Eco-Driving --- Current Strategies and issues, A Preliminary Survey

Chunxiao Li[a], Aiping Ni and Jie Ding

School of Information Engineering, Yangzhou University, Yangzhou, 225009, China

[a]licx@yzu.edu.cn

Keywords: Eco-driving, emission estimation model, eco-driving strategies, driving control

Abstract. After safe driving, eco-driving has become an economic and green driving idea, which is adapted to the modern engine technology and typically consists of changing a person's driving behavior based on general advice to drivers, such as accelerating slowly, driving smoothly, etc. The concept of eco-driving can help save energy and reduce pollution emissions in an efficient way. In this article, a comprehensive preliminary overview of state-of-art research on this issue is presented in several parts: methods for emission estimation, traffic signal control, cruise control, and eco-driving assist systems. Besides, the challenges and opportunities associated with eco-driving are discussed as well.

Introduction

In the 1970s, energy consumption patterns came to a historical turning point when the petroleum price crisis happened again in western developed countries. What's worse, the problem of environment pollution and the change of climate are getting more and more serious, which has brought great challenges to the service of global energy. Thus, the energy conservation and emission reduction has become the core content of energy policy in many countries. Besides, about 20% CO_2 emissions come from energy consumption of transportation. All above reasons make the eco-driving play important roles in energy saving and emission reducing.

The core of eco-driving is to keep vehicles moving at a constant speed as much as possible. The most comprehensive and representative law was made in 2003, Japan, it suggested that: the speed should be kept at around 20 kilometers per hour during the first five seconds, the number of acceleration or deceleration should also be tried best to reduced and the unnecessary idling running ought to be stopped. More and more researches on eco-driving have been made to devote to the fuel efficient intelligent driving. For reducing the emissions, researchers have done lots of models for emissions estimation, and in the following part, we will discuss and analyze these models.

Methods for Emission Estimation

Emission estimation is an important factor when evaluating a control scheme. In general, methods for emissions estimation can be divided into two types according to the scope level: microscopic level and macroscopic level. For the microscopic level, the microscopic traffic simulation models are coupled with instantaneous emission models, which have potentials to provide improved assessments of the environmental impact of traffic networks, management strategies and technology implementations. In [1], a toolbox is presented to simulated traffic conditions, which links the microscopic traffic flow simulator VISSIM with the instantaneous emission model named Passenger car and Heavy-duty Emission Model (PHEM). It calculates fuel consumption and emission from vehicles' instantaneous changes in speed and acceleration. In addition, this toolbox allows simulating different traffic scenarios for urban and interurban road networks. Thus, the authors have discussed the evaluation of the modeled traffic situations in urban road network with VISSIM and PHEM by measurements on the road and on the chassis dynamometer. The prototype of the toolbox has proven to be a valuable framework for detailed emission calculations which fit very well with measured single vehicle emissions. Compared with [1], the authors in [2] presents an intermediate calculation step to make a first estimation of the environmental impacts to avoid unessential detailed investigations and simulates the traffic flow. The traffic induced emissions are not calculated for each vehicle but by representatives using an averaging method of single vehicle trajectories produced by the traffic flow simulator. By this new approach, a faster emission simulation should be feasible whereby the time for the optimization should also be in manageable limits.

To macroscopic level, an approach to eco-speed control at a microscopic level is presented in [3]. They used a model to calculate the instantaneous fuel consumption which is proposed by [4]. Furthermore, a macroscopic non-iterative algorithm in [5] uses the Willan's internal combustion engine model, which is no need the instantaneous values of speed and acceleration. The equations and models to derive the macroscopic fuel estimation algorithm are detailed discussed in [6, 7]. The Willan's fuel estimation model studies the number of stops, the average speed, the efficiency of the gearbox, the air-drag coefficients, and the engine parameters available from the automaker. It has been found that there are compromises between the fastest route and fuel consumption. A new method to model and optimize the vehicle fuel consumption is also presented in [8] in designing of an eco-driving assistance system (EDAS). The instantaneous fuel consumption rate is expressed as a piecewise polynomial of the instantaneous engine speed and engine torque in a creative way. A dynamic programming technique is used to optimize the vehicle fuel consumption considering the safety requirements. The real vehicle experiments show the good performances of the piecewise model. In [9], the authors have analyzed the performances of three feature subset selection (FSS) to the MLP-LM network in injected fuel flow forecasting.

From the above analysis, the macroscopic and the microscope methods both hold their advantages and disadvantages: macroscopic estimation models are usually established on large amount of statistic experiments while microscopic models tend to theoretic analysis. In general, it is much more convenient when using macroscopic models for emission estimation and the shortcoming is the lack of theoretical foundation. On the contrary, microscope models often pay much attention to the theoretical demonstrations. They are usually precise but sometimes not so convenient.

Traffic Signal Control

Nowadays, the traffic lights at an intersection are controlled by a fixed-cycle in the urban transport system. This is bound to have some drawbacks: when there is a large amount of cars at one traffic lane, but they have to stop at a red light for a long time; on the contrary, the traffic at another lane is little, but they have always the green light. Thus, current traffic light control cannot ensure the high road travel efficiency. For years, many investigators have conducted research into optimal signal control algorithms. With the development of a variety of inexpensive sensors and computer and communication technologies, many advanced methods have been developed to adjust signal timings according to real-time traffic data.

For cutting down vehicles stop times scheme, a novel fuzzy model and logic controller for an isolated signalized intersection is presented in [10]. They propose a novel fuzzy traffic controller that can optimally control traffic flows under both normal and exceptional traffic conditions. Meanwhile, in view of the complicated traffic condition in the traffic lights monitoring-control system, the current conventional fixed-cycle traffic light control is unable to make full use of lanes. Therefore, the authors in [11] present a novel simple and economic way to improve the traffic conditions as well as to reduce the average waiting time. Clearly, this approach holds two advantages: 1) it has the ability to collect traffic flow information and to transmit data by using wireless sensor networks; 2) it can dynamically adjust the delay for green light and change the cycle of signal light according to real-time traffic flow. For reducing the emissions scheme, a decentralized signal control technique is proposed in [12] for reduction of vehicle stops using vehicle arriving information collected by inter-vehicle communication. They introduce a real-time signal control method to minimize vehicular CO_2 emissions. Similarly, a decentralized control system proposed in [13] obtains traffic data using Radio Frequency Identification (RFID) technology for controlling the junctions' traffic lights and a real-time traffic lights control scheme is presented in [14] based on the Electronic Toll Collection (ETC). A complicated three-tier structure is proposed in [15] to realize dynamic traffic light control for smoothing vehicles' travel. After smoothing vehicles' travels, more vehicles can pass intersections with less waiting time and fewer short-time stops, so that the vehicles' CO_2 emissions can be reduced. Simulation results indicate that the proposed scheme performs much better than the adaptive fuzzy traffic light control method: The average waiting time, short-times, and CO_2 emissions are greatly reduced, and the nonstop passing rate is greatly improved.

In conventional studies, the advanced methods of traffic signal control usually require the installation of detectors on all links in the network such as the wide-area traffic signal control in [16], but that method has an interpolation function, it can be applied to a wide-area road network that includes links on which traffic meters have been not installed. For instance, the authors in [17] collect and aggregate real-time speed and position information on individual vehicles to optimize signal control at traffic intersections by vehicular ad hoc networks (VANETs). They explain how a VANET can be used to group vehicles into approximately equal-sized platoons. And in [18], they use camera sensors for providing real-time data.

The public literature does not address the way in which the signal-control logic is implemented. In order to implement or test any control strategy in the field or simulation, the control logic has to be translated into computer code. The authors in [19] present the use of Petri nets (PN) in modeling traffic signal control. Structural analysis of the control PN model is performed to demonstrate how the model enforces the traffic operation safety rules. More details can be found in [20], a model of such a network via hybrid PN is used to state and solve the problem of coordinating several traffic lights with the aim of improving the performance of some classes of special vehicles. In this work, an urban transportation network is considered to be a hybrid system, including both continuous-time and discrete event component. Petri nets play a key role among the modeling methodologies for discrete event systems (DES), they are able to capture the precedence relations and interactions among the concurrent and asynchronous events that are typical of DES. Several kinds of control problems can be addressed and solved by means of the proposed model. With special reference to the issues of the traffic light plan optimization, dynamic routing and special vehicle control. The hybrid modeling formalism is based on High Petri nets (HPNs), which has been adopted to represent an urban network of signalized intersections.

Considering the stochastic features of traffic conditions, [21] presents a stochastic and microscopic simulation model called application programming interface (API) based on AIMSUN and evaluates a novel real-time signal control technique based on the dynamic programming (DP) algorithm. The algorithm utilizes the detected vehicle counts and speeds to find the optimal signal plan that involved both phase sequence and duration over horizons which could be extended to any infinite time needed. Micro-simulation models are normally used to evaluate traffic-adaptive signal control systems. Analogously, an evolutionary algorithm in [22] is presented to solve the optimal control problem for energy optimal driving. Results show that the algorithm computes equivalent strategies as traditional graph searching approaches like DP. Another stochastic model is also established by the authors in [23] to dynamically optimize the minimum and maximum green times using real-time queue lengths and traffic arrival characteristics for each phase. The results show that the control system operated by the proposed algorithm produces promising improvements in system operation efficiency and fairness under various traffic demands. A methodology for developing a control policy that prescribes vehicle speed to minimize on average a weighted sum of fuel consumption and travel time, while travelling along the same route or a set of routes in a given geographic area is demonstrated in [24], which provides theory evidence for fuel efficient in traffic driving when it comes to stochastic dynamic programming control.

Advances in autonomous vehicles and intelligent transportation systems indicate a rapidly approaching future in which intelligent vehicles will automatically handle the process of driving. A novel model with a neural network is presented in [25] for public transport, normal cars, and motorcycles. The model controls traffic-light systems to reduce traffic congestion and help vehicles with high priority pass through. A fuzzy neural network (FNN) calculates the traffic-light system and extends or terminates the green signal according to the traffic situation at the given junction while also computing from adjacent intersection. Besides, it also monitors the density of car flows and makes real-time decisions accordingly. The authors in [26] propose a new intersection control mechanism called Autonomous Intersection Management (AIM). In [27], the signal control system of the congestion length is described by a nonlinear time-varying discrete dynamic system and synthesized by using the feedback control based on the volume balance at each signalized intersection. From the comparison of congestion lengths between measurement values controlled by a pattern selection method and simulation values, it is confirmed that the signal control system and the signal control algorithm work effectively in Hiroshima city, Japan. For the fact that the non-signal roundabout allows less flow rate, and with the increasing of roundabout flow rate, series of problems have occurred in respect of traffic jam, rising of accident rate, growth of traffic delay and increasing of saturation degree, the authors in [28] propose a concept based on the three control methods related with "Control of In-turn Discharge Clockwise at Signal-entrance Path", "Control of In-turn Discharge Clockwise at Signal-entrance Path + Interlace of Minor Flow" and "Association Roundabout Control at Multi-entrance Path". The results indicate that the arrangement of signal control at roundabout can greatly help to increase the traffic capacity and safety. Thus, adaptive traffic signal control is a promising technique for alleviating traffic congestion.

With mobile agent technology, traffic control strategies are designed as traffic control agents, which can move from device to device in a network. For a single agent, reinforcement learning (RL) has the potential to tackle the optimal traffic control problem. However, the ultimate goal is to develop integrated traffic control for multiple intersections. Integrated traffic control can be efficiently achieved using decentralized controllers. In [29], an extension of RL techniques, multi-agent reinforcement learning (MARL) makes it possible to decentralize multiple agents in non-stationary environments. Most of the studies in this field of traffic signal control consider a stationary environment. The models proposed are tested on a typical multiphase intersection to minimize the vehicle delay and are compared to the pre-timed control strategy as a benchmark. Similarly, a hierarchical networked urban traffic signal control system based on Multi-agent is proposed in [30]. This system can reconfigure and replace these agents according to inconstant states of traffic environment and performances of agents.

Traffic signal control is a very important method for both improving the traffic condition and saving energy and reducing gas emissions. It is the key embodiment of the idea for eco-driving. Besides, vehicles' cruise control is another important method for eco-driving, which will be detailed described in the following section.

The Cruise Control Methods

This section is focused on the cruise control methods. Cruise control can make the travel much more smoothly, so that the fuel economy and emissions are able to be reduced. Driving styles may result in large fluctuations in fuel efficiency. The authors in [31] explain how to determine the fuel-optimized operating strategies of passenger cars under cruising process. In the periodic operation, the engine switches between the minimum brake specific fuel consumption (BSFC) point and the idling point. The formation of periodic operation are analyzed and explained by the π-test theory and steady state analysis methods. But the use of periodic operation is not completely free but limited by other considerations in engineering practice. To avoid this problem, the concept of connected cruise control (CCC) is investigated in [32], where vehicles rely on ad-hoc wireless V2V communication to control their longitudinal motion. Intelligent vehicle cooperation based on reliable communication systems contributes not only to reduce traffic accidents but also to improve traffic flow.

For Advanced Driver Assistance System (ADAS) and self-driving cars, obstacle detection and fault tolerant are fundamental tasks. In [33], the authors present the design, development, implementation, and testing of a Cooperative Adaptive Cruise Control (CACC) system based on vehicle-to-vehicle (V2V) communications. A framework for the development of a CACC system is proposed in [34] and it presents the process for establishing an infrastructure for high performance vehicles, which is designed to be fault tolerant with the concept of sub-platoons. Meanwhile, the authors in [35] investigate the sampled-data CACC of vehicles with sensor failures and a novel switched sampled-data CACC system model is established. However, most of them are limited to specific scenarios and restricted conditions.

A robust sensor fusion-based method capable of detecting obstacles in a wide variety of scenarios using a minimum number of parameters is proposed in [36], which is based on the spatial-relationship on perspective images provided by a single camera and 3D Light Detection and Ranging (LIDAR).

When it comes to the concept of vehicle platoons, the cooperative adaptive cruise control strategy in [37] for platoon is extended. The control objective is to guarantee that the fleet moves forward with a given spacing policy at the leader velocity. For safety conditions, the authors in [38] outline a fuzzy logic based ADAS with integrated speed sign detection (SSD) capability. An ACC system considering the optimal energy and fuel consumption of the vehicle as well as safety aspects is designed in [39], the main novelty of which is the adaptation of forward traffic mean speed and safe cornering velocity in the look-ahead control algorithm. However, [40] concerned more about the idle time. To achieve the goal of reducing idle time at stop lights and fuel consumption, an optimization-based control algorithm is formulated to schedule an optimum velocity trajectory for the vehicle. What's more, a multi-objective Adaptive Cruise Controller of Hybrid Electric Vehicle (i-HEV-ACC) is proposed in [41]. It integrates both advantages of ITS and HEV, and it reaches comprehensive performances on traffic safety, fuel efficiency and ride comfort.

Different from the concern about safety or idle time factor, the approach named Linear Model Predictive Control is proposed in [42], which directly minimizes the fuel consumption rather than the acceleration of the vehicle. A novel learning-based cruise controller for autonomous land vehicles (ALVs) is presented in [43], which consists of a time-varying proportional-integral (PI) module and an actor-critic learning control module with kernel machines. The learning objective for the cruise control is to make the vehicle's longitudinal velocity follow a smoothed spline-based speed profile with the smallest possible errors. The experimental results of the cruise control show that the learning control method can realize data-driven controller design and optimization based on KLSPI and that the controller's performance is adaptive to different road conditions.

From the 90s, the Engine Control Unit (ECU) has been introduced at the first time on the gasoline powered vehicles. In [44], the authors study the hierarchical control approaches and improve the engine torque dynamics. What calls for special attention is that the normal adaptive cruise control doesn't work under the speed below 30 to 50 km/hour, which might cause driver inconvenience to drive. To solve this problem, the ACC with Stop \& Go is designed in [45] to work even at zero speed. In this case, vehicles can vary their speed within a preset speed window according to a vehicle predictive eco-cruise control system in [46] so that drivers can travel in a fuel-saving manner. Another prediction algorithm is presented in [47] by using multi-sensor fusion, which suggests the time series prediction of future vehicle states and the corresponding covariance matrixes for the pre-defined future time horizon. In research [48], an adaptive cruise control system is developed and implemented on an intelligent vehicle, the contribution of which is the modification for the original throttle system that is controlled by a cable from the accelerator pedal and braking system.

One more control method with error compensation algorithm is proposed to perform the velocity control model. In [49], a combined lateral and longitudinal rule based upper level control algorithm of a cooperative vehicle is presented. The control system architecture is designed to be hierarchical; the lower level controllers receive the commands from the higher level controller that defines the driving mode of the vehicle. Analogously, the architecture proposed in [50] is also divided into two loops. The nonlinear balance-based adaptive control (B-BAC) technique accounts for system nonlinearities and it allows for split range control of both the brake and the throttle. Furthermore, The hardware design and the low level control strategy for braking, throttle and gearshift actuators for these case studies are presented in [51], the general ACC structure and different cooperative CACC approaches are discussed for highway platoon. To develop ACC, the conventional throttle valve system in [52] is modified to the drive-by wire system. The results show good performance of the ACC system.

This section mainly discuss the methods for cruise control, the core idea of which is to smooth the whole travel process by dynamically adjust the vehicles' speed based on the collected traffic information. In the next section, we will introduce some eco-driving assist systems.

The Eco-Driving Assist System

This part aims to present several kinds of the up-to-data eco-driving assist system. The goal of adaptive infrastructure designs and strategies for speed control is to help drivers improve their skills for the energy conservation and emission reduction. In [53], the authors developed the components which can obtain the eco-driving and safe-driving information. The drivers can change the wrong driving styles and behaviors for themselves after they have checked the eco-driving and safe-driving information provided by the components. Besides, an intelligent eco-driving suggestion system based on vehicle loading model is presented in [54]. The instantaneous fuel economy is computed according to the information from vehicle on board diagnostic system and the experimental results indicate that 7% fuel economy can be improved. An effective eco-driving assist system adaptive to a driver's skill is presented in [55]. In this proposed adaptive system, the resolution of the indicator and the threshold of eco-driving are changed to adapt to the driver's skill.

An intelligent technology for real-time vehicle diagnostics and early fault estimation is developed in [56]. This system can increase the driving safety as well as decrease the air pollution and unnecessary fuel consumption caused by vehicle faults. The authors in [57] present the construction of an aggregated indicator of a fuel-efficient driving style. Depending on some driving indicators, the estimated probability of being an eco-driver is used as an eco-index to characterize that driving pattern. A driver assisting system for cooperative cruising of multiple cars is presented in [58], the advantage of global optimization for cooperative safety is confirmed by comparing its control performance with the local optimization for individual safety. In addition, the Artemisa's assistant runs on a mobile device with Android O.S. and it does not need to install addition hardware compared to other similar systems in [59].

Issues & Summary

Nowadays, the mainstream methods for eco-driving usually contains two aspects: one is to give drivers optimal velocity by the control algorithms based on the current collected real-time traffic information via V2V communications or short radars. The other aspect is the adaptive design for public infrastructures such as traffic lights, which can work in a dynamic prediction way to reduce the idling and waiting time. The purpose of both aspects is to make the travel trip smoothly as much as possible. Driving cycle has the underlying markov property to some extent, it can be a new method to save energy and reduce emission in the future. For automakers, they can produce the engines that can reduce the fuel consumption; the streamlined design for coachwork is also efficient. For express highway, new manufacturing processes can do well job to eco-driving, because improvements of highways play an important role in fuel saving. In addition, low-performance vehicles and unchecked vehicles may consume higher amounts of fuel than frequently checked vehicles; drivers should do maintenance on vehicles at regular time and keep them in good conditions.

Acknowledgment

This work is supported by the National Science Foundation of China (No.61401387 and No.61472343), Universities Natural Science Research Project of Jiangsu Province (No.14KJB510035) and the Innovation Fund from YZU (No. 2013CXJ023). J. Ding also acknowledges the support by SRF for ROCS, SEM, and Talent Project of New Century, Yangzhou University.

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