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Energy-efficient routing based on vehicular consumption predictions of a mesoscopic learning model

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ABSTRACT

This paper proposes an alternative approach for determining the most energy efficient route towards a destination. An innovative mesoscopic vehicular consumption model that is based on machine learning functionality is introduced and its application in a case study involving Fully Electric Vehicles (FEVs) is examined. The integration of this model in a routing engine especially designed for FEVs is also analyzed and a software architecture for implementing the proposed routing methodology is defined. In order to verify the robustness and the energy efficiency of this methodology, a system prototype has been developed and a series of field tests have been performed. The results of these tests are reported and significant conclusions are derived regarding the generated energy efficient routes.

1. Introduction

Environmental impact and economic factors impose the need for reducing the amount of energy spent by a vehicle in order to travel from a source to a destination point. Minimizing the consumed fuel leads not only to financial savings but also to simultaneous reductions in the released emissions, as their volume is proportional to the vehicles consumption rate [1]. Even in the case of zero emission vehicles, like Fully Electric Vehicles (FEVs), reducing the energy consumption contributes into limiting both the travel cost as well as the environmental impact coming from the generation (in power stations) and transfer of the energy required for vehicle recharging.

Considering the current progress in the development of energy-efficient vehicles, which achieve low consumption rates by means of aerodynamic shapes, energy-efficient engines or the use of alternative fuel resources (e.g. FEVs), further improvements can be enabled through the utilization of information and communication technologies (ICT). Eco-driving and eco-routing techniques implemented by intelligent transportation systems have been proposed for enhancing the vehicles energy efficiency. In particular, eco-driving systems [2,3] analyze the current status of the vehicle together with consumption-related parameters and provide valuable feedback to the user in order to modify his/her driving style and attitude in an energy-efficient manner. Thus, such systems are quite efficient in reducing a vehicles current energy consumption when following an energy-demanding route (e.g. a route characterized by steep upward slopes), but they do not inform the user beforehand to avoid (if possible) such routes and to follow better ones [4,5]. This latter task, due to its inherent uncertainty, is not as straightforward and is performed by the so-called eco-routing systems [6,7].

Eco-routing systems [8] try to identify the most energy-efficient route towards the desired destination based on their estimation about the energy required to travel along each one of all the possible routes and prevent the driver from making a bad choice (i.e. selecting an energy demanding route). The effectiveness, however, of such systems is limited due to the incertainty of predictions that introduces an amount of error into the calculations. In addition to this limitation the existing systems cannot be used in case of FEVs as the FEVs' peculiarities were not taken into consideration during their development. Existing eco-routing systems can be effectively applied only in case of vehicles powered by internal combustion engines. The proposed system aims at tackling both these limitations by implementing an innovative mesoscopic consumption model that minimizes prediction error and an advanced routing engine that is especially designed for FEVs.

Such an eco-routing system is proposed in the present paper, enabling the discovery of the most energy-efficient route towards the destination based on more accurate energy cost predictions. In order to improve the estimation accuracy achieved by

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existing eco-routing techniques, the proposed system implements a context-aware learning model. Implementing a learning model involves defining an appropriate model that comprises a set of parameters and then optimizing these parameters using past experience [9,10]. A systematic description of the developed learning model and the introduced routing methodology is presented in the rest of this paper. In particular, Section 2 contains an overview of the existing eco-routing techniques and energy consumption models developed so far. Section 3 describes in detail the development process of the proposed routing methodology and elaborates thoroughly on the introduced learning model. A system architecture suitable for application in FEVs is presented in Section 4. Based on this architecture, a system prototype is implemented and installed in a FEV so as to perform a series of field trials. The prototype implementation as well as the field trials results are reported in Section 5. Finally, Section 6 summarizes the work described in the present paper and emphasizes on the degree of energy efficiency achieved by the proposed methodology.

2. Related work

Several studies have investigated the impact of route choices on the energy consumption and emission rates of vehicles [11–14,6,15,16]. The common finding of these studies is that following the fastest path towards the destination is not always the best choice from an environmental and energy consumption perspective. For example, comparing the results of a driving experiment performed in Japan [11], the fuel consumption of the ecological route is 9% lower than that of the time priority route, while its travel time is 9% longer. In another experiment performed between the Los Angeles Airport and the Los Angeles center [12], the least fuel consumption route is compared against the shortest duration route. According to this comparison, the least fuel consumption route is 25% more energy efficient and 8% slower than the shortest duration route. Likewise, the results of a field trial performed in the Northern Virginia area [13] demonstrate that significant improvements in energy consumption (18–23%) and air quality (4–5% reduction in NOx and 20% reduction in CO_2) can be achieved when motorists utilize a slower and 30% longer arterial route instead of a faster highway route.

Hence, considering the existence of an eco-friendly route as a possible routing choice, several models have been proposed for finding the path that minimizes vehicular consumption. A classification of these models can be based on the type of the methodology employed for predicting the energy consumption along all possible paths towards the destination, which enables their categorization into macroscopic, mesoscopic and microscopic models.

A macroscopic, non-iterative algorithm for estimating vehicular fuel consumption is presented in [17]. The algorithm uses Willan's internal combustion engine model [18] and needs no instantaneous values of speed and acceleration. The efficiency of the proposed algorithm has been verified with measurement results for the following three cycles: motor vehicle expert group (MVEG-95), European driving cycle (ECE), and extra-urban driving cycle (EUDC). Another macroscopic emission estimation tool, called MOBILE6, is utilized in the study performed in [13], and its performance is compared against that of two microscopic tools, i.e. the VT-Micro model and the comprehensive modal emissions model (CMEM). The comparison results of the study, however, demonstrate that macroscopic tools can produce erroneous conclusions given that they ignore transient vehicular behavior along a route.

Transient vehicle states are captured by microscopic models like the one presented in [11]. Authors describe a fuel consumption factor analysis using Oguchis consumption model and identify five factors as major contributors in vehicular consumption, i.e. the base consumption, the friction loss, the altitude change loss, the air drag loss and the acceleration loss. The base fuel consumption factor refers to fuel used for the inertial resistance of the engine and the transmission, the air conditioner and some other electric components, while the other four factors express energy losses due to the vehicles movement. The consumption values estimated by the microscopic tool are, then, fed to a Dijkstra-based [19] routing engine and the most energy-efficient route is extracted. The driving experiments conducted in areas with different geographical features and in various traffic conditions identified base consumption and geographic morphology as the dominant determinants of vehicular fuel consumption.

Apart from deterministic models that are usually based on the laws of physics [11], microscopic tools include also models that exploit artificial intelligence techniques. The fuel consumption predictive system described in [20,21] uses a neural network in order to infer vehicular consumption from previously collected experience. The inputs of the network include the brand of the vehicle, the engine type, the vehicle weight, the vehicle class and the transmission system type, while the output corresponds to the vehicles fuel consumption rate indices for each test cycle (i.e. city, highway or combined).

Despite their acceptable performance, microscopic consumption estimation models are quite complex and detailed for application in dynamic route guidance systems. Building a system whose performance depends on the continuous retrieval of microscopic parameters (e.g. instantaneous speed, instantaneous acceleration, or road grade) is not practical, considering that acceptable accuracy can also be achieved by less complex mesoscopic models.

Mesoscopic models estimate emissions and/or fuel consumption on a link basis. Their input parameters reflect average values of observable variables in the context of a time period, e.g. average speed, average acceleration or deceleration, etc. The mesoscopic research tool presented in [7] generates synthetic speed profiles based on historical link speed data, stores them as digital map attributes and uses them for calculating fuel costs per link. Link travel speeds are also employed in the mesoscopic energy consumption model of [22] together with the actual power needed to overcome the driving resistance for each link and with the volume over capacity traffic ratios. In [23] the authors introduce a dynamic eco-route planning system utilizing Dijkstras shortest path algorithm and consisting of a power-dependent consumption model and a dynamic traffic information database. A special mechanism for integrating the impact of dynamic changes of traffic conditions on route planning is described in [12]. In particular, the authors propose an eco-routing navigation system that consists of: a Dynamic Roadway Network database, which is a digital map of a roadway network that integrates historical and real-time traffic information from multiple data sources through an embedded data fusion algorithm; a multivariate regression model that estimates an energy/emissions operational parameter set [fuel, CO_2, CO, HC, NO_x] based on vectors of vehicle characteristics, roadway characteristics, traffic characteristics and other explanatory variables; a routing engine, which contains shortest path algorithms used for optimal route calculation; and a user interface that allows the interaction with the user. The reported validation results suggest a reasonable estimation performance; nevertheless, researchers identify some system limitations that may result in errors in the estimated trip fuel consumption and emissions.

Considering the progress achieved in the area of eco-routing, the characteristics of the developed models and the results of the performed sensitivity and empirical analyses (e.g. [24,25]), the authors of the present paper introduce an innovative mesoscopic approach for energy-efficient routing based on machine learning