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Comparing Fuel Consumption and Emission Levels of Hybrid Powertrain Configurations and a Conventional Powertrain in Varied Drive Cycles and Degree of Hybridization

W. U. Maddumage[1], K. Y. Abeyasighe[1], M. S. M. Perera[1], R. A. Attalage[1], P. Kelly[2]

[1]Sri Lanka Institute of Information Technology (Malabe, Sri Lanka),
[2]Loughborough University (Loughborough, United Kingdom)

Abstract. Hybrid electric powertrains in automotive applications aim to improve emissions and fuel economy with respect to conventional internal combustion engine vehicles. Variety of design scenarios need to be addressed in designing a hybrid electric vehicle to achieve desired design objectives such as fuel consumption and exhaust gas emissions. The work in this paper presents an analysis of the design objectives for an automobile powertrain with respect to different design scenarios, i. e. target drive cycle and degree of hybridization. Toward these ends, four powertrain configuration models (i. e. internal combustion engine, series, parallel and complex hybrid powertrain configurations) of a small vehicle (motorized three-wheeler) are developed using Model Advisor software and simulated with varied drive cycles and degrees of hybridization. Firstly, the impact of vehicle power control strategy and operational characteristics of the different powertrain configurations are investigated with respect to exhaust gas emissions and fuel consumption. Secondly, the drive cycles are scaled according to kinetic intensity and the relationship between fuel consumption and drive cycles is assessed. Thirdly, three fuel consumption models are developed so that fuel consumption values for a real-world drive cycle may be predicted in regard to each powertrain configuration. The results show that when compared with a conventional powertrain fuel consumption is lower in hybrid vehicles. This work led to the surprisingly result showing higher CO emission levels with hybrid vehicles. Furthermore, fuel consumption of all four powertrains showed a strong correlation with kinetic intensity values of selected drive cycles. It was found that with varied drive cycles the average fuel advantage for each was: series 23 %, parallel 21 %, and complex hybrids 33 %, compared to an IC engine powertrain. The study reveals that performance of hybrid configurations vary significantly with drive cycle and degree of hybridization. The paper also suggests future areas of study.

Keywords: hybrid electric vehicle, vehicle performance, emissions, fuel economy, driving cycle, degree of hybridization, powertrain simulation, conventional vehicle, three wheeler

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Сравнение расхода топлива и уровня выбросов при обычной и гибридных конфигурациях трансмиссий с учетом циклов движения и степени гибридизации

В. У. Маддумаге[1], К. И. Абеясиге[1], М. С. М. Перера[1], Р. А. Атталаге[1], П. Келли[2]

[1]Институт информационных технологий Шри-Ланки (Малаб, Шри-Ланка),
[2]Университет Лафборо (Лафборо, Великобритания)

Реферат. Применение гибридных электрических трансмиссий в автомобильной промышленности – это решение проблемы выбросов и экономии топлива в сравнении с обычными автомобилями с двигателем внутреннего сгорания. Для достижения желаемых результатов при проектировании гибридного электромобиля необходимо рассматривать

Адрес для переписки
Маддумаге Варуна
Институт информационных технологий Шри-Ланки
Нью Кэнди роуд,
10115, г. Малаб, Шри-Ланка
Тел.: +9471 815-03-28
waruna.m@sliit.lk

Address for correspondence
Maddumage Waruna
Sri Lanka Institute of Information Technology
New Kandy Road,
10115, Malabe, Sri Lanka
Tel.: +9471 815-03-28
waruna.m@sliit.lk

различные варианты, учитывая при этом расход топлива и выбросы выхлопных газов. В статье представлен анализ проектирования автомобильной трансмиссии, рассмотрены различные варианты и ситуации, например целевой цикл движения и степень гибридизации. Разработаны четыре модели конфигурации трансмиссии (двигатель внутреннего сгорания, серийная, параллельная и комплексная конфигурации гибридной трансмиссии) для небольшого транспортного средства (моторизованный трехколесный автомобиль) с использованием программного обеспечения Model Advisor. Перечисленные конфигурации трансмиссии моделировались с различными циклами движения и разной степенью гибридизации. Во-первых, влияние стратегии управления мощностью транспортного средства и эксплуатационных характеристик всевозможных конфигураций трансмиссии исследуется на основе анализа выбросов выхлопных газов и расходов топлива. Во-вторых, циклы движения масштабируются в соответствии с кинетической интенсивностью и оценивается взаимосвязь между расходом топлива и циклами движения. В-третьих, разработаны три модели расхода топлива, так что расход топлива для реального цикла движения может быть спрогнозирован в отношении каждой конфигурации трансмиссии. Исследования показали, что по сравнению с обычной трансмиссией потребление топлива меньше у гибридных транспортных средств. Испытания дали неожиданный результат: более высокие уровни выбросов CO у гибридных транспортных средств. Кроме того, расход топлива всех четырех трансмиссий указывает на сильную корреляцию со значениями кинетической интенсивности выбранных циклов движения. Выявлено, что при различных циклах вождения в среднем предпочтение по топливу для каждого цикла составило: 23 % – для последовательных, 21 % – для параллельных и 33 % – для комплексных гибридов в сравнении с трансмиссией двигателя внутреннего сгорания. Эксперименты показали, что производительность гибридных конфигураций варьируется в зависимости от цикла вождения и степени гибридизации. В статье определены перспективные направления исследований.

Ключевые слова: гибридный электромобиль, работа транспортного средства, выбросы, экономия топлива, цикл вождения, степень гибридизации, моделирование трансмиссии, обычное транспортное средство, трехколесное транспортное средство

Для цитирования: Сравнение расхода топлива и уровня выбросов при обычной и гибридных конфигурациях трансмиссий с учетом циклов движения и степени гибридизации / В. У. Маддумаге [и др.] // *Наука и техника*. 2020. Т. 19, № 1. С. 20–33. https://doi.org/10.21122/2227-1031-2020-19-1-20-33

Introduction

Hybrid electric technology is of great interest to users and manufacturers alike due to the technologies ability to reduce fleet fuel consumption and emissions [1]. When designing a hybrid powertrain system particular set of scenarios need to be considered, and each of these scenarios directly affects the performance or design objectives of the final vehicle design, e. g. fuel consumption, emissions [2]. Solving the design problem of a hybrid vehicle implies, identifying the suitable design parameters, that maximize the design objectives of the vehicles for a given set of design scenarios. Design parameters in a hybrid vehicle may be categorized into three layers as topology, component size and control strategy [3]. The present study examines how the topology parameters in a hybrid design affect the performance or design objectives of a hybrid vehicle for varied design scenarios.

Design scenarios are the main set of decisions considered by a design engineer or a researcher when developing a hybrid powertrain, such as vehicle type, vehicle application, drive cycle, degree of hybridization and duty cycle. Design scenarios set the roadmap for the development of the hybrid vehicle.

Present study examines design objectives under three design scenarios: vehicle type, drive cycle and degree of hybridization. Firstly, the vehicle type, a motorized three-wheeler is used as the developing hybrid vehicle. Three-wheelers are a type of vehicle that has three wheels in a Delta configuration (1 front, 2 rear), powered by an internal combustion engine. The current numbers of three-wheelers globally are approximately 4.5 million. According to WHO 2017 report, these vehicles contribute to ground level ozone, particles in the air and other types of pollution that impact human health and welfare [4]. Secondly, the drive cycle, range of drive cycles are used, representing highway, country and urban cycle characteristics. Thirdly, degree of hybridization, three parallel hybrid powertrains with varied hybridization values are developed.

Design objectives for a hybrid vehicle design are derived from the vehicle type (e. g. three-wheeler, car, bus) and application (e. g. heavy-duty, comfort, operation cost). In solving the design problem of a hybrid vehicle, the goal is to maximize the design objectives by varying design parameters [5]. This paper considers four design objectives, i. e. fuel consumption, CO, HC and NO_x gas emissions.

Nomenclature		Variable	
		t	Time
Acronym		h	Height
WHO	World Health Organization	g	Gravity
IC	Internal Combustion	HA	Hybrid Advantage
CG	Center of Gravity	FC	Fuel Consumption
HWFET	Highway Fuel Economy Test	EL	Emission Level
CSHVC	City Suburban Heavy Vehicle Cycle	H	Degree of Hybridization
CBD	Central Business District	P_{EM}	Power of electric motor
OCC	Orange County Cycle	P_{ICE}	Power of engine
GPS	Global Positioning System	KI	Kinetic Intensity
SOC	State Of Charge	v	Speed
DC	Drive Cycle	$\tilde{a}$	Characteristic acceleration
US	United States	v_{aero}^2	Square of aerodynamic speed
WLTP	Worldwide harmonized Light vehicles Test Procedure	D	Distance

Topology design parameters determine the components and energy flow of the hybrid powertrain. The top layer of the topology parameters is the powertrain configuration. Three types of hybrid powertrain configurations may be identified as series, parallel and complex hybrid configurations. Series hybrid configuration is an extension of the electric powertrain by introducing an IC engine in series to the vehicle powertrain. In the parallel hybrid configuration, both engine and motor are connected parallelly to the transmission. The complex hybrid utilizes the best of both series and parallel configurations. By integrating an additional linkage and a generator between the IC engine and battery allows the complex hybrid to operate as both a series and a parallel hybrid. All three configurations harness from down-slope driving and braking to recharge the battery [6].

Many studies have been carried on fuel consumption and emissions of hybrid vehicles with varied design scenarios [7–9]. Y. Huang et al. [1] study fuel consumption and emissions of a conventional and hybrid vehicle under real driving. A. Ahmed in [10] examine emissions and fuel economy of a parallel hybrid and a conventional vehicle for varied drive cycles. M. Karaoglan in [11] investigated the effect gear ratios (design scenario) on emission and fuel consumption for a parallel hybrid. However, a comprehensive study investigating the effect on design objectives of hybrid vehicles with varied design scenarios is yet to be concluded. Hence, present work investigates how different hybrid configurations performs compared to its counterpart conventional powertrain configuration (IC engine powertrain) with varied drive cycles and hybridization values.

Contribution of this paper can be elucidated as follows. First, the fuel consumption and emission values are examined for series and parallel configurations. Relationship between these factors is examined with hybridization and drive cycle. Next, fuel consumption of series hybrid, parallel hybrid, complex hybrid and conventional configurations under various drive cycles are examined. Thereafter, three fuel consumption models to predict fuel economy of the hybrid configurations are proposed. Models are tested with a real-life drive cycle and accuracy of the models are examined. Finally, Hybrid advantage of the three hybrid configurations under varied drive cycles is discussed.

Methodology

Simulation of the four powertrains (i. e. series, parallel, complex hybrid and conventional powertrains) with different drive cycle and hybridization values are done using the MatLab/Simulink based ADVISOR software environment. Advance Vehicle Simulator (ADVISOR) was first developed in September 1994 by the US department of energy's National Renewable Energy Laboratory (NREL) [12]. The software was created in support of the hybrid vehicle subcontracts with the auto industry and the Department of Energy [13]. The number of public users of the software tool has grown since, with academics and industry users alike [14].

Software is open-source and used offline. A lot of users have contributed to libraries of ADVISOR through new components and data. The robustness of the model and relevance of the model with other simulators are crucial for determining the authenticity of the software. NREL has been making agreements with universities to encompass more accurate data for models [15].

The model used in the simulation is backwards-looking. The drive cycle speed is traced by controlling the vehicle speed using a driver model. Torque, speed and power are propagated backwards from the wheels to the engine and battery. All four configurations share a common driveline (final drive, wheels and chassis).

Vehicle model

Vehicle model for the simulation of the present study is defined with the characteristics of a motorized three-wheeler, based on the BAJAJ RE 205cc three-wheeler (Fig. 1) [16].

Fig. 1. BAJAJ RE 205cc motorized three-wheeler [17]

The main assumptions in modelling the four powertrain models are as follows, the road-load equations considered are for the longitudinal movement of the vehicle; it is assumed that the vehicle model is always capable to meet the power demands of the drive-cycles; tire model assumes a constant rolling resistance coefficient and a constant tire radius; and the system vibrations are neglected.

Road-load acting on the vehicle is modelled as a representation of the force balance at the tire patch. The classical equations of longitudinal vehicle dynamics are considered, i. e. force equals mass into acceleration, where among the forces are rolling resistance, aerodynamic drag, and the force of gravity [16].

A common set of powertrain components were chosen and scaled to meet the vehicle requirements. Engine, Motor and Battery of the powertrains were modelled as quasi-static models (Fig. 2). Data of powertrain components such as efficiency maps, torque maps and model specifications are from the ADVISOR software libraries (Tab. 1) [18].

Table 1

Specifications of the vehicle model

Coefficient of drag [16]	0.44
Frontal area	1.86 m^2
CG height from ground	0.4 m
Wheelbase	2 m
Rear track	1.3 m
Wheel radius	0.2 m
Glider mass (without propulsion)	280 kg
Final drive ratio [16]	0.24
Primary ratio [16]	0.88
Rolling resistance coefficient [16]	0.015

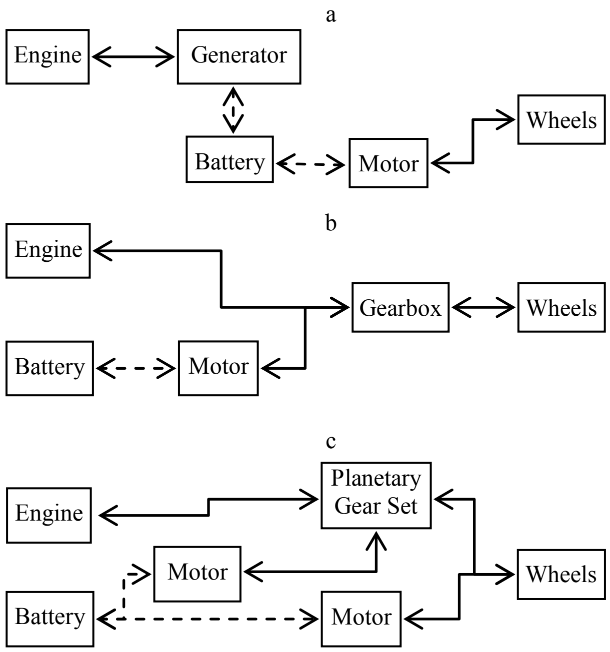

Fig. 2. Hybrid configurations: a – series; b – parallel; c – complex configurations

Battery model used is based on the test data of the 12 V/6 Ah Saft Lithium-Ion battery. Number of batteries were varied to match necessary vehicle characteristics in each powertrain.

Main characteristics of the mechanical components are summarized in Tab. 2.

Table 2

Motor and engine characteristics

Component	Peak efficiency, %	Remark
Engine	30	Gasoline, spark-ignited, Geo Metro 1.0 L SI engine
Traction motor	94	Permanent magnet, top speed 7500 RPM, max torque 112 Nm
Generator	84	Permanent magnet, top speed 5500 RPM, max torque 55 Nm

The transmission used in the conventional powertrain is a 4-speed manual with gear ratios 7.4, 4.1, 2.7 and 1.8 (final and primary ratio included). The gearbox of the parallel transmission is modelled as a 4-speed automatic with the same gear ratios. In series and complex hybrids same final drive ratio was considered, primary drive ratio (between the engine and generator) is considered as two. The planetary gearbox of the complex hybrid powertrain is modelled similar to a Toyota Camry/Prius power split device with 30 teeth in sun gear and 78 in ring gear [8].

Additional electric load of 300 W was considered in the four vehicle models for the load exerted by the accessories.

Control strategies of the four powertrain configurations were taken from ADVISOR libraries, hybrid control strategies are optimized for a small car considering a single objective, i. e. fuel consumption. Control strategy for the parallel hybrid was implemented using the basic power assist control strategy of the ADVISOR software, series hybrid using the power follower control strategy and complex hybrid with the Toyota Prius hybrid 1999 control strategy.

Vehicle sizing

For the four vehicle models to be comparable, a set of requirements are pre-defined. Powertrain components of the four vehicles are sized to meet the said requirements. The vehicle requirements are chosen based on the characteristics of a typical motorized three-wheeler [16, 17, 19]. Vehicle requirements are as follows [8].

- Perform the real world Malabe drive cycle derived for a three-wheeler indefinitely (indefinitely here means using fuel as the energy source and, if applicable, operating any electric machine at or below its maximum continuous torque).
- Reach 0–20 km/h in 6 s and 20–40 km/h in 10 s.
- Reach a top speed greater than 65 km/h.
- Sustain 5 % grade at 35 km/h indefinitely.

Powertrain components for each powertrain configuration differ due to the different power source combinations.

To calculate the component sizes of the four hybrid power trains. a sizing routing is carried out through the automated sizing option available in the ADVISOR software. All the powertrain components are sized, the characteristic maps of the powertrain components are linearly scaled to match required power levels to achieve the defined vehicle requirements. Firstly, Battery and electric motors are sized for the acceleration and maximum speed characteristics, i. e. 0–20 km/h in 6 s/(20–40) km/h in 10 s and top speed greater than 65 km/h. Then the engine is sized to meet the grade requirements. Then the vehicle is tested for the Malabe drive cycle. If the vehicle failed to trace the drive cycle, engine size is increased. This routine is done for several iterations until results converge. The characteristics of the sized vehicles are summarized in Tab. 3. Each powertrain is developed with the same glider mass (Vehicle mass without the propulsion system). However, the overall weight of each configuration varies in comparison to the conventional powertrain due to the different powertrain component combinations equipped in different configurations.

Table 3

Specifications of the four vehicle models

Component	Conventional configuration	Series configuration	Parallel configuration (degree of hybridization)			Complex configuration
			0.2	0.3	0.4	
Engine max power, kW	8	4	7	6	5	5
Traction motor max power, kW	–	5	2	3	4	3
Generator max power, kW	–	4	–	–	–	2
Battery, No of modules	–	15	5	6	7	12
Total weight, kg	438	465	452	448	448	458

Hybrid advantage

The degree of hybridization explains how much the electric machine is involved in vehicle propulsion and it is defined as the ratio of the electric motor power over the total power of the IC engine and the electric motor, as shown in the following equation

$$H = \frac{P_{EM}}{P_{EM} + P_{ICE}}. \quad (1)$$

Two examples in the extreme are the conventional vehicle with the hybridization value of 0 and a full electric vehicle with a hybridization value of 1.

Drive cycles

Several standard drive cycles are chosen for the simulation with a range of kinetic intensity values, representing urban, country and highway driving characteristics. Due to the low-performance characteristics of the motorized three-wheeler, standard drive cycles are modified by linearly scaling down. Five standard drive cycles are used, i. e. Cons (Constant drive cycle), HWFET (EPA Highway Fuel Economy Test), CSHVC (City Suburban Heavy Vehicle Cycle), CBD (Central Business District Segment) and OCC (Orange County Transit Bus Cycle) [20]. Cons, HWFET to represent highway conditions, CSHVC to represent suburban country conditions and OBD, OCC to represent urban driving conditions.

The real-world "Malabe" drive cycle represents an unknown drive cycle. Drive cycle data was found by driving a real-world motorized three-wheeler in local roads. The exact route followed is represented in Fig. 3. The speed and time data represented in Fig. 4 were recorded using the GPS Module NEO-6M. It should be noted that this drive cycle only represents the driving characteristics of the route represented. Tab. 4 summaries the characteristics of the used drive cycles.

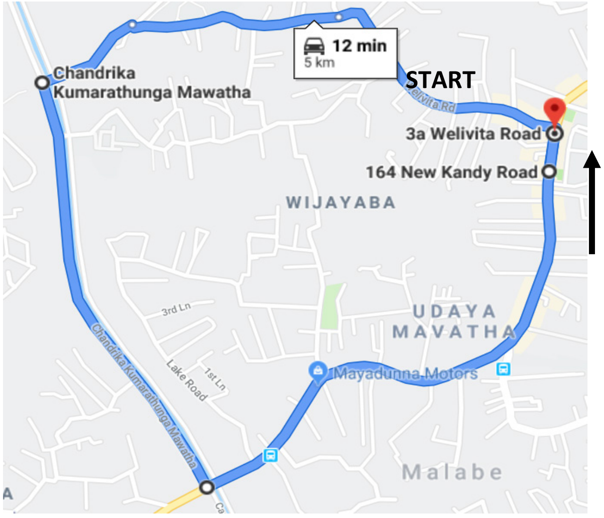

Fig. 3. Malabe drive cycle route (New Kandy road – Waliwita road – Chandrika Kumaratunga road)

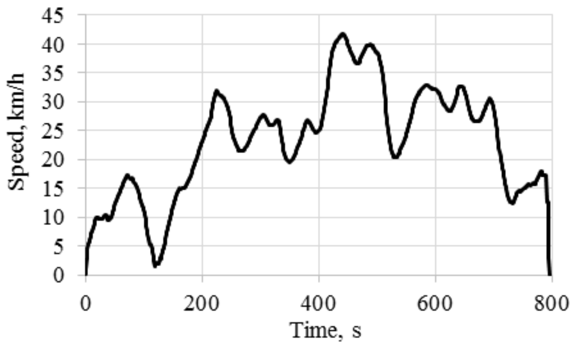

Fig. 4. Malabe drive cycle speed profile (from a real-world driven motorized three-wheeler)

Table 4

Characteristics of the drive cycles

	Cons (modified)	HWFET (modified)	Malabe (real world)	CSHVC (modified)	CBD (modified)	OCC (modified)
Kinetic intensity, 1/km	0.065	0.275	1.33	1.8	2.52	4.45
Duration, s	360	765	800	1700	850	1900
Distance, km	4	8	5.13	6.5	4	5
Max speed, km/h	40	50	40	40	30	30
Average speed, km/h	40	39	25	14	15	10
Max acceleration, m/s^2	0	0.71	0.51	0.7	0.36	0.91
Max deceleration, m/s^2	0	–0.73	–1.4	–1.06	–0.63	–1.15
Average acceleration, m/s^2	0	0.1	0.07	0.24	0.29	0.23
Average deceleration, m/s^2	0	–0.11	–0.09	–0.29	–0.56	–0.32
Idle time, s	0	6	1	397	159	407

Kinetic intensity

Kinetic intensity metrics introduced by O'Keefe et al. is used to analytically characterize drive cycles [7]. Kinetic intensity relates well with the inherent qualities of a hybrid vehicle such as energy harvesting from brake energy. An apparent relationship between fuel usage of a hybrid as well as a conventional vehicle exists for cases where idle fuel usage and vocational loads are small compared to the fuel usage consumed to meet the road load. Kinetic intensity is derived from characteristic acceleration and aerodynamic speed, based on basic road load equations [21]

$$KI = \frac{\text{Characteristic acceleration}}{\text{Aerodynamic speed}^2}. \quad (2)$$

Characteristic acceleration ($\tilde{a}$) and the square of aerodynamic speed (v_{aero}^2) can be calculated for an entire drive cycle as follows:

$$\tilde{a} = \frac{\sum_{j=1}^{N-1} positive\left(\frac{1}{2}\left(v_{j+1}^2 - v_j^2\right) + g\left(h_{j+1} - h_j\right)\right)}{D}; \quad (3)$$

$$v_{aero}^2 = \frac{\sum_{j=1}^{N-1} \overline{v_{j,j+1}^3} \cdot \Delta t_{j,j+1}}{D}; \quad (4)$$

$$KI = \frac{\sum_{j=1}^{N-1} positive\left(\frac{1}{2}\left(v_{j+1}^2 - v_j^2\right) + g\left(h_{j+1} - h_j\right)\right)}{\sum_{j=1}^{N-1} \overline{v_{j,j+1}^3} \cdot \Delta t_{j,j+1}}. \quad (5)$$

Present study uses the kinetic intensity metrics to characterize the drive cycles assuming that idle and vocational load fuel consumption is negligible compared to the fuel consumed for the road load.

Simulation results and discussion

A two-fold approach is followed to assess the effect of design scenarios on traditional hybrid configurations in terms of design objectives. Firstly, the impact of drive cycles and hybridization is assessed in regard to fuel consumption and vehicle emissions for three different powertrain configurations. Secondly, the fuel consumption of four different powertrain configurations is investigated with five drive cycles.

Powertrain models are developed with similar characteristics, thus operational behaviour may be compared. Four powertrain configurations (i. e. series, parallel, complex and conventional) are modelled with the same vehicle characteristics, powertrain components and drive cycle, eliminating the effect of vehicle configuration, driving behaviour and initial conditions from the performance comparison. In general, motorized three-wheelers in the consumer market are not equipped with any emission control technology. Hence, powertrains were modelled without an emission control technology such as a catalytic converter to represent the actual characteristics of a motorized three-wheeler.

Vehicle emissions and fuel consumption

Generally, a hybrid vehicle is designed with the design objective as either fuel consumption or vehicle emission levels. In some cases, both factors are considered, approaching the design problem with multiple objectives. Solving the design of a hybrid is complex, with two objectives. Understanding the behaviour of emissions and fuel rate with operational characteristics of the engine simplifies the design problem. In general, literature considers the fuel consumption as the sole design objective, assuming fuel consumption level as an adequate comparator for emission levels.

Present work assesses the fuel consumption rate and emission gases: CO, NO_x and HC rates with series hybrid, parallel hybrid and conventional powertrains. Moreover, Parallel configuration is further investigated with three different degrees of hybridization. The effect of drive cycle and hybridization on fuel consumption and emissions under different powertrain configurations is examined.

Fig. 5, 6 compare the fuel consumption values and emission values of series and parallel configurations against a conventional powertrain. The three powertrain configurations are simulated on the modified HWFET drive cycle.

Fig. 5 compares the fuel consumption, CO, HC and NO_x emissions for the three vehicle configurations. Fig. 6 compares the hybrid advantage in each hybrid vehicle design compared to the conventional powertrain using the following relationship

$$HA = \frac{FC \text{ or } EL._{Hybrid} - FC \text{ or } EL._{Conv}}{FC \text{ or } EL._{Conv}} \cdot 100\,\%. \quad (6)$$

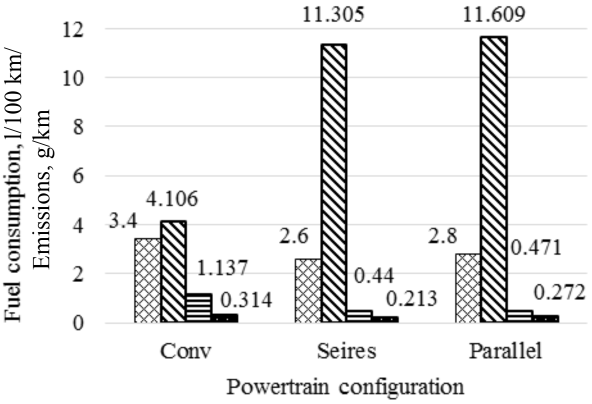

Fig. 5. Fuel consumption and emission values for series, parallel and conventional vehicles: – fuel consumption; – CO; – No_x; – HC

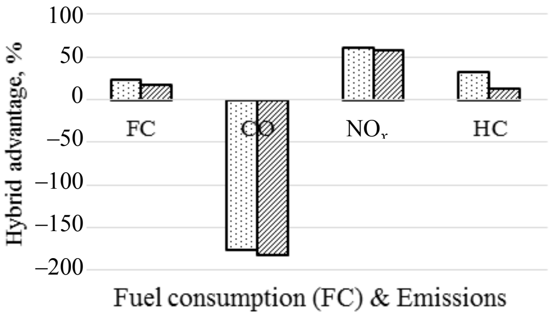

Fig. 6. Hybrid advantage (HA) of series and parallel powertrains for fuel consumption (FC), CO, NO_x and HC emissions: – HA (series); – HA (parallel)

Fig. 5, 6 indicate even though a reduction in fuel consumption may be expected in a hybrid vehicle, a reduction of emissions cannot be expected conclusively. Series and parallel configurations show a clear advantage in fuel consumption compared to conventional powertrain with 24 % fuel saving with series and 18 % fuel saving with the parallel configurations. Though, in terms of emission levels only HC and NO_x levels has a hybrid advantage. Both configurations show surprisingly higher CO emission levels with a 175 % increase with series configuration and a 183 % increase with parallel configuration compared to the conventional powertrain. However, results reinforce the findings from [1], Yuhan Huang et al. investigates the emission levels with a real-world hybrid car and a conventional car using a portable emissions measurement system. Similar to the present study, consistently higher CO emissions were observed with the hybrid vehicle.

Higher emission levels may be caused by the following two reasons. Firstly, the engine operating conditions. Engine operation conditions are different with a hybrid vehicle compared to a conventional vehicle. The higher amount of engine on and off frequency and higher engine power fluctuations may be a contribution for the increased emissions. Secondly, more power is required of a hybrid configuration due to the higher weight of the vehicle from the relatively smaller IC engine, with the engine of series 50 % and parallel 25 % smaller than the size of the convention vehicle. In order to understand the effect of engine operation and power requirement with the drive cycle and the effect on fuel consumption and emission levels, through Fig. 5–7 fuel rate and emission rate is investigated.

Fig. 7 compares the fuel consumption rate of the IC engine against CO emission rates, Fig. 8 against HC and Fig. 9 against NO_x emission rates for series, parallel and conventional powertrains under 100–425 s of the modified HWFET drive cycle. To understand the effect of engine operation in response to the drive cycle, the fuel rate and emission rates are plotted against the drive cycle (as km/h) after scaling, so that drive cycle characteristics can be shown against other parameters. Energy management strategy dictates the operation characteristics of the engine. Battery State of Charge minimum (SOC min.) point indicated is the minimum SOC level allowed. After this point, the power management strategy increases the power of IC engine to accelerate recharging of the battery.

Results from Fig. 7 indicate the fuel rate of series and parallel powertrains are relatively low compared to a conventional powertrain. With the series configuration, before SOC min. point indicated CO levels are lower, however after the SOC min. point power of the engine will be increased considerably by the power management strategy. Thus, increasing the CO emission rate. With the parallel configuration, the fuel rate indicates a higher fluctuation of the engine operation points than the conventional powertrain and a resulting increase in CO emissions. Similar to the series powertrain, after the SOC min point engine power is increased in the parallel hybrid resulting an increase in CO emission levels.

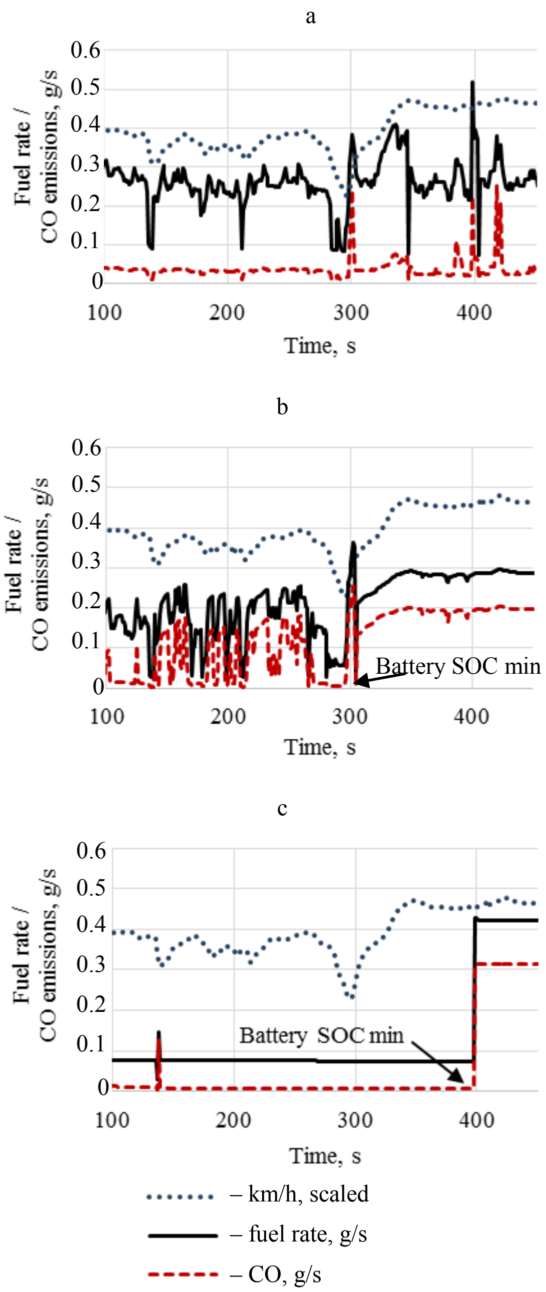

Fig. 7. Fuel rate against CO emissions:
a – conventional; b – parallel; c – series

Even though CO emissions are increased, NO_x and HC emissions are lower compared to the conventional powertrain. HC and NO_x levels for the drive cycle are respectively 32 % and 61 % lower with series hybrid and 13 % and 59 % lower with the parallel hybrid. Both hybrids significantly reduced NO_x emission levels. With HC emissions, the series hybrid has the highest advantage, which may be caused due to the stable operation of the series IC engine compared to the parallel hybrid. Fuel rate of the parallel hybrid indicates that with fluctuating engine operation, higher HC emissions are resulted compared to a series hybrid.

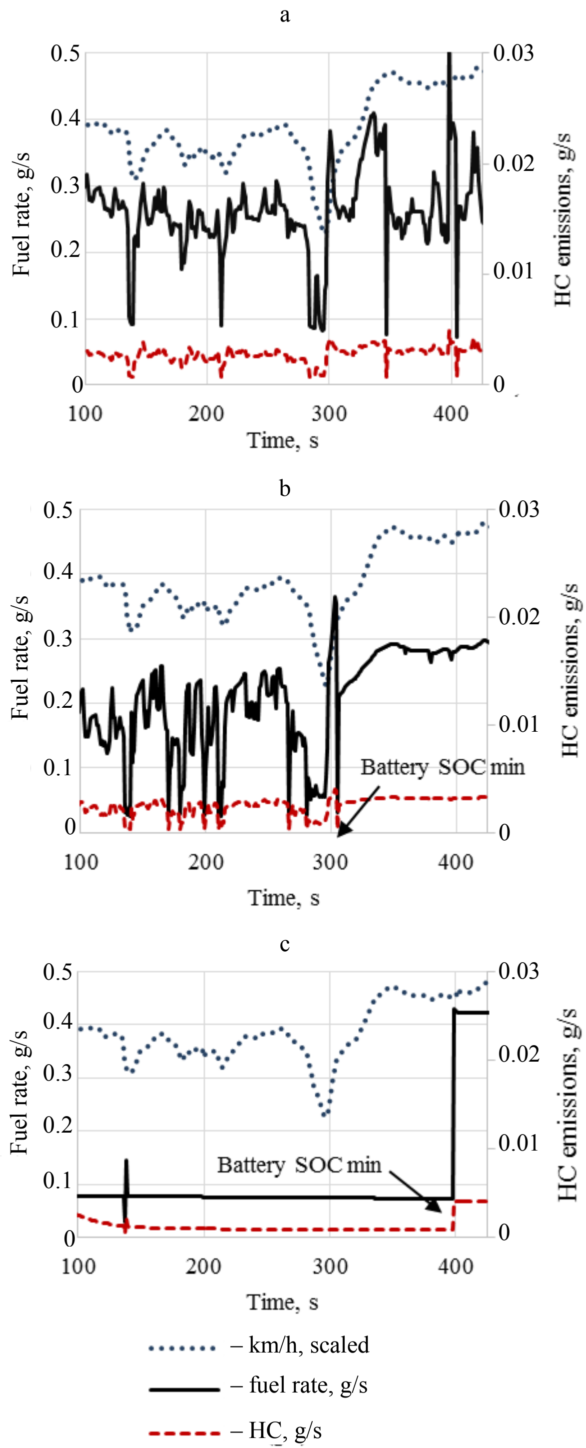

Fig. 8. Fuel rate against HC emissions:
a – conventional; b – parallel; c – series

Similar to powertrain configuration, hybridization affects the fuel consumption and emission levels for a hybrid vehicle. Fig. 10 indicate the fuel consumption and emission levels of CO, NO_x and HC for three parallel hybrid powertrains with varying degrees of hybridization against a conventional powertrain. Four powertrains, i. e. conventional, parallel (0.2), parallel (0.3) and parallel (0.4) are simulated on the modified HWFET drive cycle.

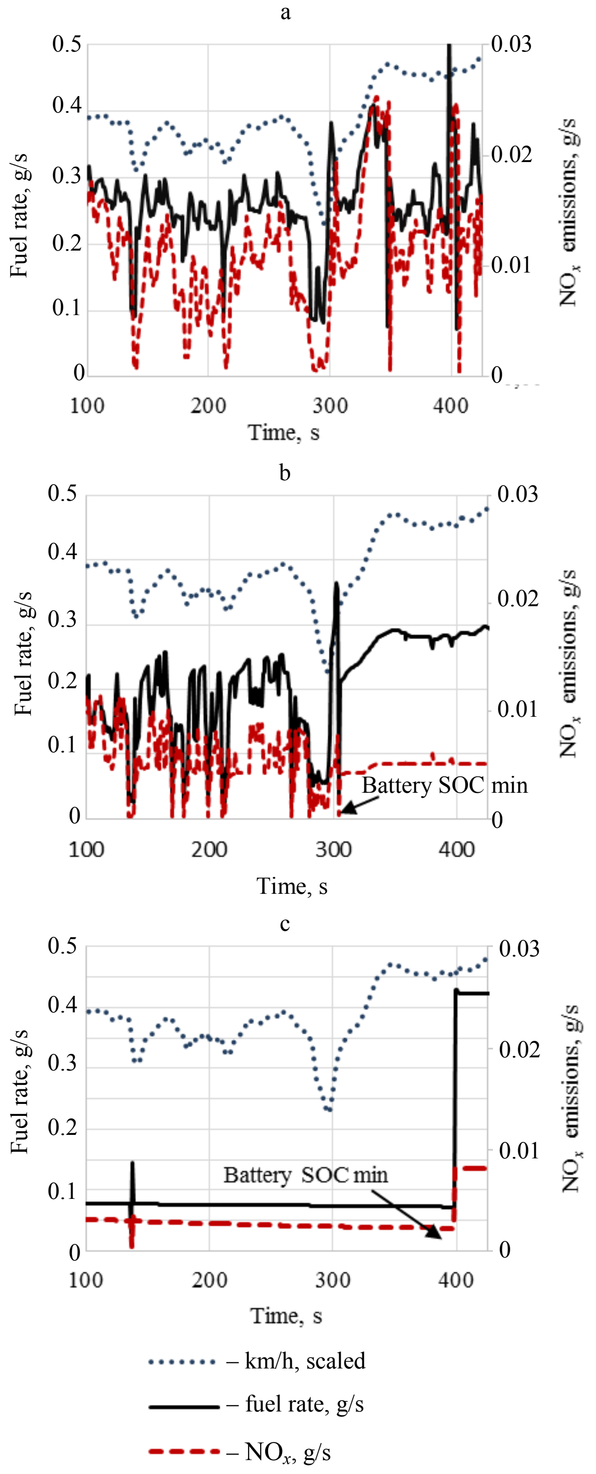

Fig. 9. Fuel rate against NO_x emissions:
a – conventional; b – parallel; c – series

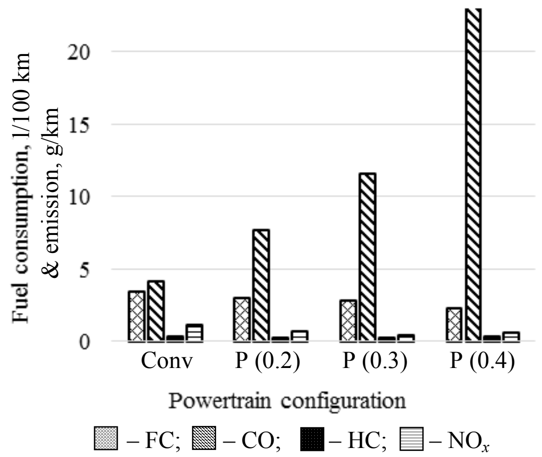

Fig. 10. Fuel consumption and emission values of conventional and parallel (with different hybridization values) powertrains

Results indicate, although fuel consumption is decreased with hybridization, CO emissions have increased significantly. Note that a catalytic converter is not modelled in the simulation. All three parallel configurations showed a significant hybrid advantage in fuel consumption with P (0.4) with 32 %, P (0.3) with 18 % and P (0.2) with 12 %. However, CO emissions increased by 88, 183 and 479 % in P (0.2), P (0.3) and P (0.4) respectively. This may be due to the power demand from the engine. Higher the hybridization, smaller the IC engine in a parallel hybrid. The power demand of the vehicle is approximately constant while the IC engine is sized smaller. Thus, increasing the power demand from the engine. Results reinforce the previous hypothesis; CO emissions increase may be caused by the higher power demand requested from a relative smaller engine.

Effect of drive cycle, hybridization and powertrain configuration on fuel consumption and emission levels is a complex relationship. Amount of data is inadequate to conclusively state that, CO emissions increases in a hybrid vehicle compared to its counterpart conventional vehicle due to the engine operation strategy and power demand. However, present study clearly shows that a reduction in fuel rate cannot be taken as an indicator for a reduction in emission levels for a hybrid vehicle.

Fuel consumption and drive cycle

A drive cycle provides a concise, repeatable sequence of vehicle operation over a time period [7]. A general drive cycle consists of second by second values of speed, some literature includes elevation and time-based information of the vehicle as well [7]. Drive cycles are valuable for the design process, as cycle data may be used to understand the vehicle behaviour in a target application. Depending on the target application (drive conditions) fuel characteristics of different hybrid powertrain configurations may vary considerably [3]. Present study examines the effect of drive cycle characteristics on the fuel consumption for different hybrids (i. e. series, parallel and complex hybrids) against its conventional counterpart.

The wide range of drive cycles makes the analysis a challenge. Most well-known characterization of drive cycle is by urban, country and highway. However, this assessment is highly objective as the route and the drive conditions are highly varying with vehicle uses and their lifestyle. Hence in order to understand the effect of the drive cycle on the energy usage of a hybrid, an analytical characterization of drive cycle is necessary. To better assess the drive cycles, the kinetic intensity may be defined using two-cycle metrics based on the road load equation: aerodynamic speed and characteristic acceleration [7]. Present study uses kinetic intensity to characterize drive cycles, and the fuel consumption is assessed against the kinetic intensity of the drive cycles.

Fig. 11 represent fuel consumption against kinetic intensity for the developed four powertrains, i. e. series, parallel, complex hybrid and conventional powertrains. Five standard drive cycled are analyzed for kinetic intensity. Fuel consumption values for the five drive cycles are plotted against kinetic intensity values of the drive cycles. Results show that with varied drive cycles; series, parallel and complex hybrids have an average fuel advantage of 23, 21 and 33 % compared to an IC engine powertrain. Moreover, the trendline for the five drive cycles are plotted, and linear regression value is calculated for the trendlines.

Strong linearity is present with all four powertrains in terms of fuel consumption and kinetic intensity values of the drive cycle. Thus, linear trendline may be used to analyze overall fuel consumption behaviour in different hybrid configurations and predict fuel consumption values for unknown drive cycles. A uniformly strong linear correlation (R^2 values <0.9) is evident between cycle kinetic intensity values and the simulated fuel consumption values. However, it must be noted that data is insufficient to accurately examine and predict fuel consumption in hybrid vehicles.

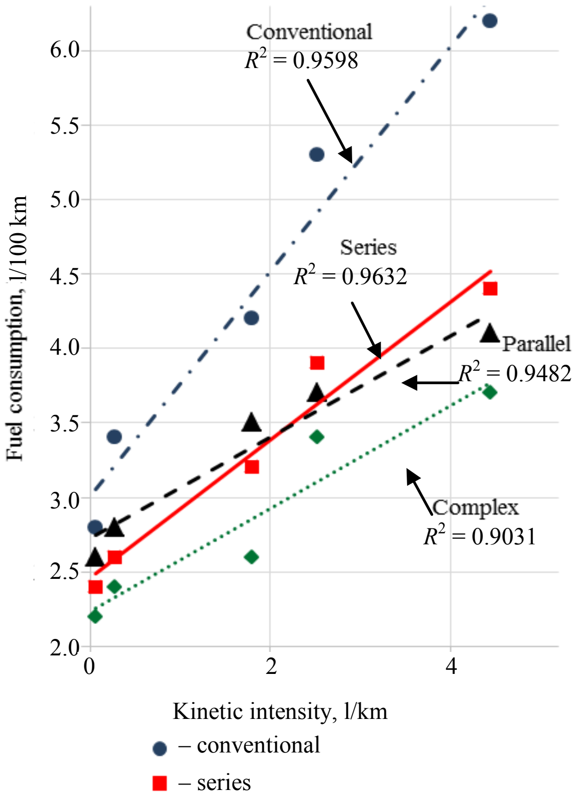

Fig. 11. Fuel consumption against drive cycles (scaled by KI factor) for conventional and hybrid powertrains

A methodology to predict hybrid fuel saving in an application is highly informative. However, finding fuel consumption values through simulation or by experimentation is a complex and tedious task that requires expert knowledge. The present study proposes the best fit linear curves of the three hybrids be adopted as fuel consumption models to approximately predict fuel consumption for an unknown drive cycle.

Proposed fuel consumption models are tested with a real-world drive cycle in Fig. 12. Three powertrains are simulated with the "Malabe" drive cycle. The "Malabe DC" points represent fuel consumption values from the simulation for the three hybrids. These points are compared with the predicted fuel consumption from the three hybrid fuel consumption models. Models predicted the fuel consumption values for the series, parallel and complex hybrids with 7, 12 and 7 % error percentages respectively. Tab. 5 summaries the predicted fuel consumption values by the best fit curve of Fig. 10 and actual fuel consumption values from the developed powertrain models in MatLab/Simulink ADVISOR.

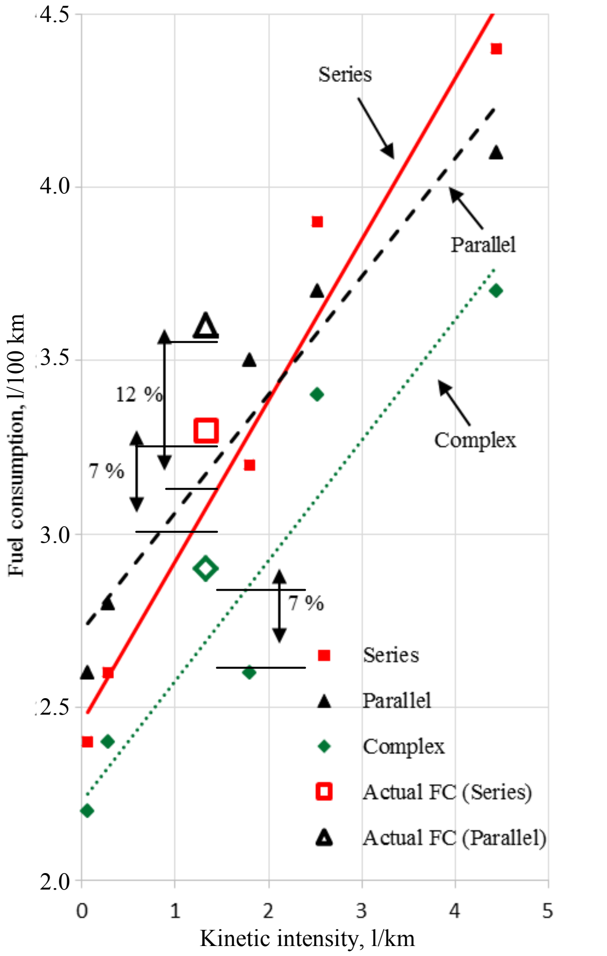

Fig. 12. Actual (simulation results from ADVISOR) and predicted (linear best fit curves) fuel consumption (FC) for the Malabe drive cycle of the three hybrid configurations

Table 5

Predicted and actual fuel consumption for the Malabe drive cycle

	Predicted FC (l/100 km)	Actual FC (l/100 km)	Error percentage, %
Series hybrid	3.0	3.3	7
Parallel hybrid	3.1	3.6	12
Complex hybrid	2.6	2.9	7

Results from Fig. 12 indicate that the approximate fuel consumption values can be predicted with reasonable accuracy (error percentages <12 %) using the proposed models. Only the parallel hybrid fuel consumption model shows a higher percentage level than 10 %. Both series and parallel hybrid models are able to predict within a 7 % error percentage.

The study proposes that fuel consumption levels with kinetic intensity metric can be used to predict approximately how a series, parallel and complex hybrid perform in an unknown drive cycle in terms of fuel consumption. However, further real-world drive cycle data is necessary to conclusively state hybrid models are capable of predicting fuel consumption values for any unknown drive cycle.

Fig. 13 represent the hybrid advantage of the three hybrid configurations against kinetic intensity. The hybrid advantage is the percentage reduction in fuel consumption of a hybrid vehicle over a conventional vehicle, calculated by equation (6). Hybrid advantage of each hybrid for different drive cycles are a good metrics to determine the performance characteristics of each vehicle. Hybrid advantage and kinetic intensity values were found for the same five standard drive cycles. The best fit line for the three data sets are plotted and linear regression values are calculated for each data set.

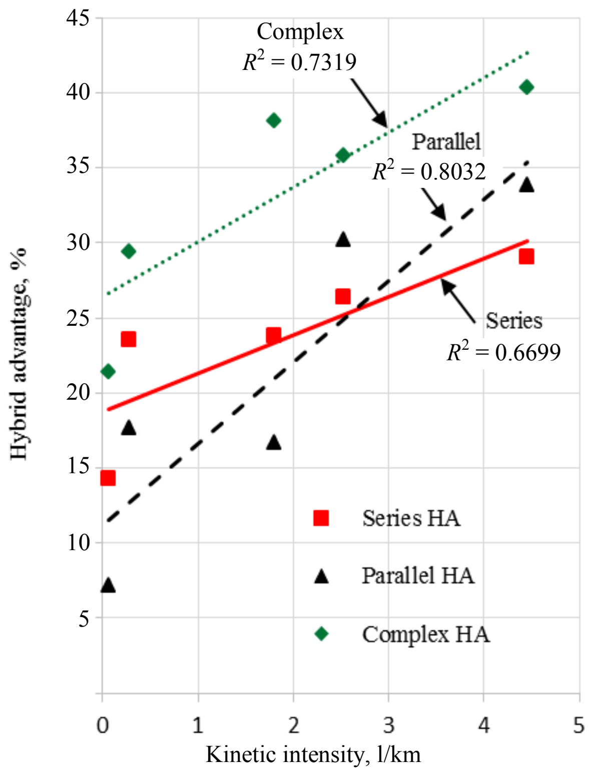

Fig. 13. Hybrid advantage of hybrid configurations against the kinetic intensity

While the linear correlation between the hybrid advantage and kinetic intensity of the drive cycles are weaker compared to fuel consumption and kinetic intensity, a linear correlation exists with R^2 values less than 0.65. Both complex and parallel hybrid has a linear regression value higher than 0.7. Trendline of all three hybrids is with a positive gradient as expected. Parallel hybrid has the highest gradient with a value of 0.054. Both series and complex have a gradient of 0.0254 and 0.0365. The kinetic intensity is a good representation of brake energy in a drive cycle, the study proposes that gradients of the three graphs may be used as an indication of the ratio between the brake energy harnessed out of the available energy of a hybrid.

CONCLUSIONS

1. Simulation of four powertrains (i. e. series, parallel, complex hybrid and conventional powertrain configurations) was carried out in MatLab/Simulink ADVISOR environment. This paper assesses the emissions and fuel consumption of hybrid configurations under varied hybridization values and drive cycles.

2. The analysis of emissions independent of the fuel consumption showed that even though both series and parallel hybrids showed a decrease of fuel consumption by 24 and 18 % respectively, CO emissions increased significantly in both hybrid vehicles (series 175 % and parallel 183 %). Similarly, with higher hybridization values fuel consumption have decreased and CO emission has increased. Note that a catalytic converter is not modelled in the simulation. Results of the study elucidate that a decrease in fuel economy is not an accurate comparator to predict the emission levels. In some instances, while fuel consumption is decreased, emission levels can be higher than a conventional powertrain.

3. When fuel consumption is assessed with kinetic intensity, a strong correlation was seen for both hybrid and conventional powertrains. Moreover, the proposed fuel consumption models were able to predict the fuel economy of an unknown drive cycle within an error percentage of 12 %. Results show that models can be used to predict the fuel consumption of an unknown drive cycle to an approximate value.

4. Present work reveals, for a particular light vehicle, the fuel and emission performance of hybrid configurations significantly vary with different drive cycles and degrees of hybridization. The study considered many variables and the following points were not included, but could be addressed in future research papers. First, the control strategy used for the complex hybrid powertrain was taken from the Toyota Prius 1999 and efforts to obtain a later version need to be investigated to assess any improvements. Secondly, the control strategies of the three hybrid configurations are optimized for a small car considering a single objective, i. e. fuel consumption. Other objectives or vehicle types could be considered to assess their impact. Thirdly, the study focusses on CO, HC, and NO_x emissions. The globally important CO_2 emission levels should be planned for the next evaluation. Finally, the WLTP (Worldwide harmonized Light vehicles Test Procedure) could be realized in a future drive cycle assessment.

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