GECM: A Novel Green Wave Band Based Energy Consumption Model for Electric Vehicles

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***Abstract*—The increasing per capita vehicle ownership has led to extremely serious traffic congestion, energy crisis and environment pollution. Electric vehicle, as a representative of energy structure transition and traffic component changes can effectively solve the mentioned issues. In this paper, we propose a novel energy consumption model for electric vehicles, Green wave band based Energy Consumption Model (GECM), which is built upon traffic signal control theory and combines with the distribution of energy consumption in a macroscopic view. This model designs green wave scenarios based on the traffic signal data in real traffic surroundings, and involves specific parameters like offset and green split for the analysis of energy consumption. Simulation results show that the energy saving and efficiency improvement are available and feasible for electric vehicles under the proposed model.**

I. Introduction

With the increasing demand for private vehicles, the urban traffic problems are becoming gradual serious, such as environment pollution, traffic congestion, potential safety risks and so on, which lead to heavy pressures and unprecedented challenges for cities.

In urban traffic scenario, the Green Wave Band (GWB) formed by traffic signal control technologies is an achievable and dependable technology, which provides an effectual solution for traffic issues [1]. It is possible that the vehicle can drive through different intersections consecutively by using the green wave strategy and greatly reduce the fragmentation effect of travel time for drivers. Simultaneously, the green wave effect can enhance the traffic capacity of the road, which makes a significant improvement.

In 1990, Gartner et al. improved the MAX-BAND method, considering the turning left of vehicles and the green wave bandwidth of different sections, MULTIBAND model was first proposed [2]. In order to reduce the amount of computation, Hu et al. simplified the MULTIBAND model [3].

In particular, by continuously optimizing the cycle of each intersection, Naohisa et al. made the sum of offset at intersections in the closed network do not have to satisfy the constraint of the integer multiple of the common cycle [4]. Besides, in 2016, Chen et al. proposed a cooperative traffic control framework for optimizing the global throughput and travel time for multiple intersections, which provides fairness for each road segment and realizes the green wave concept for arterial roads [5]. Specifically, the green split, offset and signal period are the principal vital parameters in GWB [6].

Electric vehicle (EV), as another approach to address urban traffic issues from the source, can significantly reduce emissions and improve air quality, and has its own unique characteristic-braking energy regeneration. Compared with the traditional vehicle, it can convert the mechanical energy into electrical energy effectively, so as to make the limited power reuse fully.

In a long-term practice, a cost-effective approach to solve the above issues could be obtained if people introduce green vehicles, change traffic flow components progressively and make full use of urban infrastructures for traffic management. However, most of the existing energy consumption models focus on the conventional fuel vehicles. Although several studies on energy consumption model have paid enough attention to EVs, they have never applied GWB and such models to actual scenario. Therefore, the energy consumption model for electric vehicles remain a promising research field.

In this paper, we present a Green wave band based Energy Consumption Model (GECM) for the sake of improving the energy efficiency of EV and taking advantages of GWB. It is the first ever attempt to design a energy consumption model with GWB for EV. In terms of applying parameters in green wave band, the proposed model can not only make the electric vehicle work efficiently, but also enable the electric vehicle to obtain a positive impact from GWB.

The remainder of the paper is organized as follow: Section II outlines the related work of energy consumption models for EV and GECM is presented in Section III. Section IV discusses the simulation results. Finally, conclusions are given in Section V.

II. Related Work

Since the concept of new energy vehicle was bought forward, energy consumption models have being paid much attention in researches. Logically, they can be divided into two categories: microcosmic model and macroscopic model [7]. Microcosmic energy model focuses on battery and considers more the characterizations of itself and chemical reaction. On the contrary, driving behaviors are enormously influenced by the complex macroscopic traffic conditions. Therefore, it is more apposite to study energy consumption of EV with microscopic model under real urban scenarios.

For the prediction of travel mileage, De Cauwer et al. established the energy consumption model of pure electric vehicle on the perspective of electricity transmission [8]. In [9], based

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on the aforementioned research results, Lebeau et al. indicated that the impact of energy consumption owing to auxiliary devices on electric vehicle can make such prediction more accurate. Besides, according to the characteristic of regeneration energy, Prandtstetter [10], Fiori [11] et al. calculated instantaneous power of EV by exploiting the instantaneous power parameters.

In addition, to make the energy consumption of EV intimately relevant to real situation, Gao et al. worked out the energy consumption in braking process as well as the overall consumption in different cities associating with various types of drive cycles (acceleration, uniform and deceleration) [12]. Considering the relationship between the surrounding environment and energy consumption of EVs, Campanari, Manzolini et al. came to a conclusion that when in a specific drive cycle, different mileage will cause different energy consumption [13].

As we can see from the above-mentioned studies, although several energy consumption models related to real traffic scenario are presented, none of these models has involved the traffic signal control theory and green wave effect. In other words, current energy consumption models lack of considerations in traffic management and corresponding analysis.

III. Green wave band based Energy Consumption Model

In this section, we first build the basic energy consumption model for EV in accordance with dynamics and the crucial parameters are introduced for GWB. The following sections describe the energy consumption model and the proposed approach of GWB in detail.

A. The Dynamics-based Energy Consumption Model

On the basis of physics theories, there are four main forces: traction F, air resistance F_a, rolling friction F_r and slope resistance F_g in the driving direction of EV, the stress analysis is shown in Fig.1 and formulated as

$$F = ma + F_a + F_r + F_g, \tag{1}$$

where m is the mass (kg) of EV, a is the acceleration created by the resultant force (m/s^2) and the air resistance, rolling friction and slope resistance can also be expand to the following formulas:

$$\begin{cases} F_a = kv^2 = \frac{\rho_a}{2} C_D A_f v^2 \\ F_r = f_r mg\cos\theta \\ F_g = mg\sin\theta \end{cases}, \tag{2}$$

where v is the velocity (m/s) of vehicle, the aerodynamic resistance coefficient k is constant, which is determined by the air density ρ_a (kg/m^3), the frontal area A_f (m^2) and the air resistance coefficient C_D, f_r is the rolling friction coefficient, g is the acceleration of gravity (m/s^2) and θ denotes the road slope (deg).

To provide the driving force for electric vehicle, the output power P should be calculated as

$$P_d = Fv = \left(ma + kv^2 + f_r mg\cos\theta + mg\sin\theta\right) v. \tag{3}$$

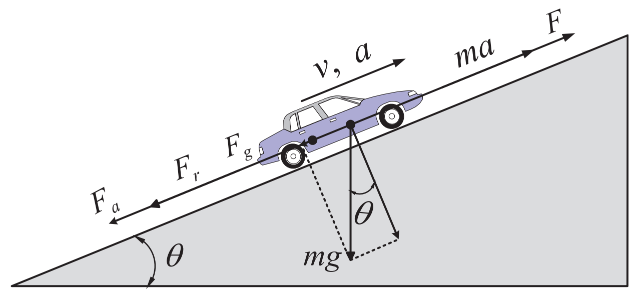

Fig. 1: Analysis of stresses exerted on vehicle

In addition, the power that EV needed also includes the auxiliary power and thermal power consumption, which is denoted as P_m. For the total amount of instantaneous consumption power of EV, we have

$$P = P_m + P_d, \tag{4}$$

combined with (3) (4), P_m can also be calculated as

$$P = P_m + v\left(kv^2 + f_r mg\cos\theta + mg\sin\theta\right) + mav. \tag{5}$$

And (5) can be transformed into the following form:

$$P = P_m + P_r + P_a, \tag{6}$$

the corresponding relationships of equations are

$$\begin{cases} P_m = P_m \\ P_r = v\left(kv^2 + f_r mg\cos\theta + mg\sin\theta\right) \\ P_a = mav \end{cases}, \tag{7}$$

P_m denotes the instantaneous consumption power of the auxiliary devices and internal depletion and P_r means the power for EV to overcome the resistances (air obstruction, rolling friction and slope resistance), P_a is the required power for electric vehicle to speed up.

Therefore, the equation to estimate the total energy consumption E for a time period T is:

$$E = \int_0^T P(t)dt. \tag{8}$$

The main difference between EV and traditional internal combustion engine vehicle is the energy regeneration in braking. Therefore, according to [10], we can obtain the energy recovered from braking, which can be formulated as

$$E^- = \frac{1}{2} m \sum_{k=0}^{n} \left(v_{k+1}^2(t) - v_k^2(t)\right), \tag{9}$$

where $v_{k+1}(t)$ and $v_k(t)$ denote the final velocity and initial velocity during braking, and k is the times of braking.

Since the kinetic energy of the brake recovery is not entirely converted into the battery power, accordingly, it is necessary to consider the conversion efficiency.

To sum up, the total energy expenditure of EV will be converted from E to E^- over a period of time, we have

$$E' = E + \mu E^-, \tag{10}$$

where μ signifies the conversion rate of regenerative energy.

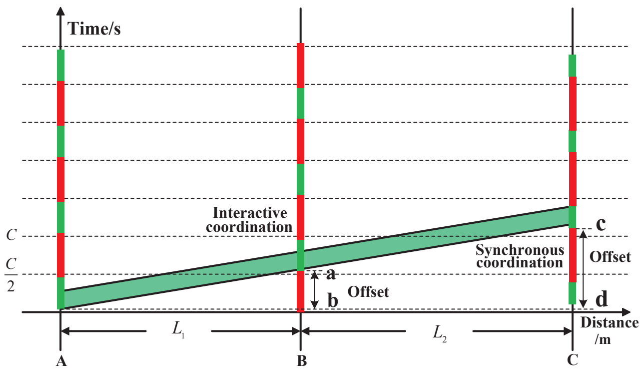

Fig. 2: Schematic design of offset in GWB

B. The Design and Optimization with GWB

For the design of green wave band, green wave effect can be formed by the traffic signal control scheme when taking into account the offset among intersections. Before offset design, the following items need to be known: 1) the distance L_i between each two intersections, 2) the average speed of traffic flow V, 3) the signal cycles at intersections and the duration of green signals (ignore amber light), which is also referred to the green split. The effectiveness of offset optimization is shown in Fig.2, the horizontal axis is the distance while the vertical axis denotes time.

In this diagram, C is the public cycle of all signals, and the two parallel lines are the boundaries of GWB, whose reciprocal of slope is the average velocity of traffic flow. Moreover, the spacing between the upper and lower boundary means the bandwidth in GWB. The vertical red and green lines further indicate the durations of red signal and green signal, which are proportional to the length of line segments. Assuming that, intersection A is the critical intersection, the absolute offsets intersection B and A as well as intersection C are ab and cd respectively. According to the junction of GWB and time axis, the coordination method will be chosen. Through the above optimization, the green wave effect appears in the arterial road.

C. Design of GECM

By above knowable, during vehicles travel between adjacent intersections in GWB, suppose that a vehicle counts the time at the start of the green signal at an intersection, it is practicable to meet another green signal at the next intersection for traveling a period of time L_i/V; in contrast, if a vehicle gets into the intersection beyond the period of green wave bandwidth, there will be encountered red light to some extent and result in a waiting queue. In order to facilitate investigation, the current traffic flow is approximately divided into four stages: the uniform acceleration, uniform motion, uniform deceleration and stop, the stop phase exists at the starting and end points, as shown in Fig.3

Assuming that EV enters the intersection at moment 0 and travels on road section i, (10) can be transformed into the following form:

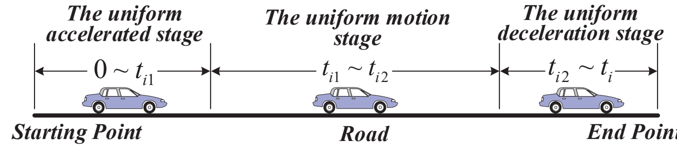

Fig. 3: Driving phases of EV

$$E_i{}' = E_i + \mu E_i{}^{-}, \tag{11}$$

specifically, E_i can be represented by three parts:

$$\begin{aligned} E_i &= E_{ir} + E_{ia} + E_{im} \\ &= \int_0^{t_i} (P_{ir}(t) + P_{ia}(t))dt + \int_{t_i}^{\frac{L_i}{V}} P_{im}(t)\,dt \\ &= \int_0^{t_{i1}} (P_{ir_1}(t) + P_{ia_1}(t))\,dt + \int_{t_{i1}}^{t_{i2}} P_{ir}(t)\,dt \\ &+ \int_{t_{i2}}^{t_i} (P_{ir_2}(t) + P_{ia_2}(t))\,dt + \int_0^{\frac{L_i}{V}} P_{im}(t)\,dt. \end{aligned} \tag{12}$$

where E_{ir} denotes the energy required to overcome resistance, E_{ia} denotes the energy required to accelerate, E_{im} denotes the heat consumption of auxiliary devices and internal resistance. With all that in mind, combined with (9) (11) (12), the total energy consumption with GWB on road section i is:

$$\begin{aligned} E_i{}' &= \int_0^{t_{i1}} (P_{ir_1}(t) + P_{ia_1}(t))\,dt \\ &+ \int_{t_{i1}}^{t_{i2}} P_{ir}(t)\,dt + \int_{t_{i2}}^{t_i} (P_{ir_2}(t) + P_{ia_2}(t))\,dt \\ &+ \int_0^{\frac{L_i}{V}} P_{im}(t)\,dt + \mu\frac{1}{2}m\sum_{k=0}^{n}\left(v_{ik+1}^2(t) - v_{ik}^2(t)\right) \end{aligned} \tag{13}$$

where $0 \sim t_{i1}$ denotes the uniformly accelerated stage, $P_{ir_1}(t)$, $P_{ia_1}(t)$ denotes the power consumption to overcome the external force and the acceleration resistance and a_1 is acceleration.

$t_{i1} \sim t_{i2}$ means the uniform motion phase, and $P_{ir}(t)$ indicates the power of overcoming the external resistance.

$t_{i2} \sim t_i$ denotes the uniformly deceleration process, $P_{ir_2}(t)$ $P_{ia_2}(t)$ signify the power consumption to overcome the external force and the deceleration resistance respectively and a_2 is deceleration.

$v_{ik+1}(t)$, $v_{ik}(t)$ represent the final state and initial state velocity of the braking energy recovery of kth time.

$P_{im}(t)$ shows the thermal-power consumption of the auxiliary devices and internal resistances.

The expressions in (13) correspond to energy consumption of the uniform acceleration stage, the uniform stage, the deceleration stage, the braking energy recovery process and the whole auxiliary device as well as the internal heat during the travel interval (offset) with green wave effect.

TABLE I: Data of Traffic Signals

Intersection	Position	Signal time(s)			
		Red	Green	Amber	Total
A	West	80	59	3	142
	East	80	59	3	142
B	West	52	39	3	94
	East	52	39	3	94
C	West	138	57	3	198
	East	138	57	3	198

Therefore, after the vehicle travelled through N intersections with green wave effect, the total consumed energy E_{all} can be formulated as

$$E_{all} = \sum_{i=1}^{N} E_i{}'. \tag{14}$$

IV. Simulation and Evaluation

A. Simulation Setup

Partial segments of east-west Youyi Road in Xi'an are selected as our simulation scenario, which involves with three intersections. Fig.4 shows the realistic map of Xi'an. Corresponding to the traffic elements, gray lines generated by VISSIM depict the topology of road networks whose size is 2778m $\times$ 975m. And the lengths of section 1, 2, 3 and 4 are 795m, 634m, 718m and 631m separately. A, B and C markers in Fig.3 represent the three intersections mentioned above. Through field testing, the data of east-west traffic signals in each intersection is shown in Table I.

We design green wave band combining with the graphical method, the results can be obtained: taking junction A as a benchmark, the absolute signal offsets of junction B and C are: 100s and 13s.

The parameters related to system model and simulation are summarized in Table II.

TABLE II: Simulation Parameters

Parameter	Value
Vehicle mass (m)	$1210kg$
Coefficient of air resistance (C_D)	0.334
Air density (ρ_a)	$1.3kg/m^3$
Frontal area (A_f)	$2m^2$
Rolling friction coefficient (f_r)	0.009
Acceleration of gravity (g)	$9.81m/s^2$
Vehicle velocity (v)	$20 \sim 25km/h$
Road slope (θ)	$0deg$
Battery self-power (P_m)	$700W$
Conversion rate of regeneration (μ)	0.6
Acceleration (a_1)	$1.265 \sim 3.4m/s^2$
Deceleration (a_2)	$2.45 \sim 3m/s^2$

B. Analysis of Results

Except the simulation setup above, we also design several function modules such as travel timer, queuing counter, data collector and so on. On this basis, we conduct a series of simulations to evaluate the indexes (e.g., average speed, delay and number of vehicle stops, etc.) involved with our proposed model. Moreover, utilizing the data collected from sensors, we simulate and compare the energy consumption of EV by ADVISOR.

Fig. 4: Partial realistic road for simulation in Xi'an

As shown in Fig.5, the average speed of vehicles significantly increases by introducing GECM. When the traffic flow increases, the average spacing between vehicles becomes cramped. Naturally, the vehicles will slow down to ensure safe driving. Furthermore, the speed of the vehicles will plummet when the traffic flow rises to an explosion, which can be mitigated by applying GECM. Meanwhile, the increase of average speed between fleets means that the delay time of vehicles and average travel time in a road segment will decline.

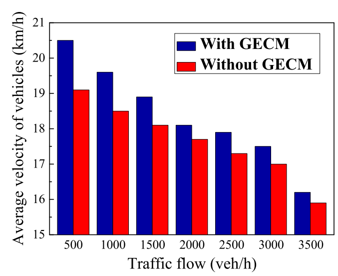

Fig. 5: Average velocity versus traffic flow in two scenarios

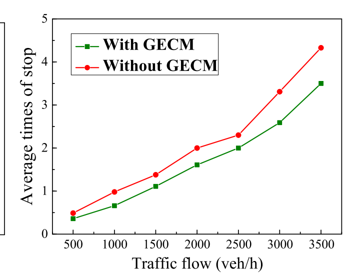

Fig. 6: Average stops versus traffic flow in two scenarios

With the growth of the traffic flow, the queue of vehicle fleet will lengthen at an intersection and vehicles will be susceptible to more stops in the process of queue dissipation. Under this circumstance, Fig.6 compares the average times of stop with and without applying GECM. In particular, this mechanism can reduce the appears of frequent running-up and stop, and the greater the flow is, the more obvious the effect is.

Fig.7 illustrates the average latency of EVs decreases by adopting GECM. In the case of traffic flow has not yet reached a high saturation, the green line in figure shows that the average delay of vehicles can be reduced by approximately 20%, which means drivers can arrive at destinations faster.

Additionally, we treat SOC (State of Charge) as a gauge of the energy consumption of EV. And SOC also means the remaining power or energy of electric vehicle.

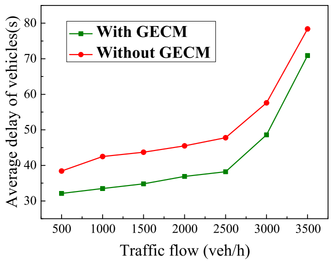

Fig. 7: Average delay versus traffic flow

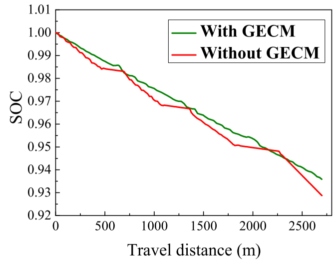

Fig. 8: SOC versus travel distance in two scenarios

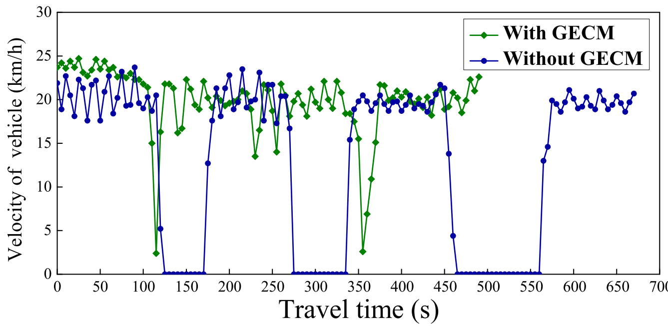

Fig. 9: Real-time velocity in different scenarios

With regard to energy consumption, a conclusion can be drawn from the changing tendency of red and green curves in Fig.8: in the case of the same driving distance, the SOC value of EV with the coordination of the GECM is slightly larger than the SOC value without it. It means that EV is more efficient with the proposal. The SOC attenuation curve is almost a straight line (linear relationship) by applying GECM, which makes it effortless to achieve load balance. On the contrary, the corresponding curve without GECM is seriously choppy. In fact, there are quite a few adverse effects on battery due to the unstable energy supply in EV. What's more, it can be perceived that the SOC curve with GECM has a minute convex during braking. The truth is that braking energy can be recycled relatively and effectively for EV.

Fig.9 shows the relationship of the real-time velocities of EVs. The state of speed 0 is essentially absent combining by applying GECM. the foremost reason is that the vehicle needs no stop or just slows down a bit at the intersection. However, in an ordinary scenario without GECM, the speed of electric vehicles fluctuates greatly, and the velocity of zero turns up repeatedly, which reflects the frequent occurrence of traffic jams. Therefore, the advantages of GWB are evident here, which can keep the vehicle system running stabely with a comparatively high speed.

V. Conclusion

In this paper, we present an innovative Green wave band based Energy Consumption Model (GECM) to characterize the benefits of EV in urban traffic scenario. The model is investigated by traffic management and electric vehicle comprehensively, resulting in that the total energy consumption of EV can be integrated with the nature of time factors in GECM. As demonstrated by simulation results, the proposed model can reveal the braking energy regeneration characteristic of EV. In the meantime, GWB can reduce the average travel time and delay of the traffic flow effectively , and bring down the queue length and stops. On the whole, the improvements and positive effects of GWB are accentuated with considering its favorable attributes, which further prove the exactness and validity of GECM.

Acknowledgment

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References

[1] R. Sundar, S. Hebbar, and V. Golla, "Implementing intelligent traffic control system for congestion control, ambulance clearance, and stolen vehicle detection," *IEEE Sensors Journal*, vol. 15, no. 2, pp. 1109–1113, 2015.

[2] N. H. Gartner, S. F. Assmann, F. Lasaga, and D. L. Hous, "Multiband–a variable-bandwidth arterial progression scheme," *Transportation Research Record*, no. 1287, 1990.

[3] H. Peifeng, T. Zongzhong, Y. Zhenzhou, and J. Shunping, "Variable-bandwidth progression optimization in traffic operation," *Journal of Transportation Systems Engineering and Information Technology*, vol. 11, no. 1, pp. 61–72, 2011.

[4] N. Aoki, H. Niimi, and S. Kamijo, "Offset optimization of traffic signals to maximize green time overlap considering the vehicle arrival profile for two-dimensional networks," in *Proc. of IEEE ITSC*, 2013, pp. 738–743.

[5] L.-W. Chen and C.-C. Chang, "Cooperative traffic control with green wave coordination for multiple intersections based on the internet of vehicles," *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, 2017.

[6] B.-L. Ye, W. Wu, X. Zhou, W. Mao, and Y.-S. Huang, "A green wave band based method for urban arterial signal control," in *Proc. of IEEE ICNSC*, 2014, pp. 126–131.

[7] H. El Fadil, F. Giri, J. M. Guerrero, and A. Tahri, "Modeling and nonlinear control of a fuel cell/supercapacitor hybrid energy storage system for electric vehicles," *IEEE Transactions on Vehicular Technology*, vol. 63, no. 7, pp. 3011–3018, 2014.

[8] C. De Cauwer, M. Maarten, T. Coosemans, J. van Mierlo, and S. Heyvaert, "Electric vehicle use and energy consumption based on real-world electric vehicle fleet trip and charge data and its impact on existing ev research models," in *Proc. of the International Electric Vehicle Symposium and Exhibition*, vol. 36, 2015, p. 111.

[9] P. Lebeau, C. De Cauwer, J. Van Mierlo, C. Macharis, W. Verbeke, and T. Coosemans, "Conventional, hybrid, or electric vehicles: Which technology for an urban distribution centre?" *The Scientific World Journal*, vol. 2015, 2015.

[10] M. Prandtstetter, M. Straub, and J. Puchinger, "On the way to a multi-modal energy-efficient route," in *Proc. of IEEE IIECON*, 2013, pp. 4779–4784.

[11] C. Fiori, K. Ahn, and H. A. Rakha, "Power-based electric vehicle energy consumption model: Model development and validation," *Applied Energy*, vol. 168, pp. 257–268, 2016.

[12] Y. Gao, L. Chen, and M. Ehsani, "Investigation of the effectiveness of regenerative braking for ev and hev," SAE Technical Paper, Tech. Rep., 1999.

[13] S. Campanari, G. Manzolini, and F. G. De la Iglesia, "Energy analysis of electric vehicles using batteries or fuel cells through well-to-wheel driving cycle simulations," *Journal of Power Sources*, vol. 186, no. 2, pp. 464–477, 2009.