρ_α (kg/m ³)	A (m ²)
Values	9.81	2	0.015	0.55	1.207	7.91

TABLE 4: Model and simulation parameters.

Para.	S (m)	I (m)	$a_j(t)$ (m/s ²)	$v_j(t)$ (m/s)	t_f (s)	N_c	N_p	N
Values	0	1100	[0, 3.5]	[0, 14]	2100	4	4	15
	1800	2900						
	4200	4700						
	5000	5900						
	6300	6600						
	6900	7200						
	8000	8300						
	8400	9000						
	9100	9500						
	10700	11200						
	11800	12300						
	12800	12900						
	14000	14900						
	15100	16200						
	16300

FIGURE 5: Spatiotemporal figure of driving routes.

FIGURE 7: Traction force of engine.

FIGURE 6: Speed suggestions.

each station are different. The vehicle crosses the intersections without stop with optimal speed v^* .

Figure 6 shows the variation curve of the optimal vehicle speed suggestion with time. The curve is periodic. In each period, the driving speeds are different. This is caused by the actual position of the stations and the total delay times.

Vehicle traction force of engine variation curves with time is shown in Figure 7. It is periodic too. In each period, the traction force of engine is zero at the station; it surges at the acceleration process and at last decreases to a constant value and maintains stability at driving mode.

7. Conclusions

According to the actual operation of the bus transit, vehicle's hybrid dynamic model is established. The dwell time of the vehicle at each station which includes two parts is proposed. Previous works have proved how the V2I has a positive impact on the energy consumption. In this work, further improvement of ecodriving to lower vehicle emission

TABLE 5: Traffic light timing.

Para.	T (s)	t_g (s)	t_g^1 (s)	t_0^j (s)
Values	120	30	0	113-31-20-90-99-26-10-72-74-12-102-113-8

TABLE 6: Simulation results and emission index.

Variables	Values
d_c (s)	42-35-46-27-13-28-37-25-11-15-11-26-11-18
f_e^m (N)	63380-36940-48227-51616-37069-48577-47011-32249-43976-50076-38406-47647-39251-60405
t_l^{j*} (s)	123-356-627-766-856-955-1102-1232-1304-1498-1630-1731-1964-2092
t_s^{j*} (s)	0-173-530-656-803-896-1033-1112-1248-1434-1554-1693-1840-1988-2100
a^* (m/s ²)	2.8-1.5-2-2.2-1.5-2-2-1.3-1.8-2.1-1.6-2-1.6-2.7
v^* (m/s)	14-7.5-10-11-7.5-10.4-10-6.3-9.2-10.7-7.8-10-8-13
J_{total}^* (g)	2420

considering dwell time of vehicle is presented. Global optimal control for minimizing the VSP index is solved based on the vehicle's hybrid dynamic model with the iterative optimization method. The simulation results show that vehicle can pass through intersections without stopping under the different scenes of waiting passenger. Further works will consider multiobjective optimization and bus transit embedded in traffic flow.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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