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Energy Management Strategy in Electric Buses for Public Transport using ECO-driving

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***Abstract*—Energy management strategy is a critical aspect in electric vehicles to increase driving range, minimize costs, and extend battery life. In electric bus drivetrains, energy management strategy can be utilized to optimize operation of auxiliary systems, charging systems, and the operation of the electric powertrain. The electric powertrain is composed of several components linked in series, each having their own optimum band of operation. The paper studies various strategies to actuate the electric motor complemented with appropriate gearbox ratios to maximize the efficiency of the propulsion energy transmission, maintain vehicle speed and acceleration constraints, and electric motor angular speed and torque constraints. This paper also proposes an ECO friendly velocity profile based on smooth velocity changes, and limitations in top speed and acceleration to reduce energy consumption and using regenerative braking to recover energy. Results show that bang-bang actuation styles have less optimal energy utilization; however, maximum power actuation style can recover the most energy from braking.**

***Keywords*—Energy Managenent Strategy; ECO-driving; Electric Bus; Public Transport; Electric Motor; Regenerative Braking.**

I. INTRODUCTION

An efficient and well-planned public transport plays a significant role in reducing the various traffic woes facing various metropolitan centers, including congestion and harmful vehicular emissions. Plentiful and accessible electrified public transport also increases the mobility coefficient of a city's residents; not only does it improve business, transport and logistics, but also incurs health benefits for the populace. All these result in increased productivity and long-term financial gain for the city, thus increasing its prosperity. Furthermore, the electrification of the city's transportation system will go a long way towards reducing greenhouse gas (GHG) emissions and making the city carbon neutral. Electrification of the city transportation system brings with it a myriad of challenges that must be met for the initiative to become successful and financially viable. These include investing in citywide charging infrastructure and replacing the Internal Combustion Engine (ICE) based bus fleet with those having an electric or hybrid powertrain.

One of the issues with electric vehicles (EV), when compared to traditional vehicles, is the driving range that the vehicle can achieve on a single battery charge. A typical 12m diesel bus, with a 227-liter (50-gallon) fuel tank, used for public transport in urban areas, has an average fuel efficiency of 80L/100km (3.5mpg) [1]. As such, a diesel-powered bus can easily cover its entire daily route of up to 250km on a single tank of fuel; furthermore, it takes less than 10 minutes to refuel its tank at a filling station. Electric buses, on the other hand, have a best-case energy consumption of 1.3 kWh/km ~ 1.6 kWh/km for a typical 12m length Battery Electric Vehicle (BEV) [2, 3]. The actual energy consumption can vary significantly with passenger load, climate & season, and road & traffic conditions. With this energy consumption, it would require 350 kWh of energy to cover the daily transit requirement of 250km; however, a 500 kWh capacity battery would be needed to maintain a battery practical State of Charge (SoC) between 85% and 15% to ensure good battery lifetime [4]. Such a battery would occupy at least 1000 liters of space, weigh at least 2.7 tons, and cost at least €100,000 [5]; thus, it is not feasible to deploy for most bus operators. Most likely, the battery capacity will be sized to allow one or two return trips along its route, while still maintaining a 70% battery Depth of Discharge (DoD). Finally, it would take a total of at least half an hour of daily charging using a 600kW ultrafast charger, currently the highest power-rated commercially available charger on the market [6-8], to recover the daily energy expenditure of the 12m electric bus.

Thus, it is desirable for electric buses to employ ECO features in order to lower its net energy expenditure, including ECO-charging, ECO-driving, and ECO-comfort. This paper will focus on ECO-driving with public buses and the proposed Energy Management Strategy (EMS) methodology for ECO-driving.

II. ECO-DRIVING

Any modern vehicle design places an emphasis on energy saving ECO features, regardless of whether the vehicle is electric or not. Such features are mainstream

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in passenger vehicles; while driving in ECO mode, the driver can expect the following: limitation of the vehicle top speed, limitation in the vehicle acceleration, regenerative braking when possible, traveling at constant speeds (cruising), Lo-G cornering, engine stopped instead of idling when vehicle is at rest, and setting the auxiliary system to a low power mode. These features taken together may significantly reduce the energy utilization of a vehicle but will also reduce the "feel-good" performance of the vehicle. In terms of energy optimization, passenger cars are far ahead of public transport buses. Not only are passenger cars designed with streamlined aerodynamic features to reduce drag, but many passenger cars already feature an ECO mode; both features that are currently missing in public transport electric buses. However, public transport buses are meant for low speed driving, typically less than 50 km/h (30 mph) in urban areas and rarely exceeding 80 km/h (50 mph) on highways, thus reducing the benefits of aerodynamic body design. Thus, the main consideration is to introduce ECO-driving energy savings technology in electric buses.

Within the context of the ASSURED EU-project, the aim is to develop a multi-objective energy management strategy for electric heavy-duty vehicles, such as buses and trucks, in order to minimize the energy consumption, the operational cost, and improve driving range. This paper will focus on achieving ECO-driving capability in a 12m electric buses used for public transport in urban areas, by optimally actuating the Electric Motor (EM) to meet the desired speed profile, through tuning of the gearbox ratio. ECO-driving for public transport buses has been implemented in [9] using an "Electronic Assistant" and in [10] using the "Eco Driving Assistant System" (EDAS); both are essentially a Human-Machine Interface (HMI) display that provides feedback to the driver, to optimize driving style. In fact, a survey of the literature shows that for public transport electric buses, ECO-driving mainly relies upon the training of the driver to conform their driving style to best practices [11-14] including cruising and coasting, avoiding hard acceleration and hard braking, and no idling of vehicle when stopped. In [13, 14], the authors also modeled the driving style in order to aid the assistant HMI to provide advice to the driver; whereas in [10], an Electric Bus simulator is used to estimate the energy expenditure of the vehicle based on several driving styles, and inform the driver of the optimal speed to maintain, given several traffic conditions. The common thread for all previous research is the modification of the driving style, which, from a simulation perspective, can be thought of as a modification of the standard driving cycle to an *ECO friendly* version as shown in Fig. 1.

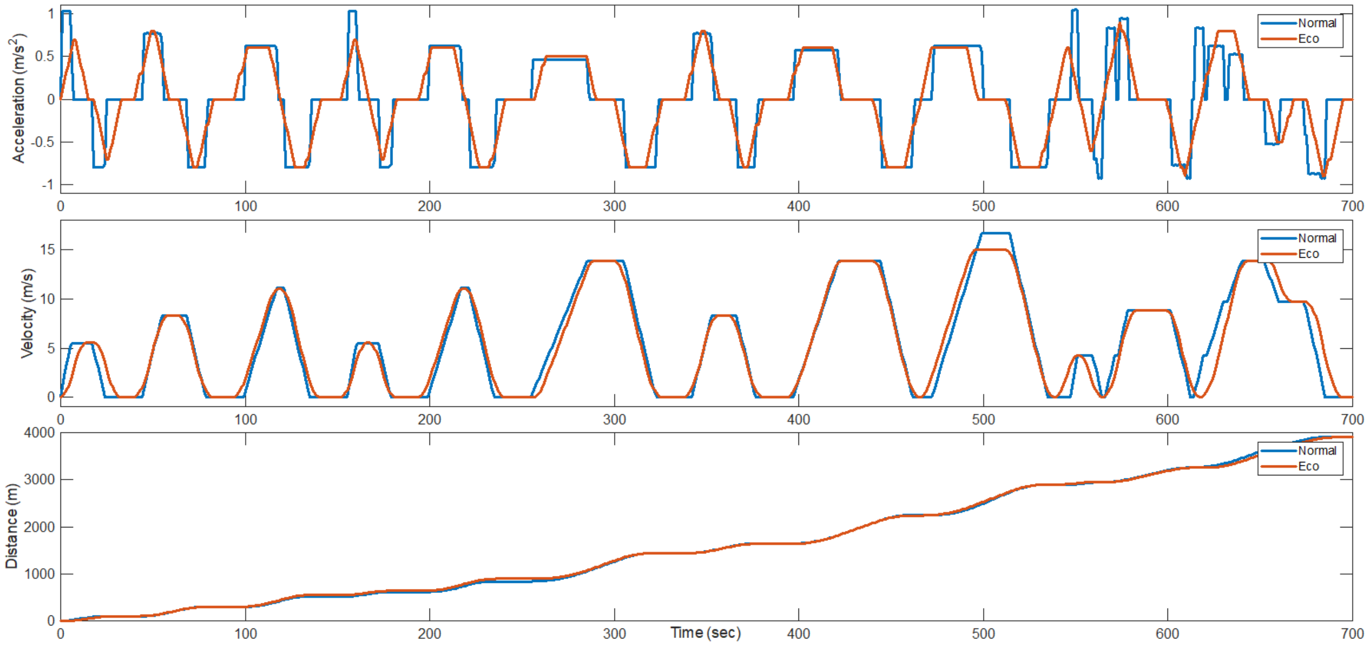


Fig. 1: ECO friendly profile generated for a standard driving cycle: a) Acceleration b) Velocity c) Distance

The proposed ECO friendly profile presented in Fig. 1 differs from ones presented in previous literature in three main respects. First, the ECO friendly profile features very smooth changes in velocity through use of ramped acceleration compared to the standard driving cycle, which features sudden acceleration. Second, the cumulative distances travelled using the ECO friendly profile and the standard driving cycle do not deviate significantly from each other at any given time instant, and the total distance travelled by both are the same. Third, the start timings of ECO friendly profile and the standard driving cycles are always synchronized. These ensure that not only do the vehicles driving with ECO friendly profile utilize less energy than vehicles driving with the standard driving cycle, but they also maintain the same average speed. Finally, the ECO friendly profile has a maximum acceleration limit of 1m/s^2 and maximum velocity limit of 15 m/s or 54 km/h. The regenerative braking (RB) strategy is adopted from [15] where RB is used to decelerate the vehicle to low speeds (chosen to be 5 m/s in this paper) and then turned off, while the friction brakes will bring the vehicle to a complete standstill. The friction brake also supplies any extra braking power beyond the capacity of the RB at any given speed. It is assumed that vehicle stability is not impacted using RB, and Anti-Lock Braking System (ABS) is not used. The second aspect that is utilized to implement the ECO-driving capability is through the smart operation of the EM. An EM is highly efficient and versatile compared to ICE; it can operate with maximum torque, maximum power, and maximum efficiency over a wide range of angular speeds as shown in Fig. 2, thus most EVs feature a fixed gearbox only. In comparison, an ICE requires a multi-speed gearbox to achieve proper balance between torque and power at various vehicle speeds, since ICEs have a narrow band of angular speed where the engine output is optimum. However, to achieve the highest energy efficiency using an EM, for ECO-driving applications, several modes of EM actuation, each mode having its own tuned gearbox parameter, have been studied. The EM under consideration is a 400Nm, 250kW, 3-phase induction motor with a rated angular speed of 4075 rpm (427 rad/s) and top angular speed of 12000 rpm (1257 rad/s).

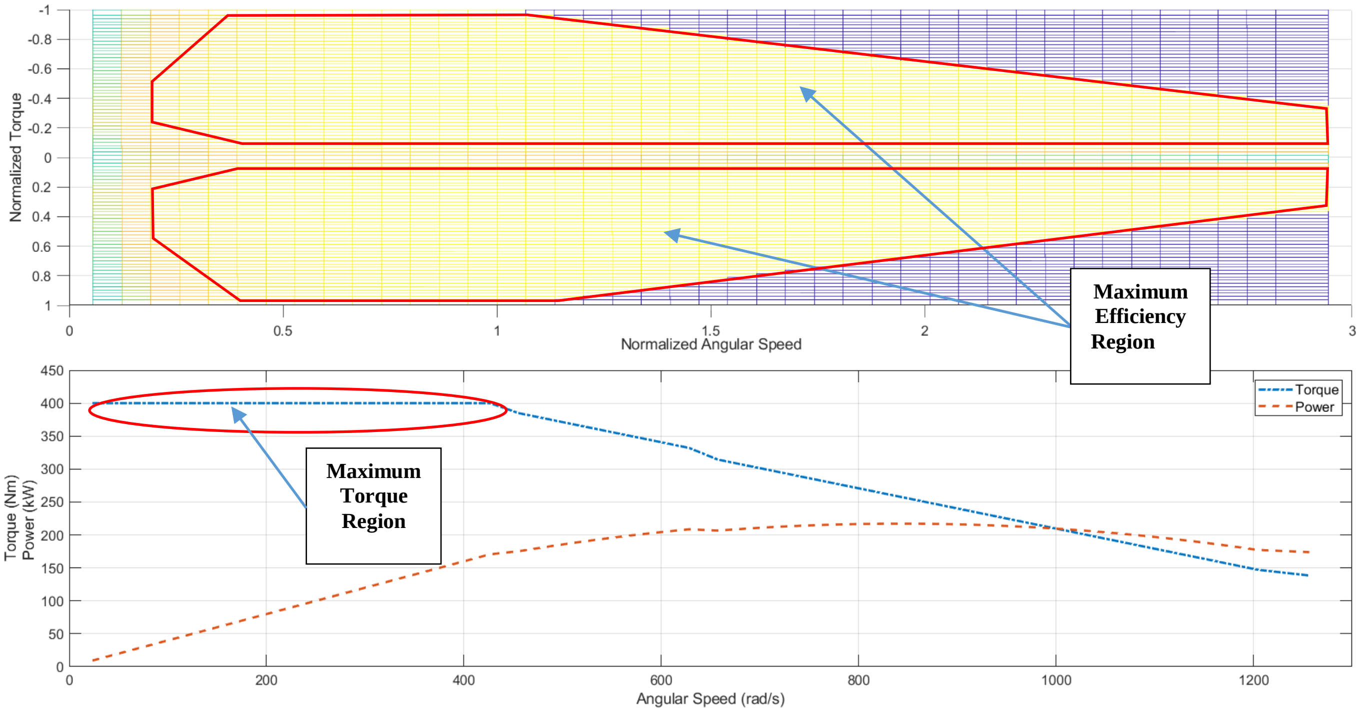


Fig. 2 Mechanical characteristics of the Electric Motor: a) Efficiency map of Motor b) Torque and power curve

III. ELECTRIC MOTOR ACTUATION MODES

A. Problem Formulation

This paper explores four different actuation styles of the EM, and how this affects the energy consumption of the EM, including operating in the maximum torque (MT) region, the maximum power (MP) region, the maximum efficiency (ME) region, and a PID controlled actuation with Torque constraint. Based on the findings, a technique to actuate the EM in the most optimum method will be proposed in this paper. Whichever method of actuating the EM is chosen, it must ensure that the vehicle can track the velocity profile depicted in Fig. 1b. The torque, power, angular speed, EM efficiency, and average energy consumption (in kWh/km) of the vehicle will be monitored and the simulation will be carried out for different maximum velocity and acceleration to analyse their effects on EM performance. Table 1 presents the technical specification of the bus used for the simulation. The parameter values shown for the Battery, EM, and gearbox are the typical specifications for a standard 12m bus participating in the ASSURED project; the remaining parameters are taken from [16]. Table 2 summarizes the parameters for the gearbox and the vehicle kinematics for the different styles of EM actuation. The vehicle acceleration is given as a range, ranging from an empty to a fully loaded bus. Sub-sections B through E discuss briefly the objectives behind each style of EM actuation. Finally sub-section F discusses the proposed EM actuation algorithm to minimize the energy utilization rate.

TABLE 1: TECHNICAL SPECIFICATIONS OF THE 12M ELECTRIC URBAN BUS

Feature	Value
Dimensions (l x w x h)	12m x 2.55m x 3.35m
Mass	12.8 tons (empty), 19.6 tons (loaded, max 80 passengers)
Battery	700V, 56kWh, Li-NMC battery, usable SoC of 85% ~ 15%
Electric Motor	Induction Motor, 700V, 350A, 400Nm, 220kW (mechanical), 4075rpm (max 12k rpm), τ_M = 0.325 second
Gearbox	Efficiency 97%, default gear ratio = 1:15, Ts = 0.3 second
Wheel radius	0.2865m
Auxiliary/HVAC	Disabled for the simulation to focus on driving related energy utilization
Kinematic constraint	***Normal***: A_{MAX} 1.5m/s^2, V_{MAX} 20m/s ***Eco***: A_{MAX} 1m/s^2, V_{MAX} 15m/s

TABLE 2: SUMMARY OF THE EM ACTUATION MODES

Mode	Gearbox Parameter			Acceleration (m/s^2)	
	1st gear	2nd gear	Cut-off speed	1st gear	2nd gear
PID	Fixed Gear, 15:1		N/A	0.34 ~ 1.50	
MT	15:1	6.45:1	7.65 (m/s)	0.93 ~ 1.50	0.40 ~ 0.65
ME	60:1	19.5:1	5.40 (m/s)	1.00 ~ 1.50	0.50 ~ 0.70
MP	17.85:1	20.93:1	6.34 (m/s)	1.17 ~ 1.80	0.90 ~ 1.36

B. PID control with Torque Constraint

In this method, the necessary torque that the EM should generate is computed by applying a typical PID control to the error in the tracked speed to ensure that the vehicle speed tracks the reference speed profile with minimal error. However, the actual torque output from the EM is constrained for a given angular speed of the motor by the torque curve shown in Fig. 2b. Using this method, the EM may operate in the MT, MP, and ME regions according to the needs of the mission profile.

C. Maximum Torque

In this method, the EM is operated entirely in the MT region of the EM, which means that the angular speed of the motor will never exceed 4075 rpm, regardless of the vehicle speed, and the maximum torque of ±400Nm will be the output, making it a true bang-bang type control mode. The gear ratio is optimized to ensure that the acceleration constraints are maintained at least in the 1st gear. The main objective is to keep the 1st gear engaged for the maximum duration of travel time, thus the higher value for cut-off speed.

D. Maximum Power

In this method, the gearbox tuning ensures that the EM operates in the MP region of the EM (i.e. where the angular speed of the EM is between 5250 rpm till 10500 rpm) for the maximum duration of travel time. Fig. 3 depicts the MP region, where the EM outputs above 90% of its rated mechanical power. The plot shown in Fig. 3 is derived by adjusting the power curve (red dashed line), shown in Fig. 2b, according to the efficiency map shown in Fig. 2a. The resulting combination shows a MP "ridge" for angular speeds higher than the rated speed, which a maximum power point (MPP) controller can track. The gear ratios allow the EM to transmit the maximum power required for acceleration in both gears.

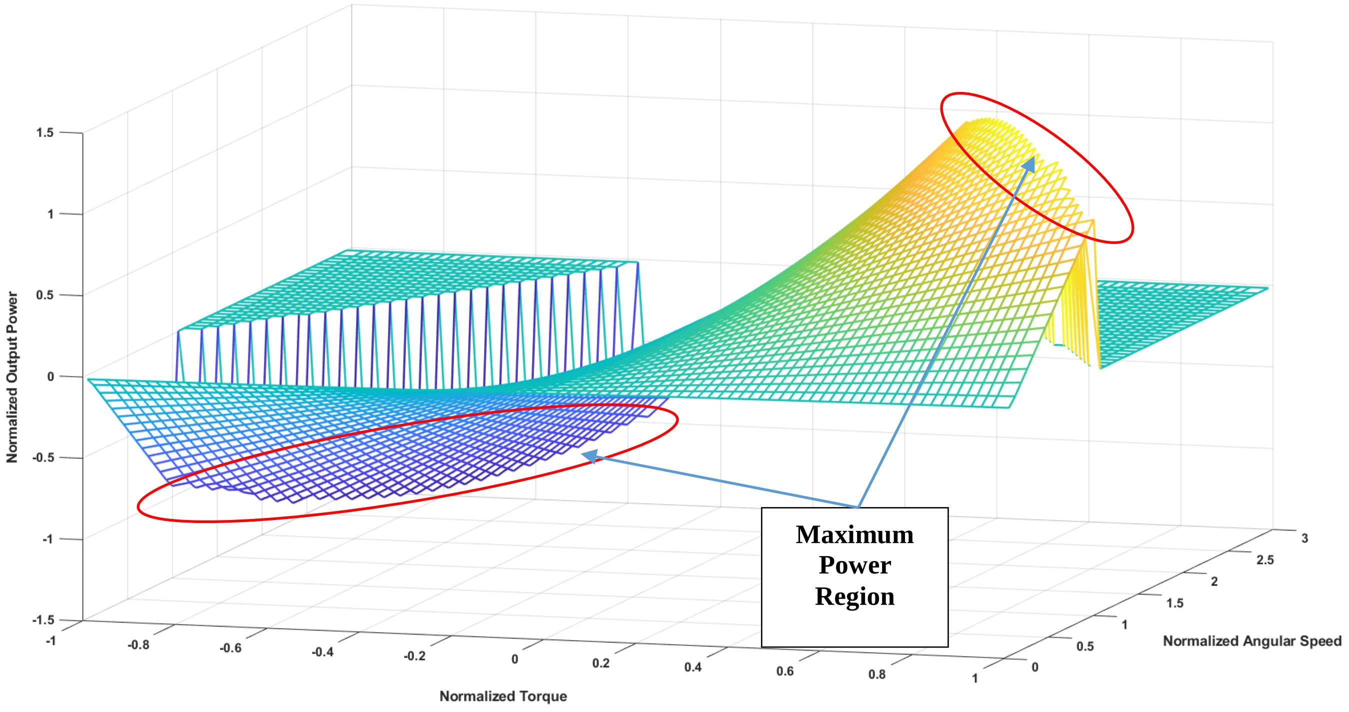


Fig. 3 Plot showing the MP region of the EM

E. *Maximum Efficiency*

In this method, the EM operates at ME at any given angular speed. Fig. 2a depicts the ME region, which is defined as efficiency above 95%. The output torque in the ME region is only a third of the EM's maximum, thus the gearbox requires large gear ratios. The main objective of the large gear ratio is to allow the EM to transmit as much required torque to the wheels as possible so that the vehicle can manage the required acceleration. Large gear ratio also ensures that the EM is mostly driven above its rated speed.

F. *Proposed EM Actuation Algorithm*

Investigating the simulations of the different actuation styles show that MP outperforms MT and ME at higher speeds, while for lower speeds ME is better. On the other hand, PID is best for cruising and coasting. Thus, the proposed actuation technique combines ME and MP based on quantized PID output, to get a balanced vehicle performance for all types of speed profiles, resulting in the most optimal energy utilization. Results show that the proposed algorithm is the most suitable when there is variable grade, or road elevation profile, in the bus route.

IV. RESULTS AND CONCLUSION

The simulation is made for the E-Bus described in Table 1, which follows the mission profile shown in Fig. 1, and covers a distance of 4km with an average speed of 20 km/h. For the purpose of the research, the bus carries the maximum passenger load of 80 passengers, having an average weight of 85 kg each. The simulation compares the result for the different styles of EM actuation, as described in Table 2, different acceleration factors, and different driving styles. Finally, the simulation compares results when road elevation (or grade) is introduced into the route versus that of a level route. A maximum grade of 5%, shown in Fig. 4, is applied to the route to test the capability of the bus to track the given speed profile with the various EM actuation algorithms. The results also show the effectiveness of the RB depicting the amount of braking energy that can be recovered during the mission using the normal and ECO speed profiles in roads with and without slope for different styles of EM actuation and for the proposed algorithm.

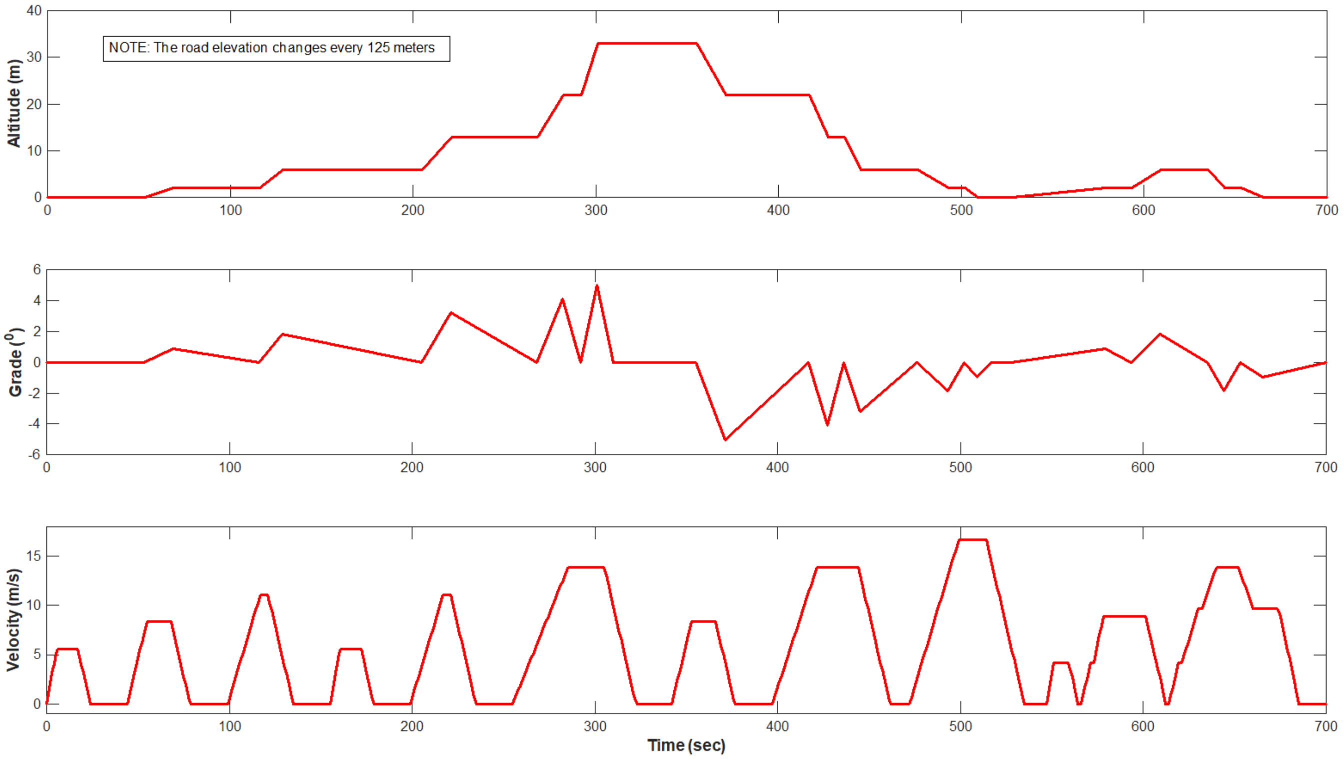
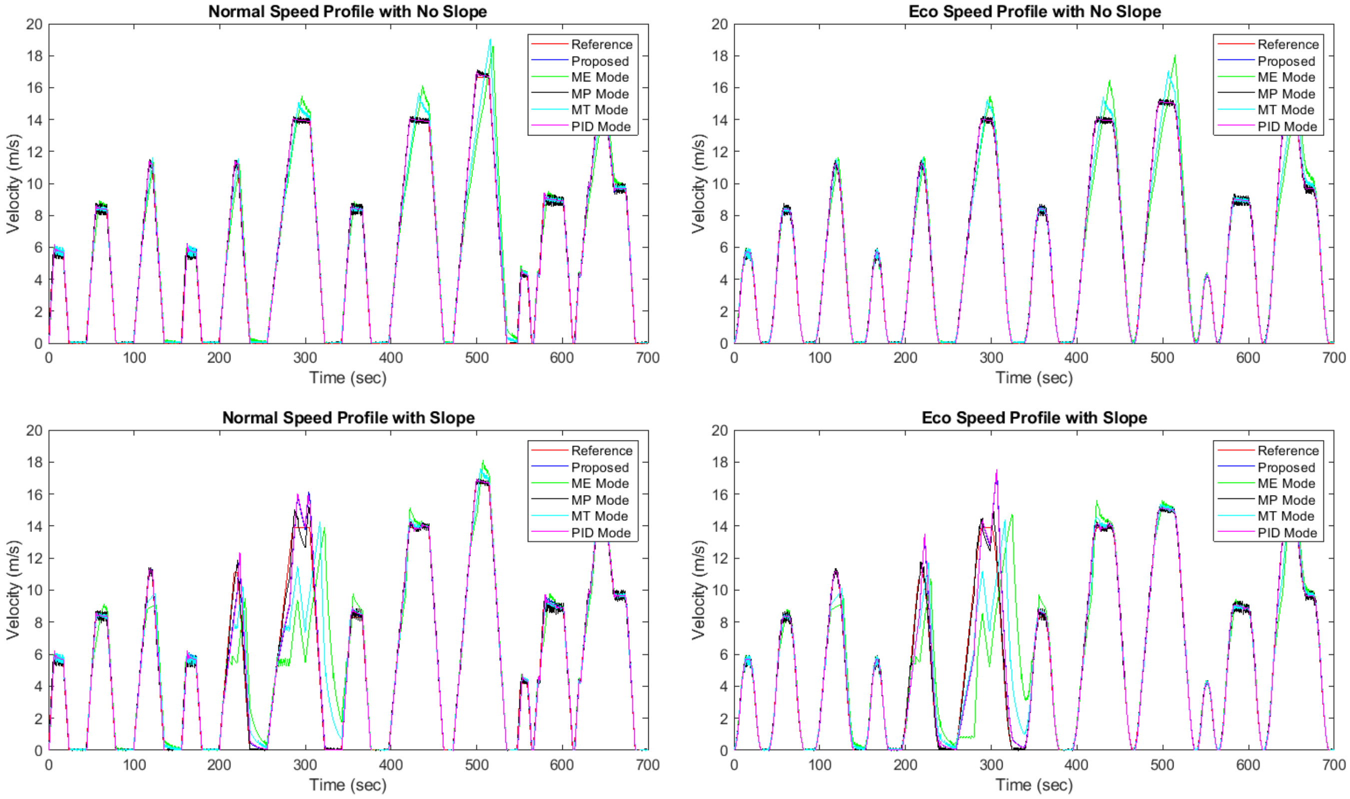


Fig. 4 The road elevation profile shown synced to the standard speed profile (a similar elevation profile exists for the ECO speed profile)

Table 3, depicting the mission energy utilization rate, shows that bang-bang actuation styles, in general, gives inferior results than the PID method. However, ECO-driving style always improves energy utilization, saving as much as 15% using MT method, and improves the braking energy recovered due to RB, with the MP method giving the best recovery, and ME and MT giving the worst recovery as depicted in Table 4. It is also shown that braking energy recovered using RB is best when average speeds are not too low and when accelerations are not too high.


Normal Speed Profile with No Slope

Eco Speed Profile with No Slope

Normal Speed Profile with Slope

Eco Speed Profile with Slope

Fig. 5 Comparison of the tracked speed using various modes of EM actuation

Table 3: Energy Utilization due to Different EM Actuation Styles and Vehicle Kinematics

Actuation Mode	**Speed Profile**	**Energy Use (kWh / km)**				
		A_{MAX}: 1m/s^2			**A_{MAX}: 0.8 m/s^2**	**A_{MAX}: 1.2 m/s^2 V_{MAX}: 20 m/s**
		V_{MAX}: 17 m/s	**V_{MAX}: 11 m/s**	**V_{MAX}: 5 m/s**		
PID	Normal	0.79	0.71	0.72	0.71	1.05
	Eco	0.71	0.68	0.70	0.68	0.89
ME	Normal	1.12	0.92	0.91	0.93	1.41
	Eco	1.04	0.90	0.94	0.86	1.39
MT	Normal	1.10	0.94	0.87	0.93	1.32
	Eco	0.93	0.86	0.88	0.85	1.24
MP	Normal	1.08	1.01	0.92	1.01	1.28
	Eco	1.02	0.98	0.92	0.99	1.14
Proposed	Normal	0.83	0.74	0.79	0.73	1.07
	Eco	0.74	0.71	0.79	0.69	0.89

Table 4: Braking Energy Recovered due to Different EM Actuation Styles and Vehicle Kinematics

Actuation Mode	**Speed Profile**	**Energy Recovered (%)**				
		A_{MAX}: -1m/s^2			**A_{MAX}: -0.8 m/s^2**	**A_{MAX}: -1.2 m/s^2 V_{MAX}: 20 m/s**
		V_{MAX}: 17 m/s	**V_{MAX}: 11 m/s**	**V_{MAX}: 5 m/s**		
PID	Normal	79.3	74.1	19.6	73.0	78.8
	Eco	79.9	74.0	15.9	71.2	85.1
ME	Normal	49.5	55.7	75.4	55.7	38.9
	Eco	57.4	60.0	76.4	61.8	40.8
MT	Normal	58.0	62.0	74.4	64.8	48.2
	Eco	68.7	68.1	73.4	70.1	52.5
MP	Normal	80.8	82.3	77.0	77.5	76.8
	Eco	81.6	82.2	77.0	79.0	82.8
Proposed	Normal	76.5	71.5	57.9	70.7	78.5
	Eco	75.5	71.1	64.0	64.0	82.6

Table 5: Braking Energy Recovered and Energy Utilization for Roads with Slope

Actuation Mode	**Speed Profile**	**A_{MAX}: ±1m/s^2, V_{MAX}: 17m/s**		
		Energy Use: (kWh/km)	**Braking Energy (kWh)**	**Recovered Energy (%)**
PID	Normal	0.98	5.212	82.7
	Eco	0.91	4.944	82.1
ME	Normal	0.99	5.164	50.3
	Eco	0.95	4.941	53.9
MT	Normal	1.06	5.218	59.3
	Eco	1.01	4.918	61.9
MP	Normal	1.19	5.972	80.6
	Eco	1.12	5.840	83.4
Proposed	Normal	0.94	4.518	80.2
	Eco	0.88	4.056	79.2

Table 5 shows the effects of adding road elevation to the mission route. As can be noticed, when variable elevation is present in the route, as is the case with many of the routes in cities participating in ASSURED, the proposed algorithm performs the best in energy utilization, and requires much less braking energy during the mission, which indicates that the proposed algorithm is better able to achieve energy balance, better utilize RB when the bus is traveling downhill, while simultaneously maintaining the proper vehicle speed and acceleration.

Fig. 5 shows how each method tracks the standard and ECO speed profile shown in Fig. 1, in roads without slope and with the slope shown in Fig 4. It is seen that MT and ME method of EM actuation are not so good at tracking the given speed profile, and it becomes even more obvious when the road contains slope. This is mainly because of the limitations of the maximum acceleration available to the ME and MT styles of EM actuation as seen from Table 2. The MP style of EM actuation is much better in tracking capability, but it suffers from overshoot, causing oscillations around the reference speed; however, it shows surprisingly the best tracking ability when the road contains slope. This suggests that the high accelerating capability available to the MP style of EM actuation is put into good use in overcoming grade resistance. The proposed algorithm and the PID style of EM actuation are more balanced in their tracking ability and show good performance in both road conditions; with the nuance that when the road contains no slope, the proposed algorithm is able to track the ECO speed profile better, and when the road contains slope, the proposed algorithm tracks the normal speed profile better.

The results prove that the maximum savings in energy utilization in ECO-driving comes from an ECO friendly speed profile; thus, the acceleration and velocity of the vehicle needs to be limited during driving. The results also indicate that if a two-speed gearbox was available instead of a fixed-speed gearbox of the ASSURED buses, the proposed algorithm could be better tuned to give more efficient energy utilization.

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