

Benefits of spark-ignition engine fuel-saving technologies under transient part load operations

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ABSTRACT

This paper presents a simulation-based study to evaluate three potential benefits of fuel-saving technologies implemented in spark-ignition (SI) engines for a passenger car over actual urban driving cycles. These technologies include cylinder deactivation (CDA), stop-start system, and engine downsizing ($\approx 20\%$ degree of downsizing). The aim of the work is to evaluate individual benefits of each system in terms of fuel consumption. GT-Power engine simulation tool is utilised to model engines which employ each of the mentioned technologies; each of the engines has identical full-load torque characteristics. Each engine model is instructed to run over a transient, part-load, torque driven operations based on actual road test measurements, and the cycle-averaged fuel consumption was evaluated. From the analysis, the contribution of each technology in terms of fuel economy can be assessed based on an actual part-load transient operation, which can be beneficial to developers to optimise the operation of SI engines. The results revealed stop-start system to be the most promising technology for the driving cycle at hand with 27.5% fuel consumption improvement over the baseline engine. CDA engine allows for 12.6% fuel economy improvement. On the other hand, the downsized turbocharged engine has caused increasing cycle fuel consumption by 7.5%. These findings are expected to be valid for typical urban driving cycles as far as they conform to the operating load residency points over the transient torque profile.

Keywords: Fuel economy; cylinder deactivation; stop-start system; engine downsizing; transient part-load operations.

INTRODUCTION

In recent years, there has been a powerful demand for manufacturers to reduce the average fleet CO₂ emissions and vehicle dependency on fossil fuel. This is clearly evident when regulations were imposed to financially penalise manufacturers who fail to comply with the CO₂ limit set by the regulatory bodies. This development has seen the industry actively introducing new fuel-saving technologies in their products. Considering this, small-medium sized vehicles and passenger cars utilise technologies, such as the stop-

start system and cylinder deactivation (CDA) to improve fuel economy. The stop-start technology involves automatic shut-down and restart of an engine which is primarily used to reduce the amount of fuel consumed by an engine during idle state or whenever the vehicle is not in motion. On the other hand, CDA is a variable displacement technology whereby several cylinders are cut-off at certain conditions of operations. While CDA and stop-start systems can be implemented on the same engine platform, another fuel-saving technology which has become ever more popular in the industry is “downsizing”. The process involves the use of a smaller engine, often forced induced to produce the same torque output as it is a naturally aspirated counterpart. This is achieved predominantly through the reduction in frictional, heat and throttling losses. In this investigation, transient 1D gas dynamics simulations were carried out on spark-ignition (SI) engines equipped with the aforementioned fuel-saving technologies. The simulations are so performed that the engines operate over driving patterns recorded from real-world test programs. As such, it is deemed to be more realistic in terms of the engine fuel consumption measurements as opposed to those obtained based on standard drive cycles.

Development of engines with fuel-saving technologies are often carried out by manufacturers and reported based on standard drive cycles such as the New European Drive Cycle (NEDC). However, large discrepancies are found between fuel consumption values obtained from these standard drive cycles and those from the real-world driving. For petrol cars, 10 – 15% under-prediction of fuel consumption is not uncommon [1] and for small gasoline passenger cars, the discrepancies can be as much as 25% [2]. While it is fully understood that type-approval tests are necessary to standardise the reporting of fuel consumption and emission, real-world tests and driving characteristics form a crucial part of the engine development and testing. Manufacturers are putting in a lot of efforts to improve fuel economy over driving cycles which include technological advances on the engine itself and the development of electrical, hybrid, and range-extended engines [3]. From the industrial perspective, variable displacement, and stop-start systems are becoming widespread technology introduced into the modern market along with engine downsizing. The first two technologies are supposed to be relatively economical to implement as compared to the development of downsized engines, which require a longer period of development and higher-cost. The use of variable displacement engines as means of reducing fuel consumption has been introduced several decades ago. As early as in 1978, Bates et al [4] described the development of CDA through valve control mechanisms. Kuruppu et al [5] showed how the potential of CDA engines can be optimised via variable valve timing strategies in. Hu et al. [6] described the benefit of fuel economy improvement on modern engines obtained through CDA by way of reducing pumping loss. It was pointed out that this can be achieved by allowing the throttle to operate at the higher opening angles during light loads, where the engine would otherwise operate at part-throttle. Development of advanced CDA technologies for spark ignition engines was demonstrated by FEV and MAHLE [7] who described a mechanism that can be employed for deactivating cylinders by way of a switchable lever. The recent simulation work by Souflas et al (2016) models the realistic performance of the system during mode-switching events [8]. The authors went on to demonstrate a method for reducing the disturbance experienced by engines during switching between operation modes. Abas et al [9] compared the fuel economy of vehicles using start-stop and CDA systems in Southeast Asian driving cycles and gave an insight for manufacturers on potential benefits of both systems.

Another fuel-saving trend within modern passenger cars is the stop-start system. The advantage of this system is dominant in city driving with frequent idling conditions. The system is simple in concept but bears with its inherent challenges such as battery lifespan, noise, vibration and harshness (NVH) issues and post-combustion after-treatments. Recent studies are largely aimed at addressing these issues. Robinette and Powell [10] reported on a method of integrating 12 Volt battery system for use in a conventional engine with the stop-start system. This work focuses on optimisation methods of engine start-up and where vibration issues and smooth take-off are issues of concern. Similar work by Wellman et al. [11] reported the work at FEV to overcome NVH and engine restart and launch delays. The work was further improved later by the authors where key events during engine starts that affect the vehicle vibration characteristics were presented [12]. Other research fronts for the stop-start system include the impact of engine stop-start events on exhaust after-treatment. In frequent engine stop events, the exhaust gas temperature may not be sufficiently high for catalyst light-off, hence the efficacy of the after-treatment system is compromised [13].

The industry is seeing a huge trend among manufacturers in adopting engine downsizing as means to improve fuel economy and reduce CO₂ emissions. This is a method of changing the speed and load operating point of an engine by replacing a large engine with a smaller one. Normally, the smaller engine is boosted to enable operation at a higher specific load to maintain the same torque output. At present, several developers have demonstrated successful engine downsizing up to 60% the displacement of a comparable naturally aspirated (NA) version while achieving the same full-load torque output with significant improvement in fuel economy [14, 15]. Forced induction systems play a central role in the development of downsized engines. An issue related to turbocharged engines is the relatively high fuel consumption at low-speed, low-load operations where the back pressure from the turbochargers is felt. This requires the tuning of the engine at a higher number of part-load calibration points as described in [16]. In addition, the presence of a turbocharger turbine in the exhaust manifold introduces addition restriction thus increasing exhaust back-pressure and consequently pumping loss. A turbocharged engine; therefore, draws more torque from the engine at idle as compared to its NA counterpart.

METHODS AND MATERIALS

Simulation Procedures

This paper presents modelling procedures to evaluate engine fuel consumption over an urban drive cycle based on actual vehicle testing carried out on Malaysia road as described by Abas et al (2014) in reference [17]. The actual test was carried out by using a vehicle with engine specifications as shown in Table 1. The engine used in this simulation is a 1.6 litre SI engine with rated power and torque of 81.5 kW at 6500 RPM and 150 Nm at 4000 RPM, respectively. This engine was intended for a B-segment four-door sedan with a curb weight of 1027 kg. The commercial GT-Power 1D gas dynamics engine performance simulation software from Gamma Technologies was used for this study. A GT-Power model for this baseline engine was constructed and steady-state simulation was carried out for engine speeds 800 – 7500 RPM. The power and torque characteristics predicted by GT-Power are shown in Figure 1 along with dynamometer test results.

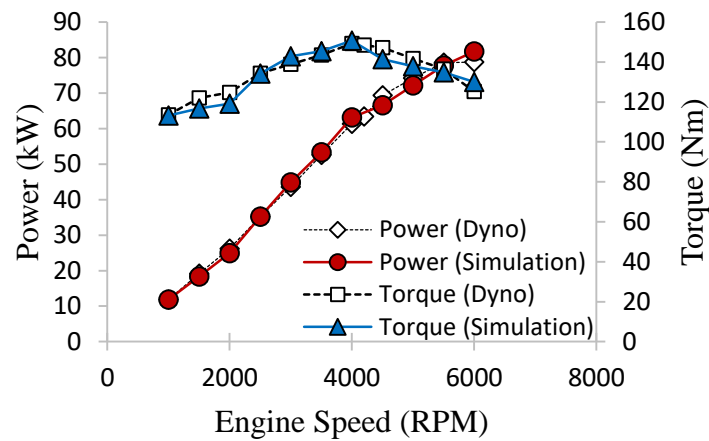


Figure 1. Baseline engine power and torque characteristics predicted through simulations.

Table 1. Basic engine specifications for simulations.

Specification	1.6 litre NA	1.3 litre turbocharged
Engine type	4-stroke Spark Ignition	4-stroke Spark Ignition
Induction type	Naturally aspirated	Turbocharged
Fuel delivery	PFI	PFI
Cylinder geometry	76 mm x 88 mm (bore x stroke)	76 mm x 73.4 mm (bore x stroke)
Displacement	1566 cc	1331 cc
Compression ratio	10	9.5
Maximum power output	81.5 kW (109 hp) at 6500 RPM	80 kW (107 hp)
Maximum torque output	150 Nm at 4000 RPM	150 Nm

The actual road tests were conducted on specified routes around the Klang Valley region in Malaysia [17]. The actual road tests were conducted on specified routes in the city of Kuala Lumpur. The selection of the route was based on criteria representing urban driving patterns, which include traffic congestion, short drive stints and highway driving with high congestion possibilities during peak hours. The traffic conditions along these routes entail a combination of smooth, slow, stand-still, and highways. Further details on the method of route and cycle selection were given by Abas et al. in [17]. One of these routes was selected for the purpose of this study with vehicle speed against time shown in Figure 2. This route comprises triple, double, and single-lane roads with junctions and several traffic light junctions. Transient data which include vehicle and engine speed and torque were logged during the road test at 100 millisecond time intervals over a total driving period of 1385 sec. Over the selected route, the vehicle covered approximately 2.4 km with an average vehicle speed of 11.3 km/h and a maximum of 55 km/h while encountering several stops along the way. Throughout the entire cycle, the engine operates mostly at part-load conditions. All simulations in this study will be based on this driving route. The measurement of transient speed-load enables the data to be imposed as profiles in the engine models described below. To perform transient analysis for each case, the throttle angle was adjusted via a controller such that the engine achieved the

transient speed-load profile obtained from the driving cycle. Three fuel-saving technologies were considered for evaluation in this study. Therefore, the simulations were conducted for four cases (Table 2), including the baseline model, which is denoted as Case A.

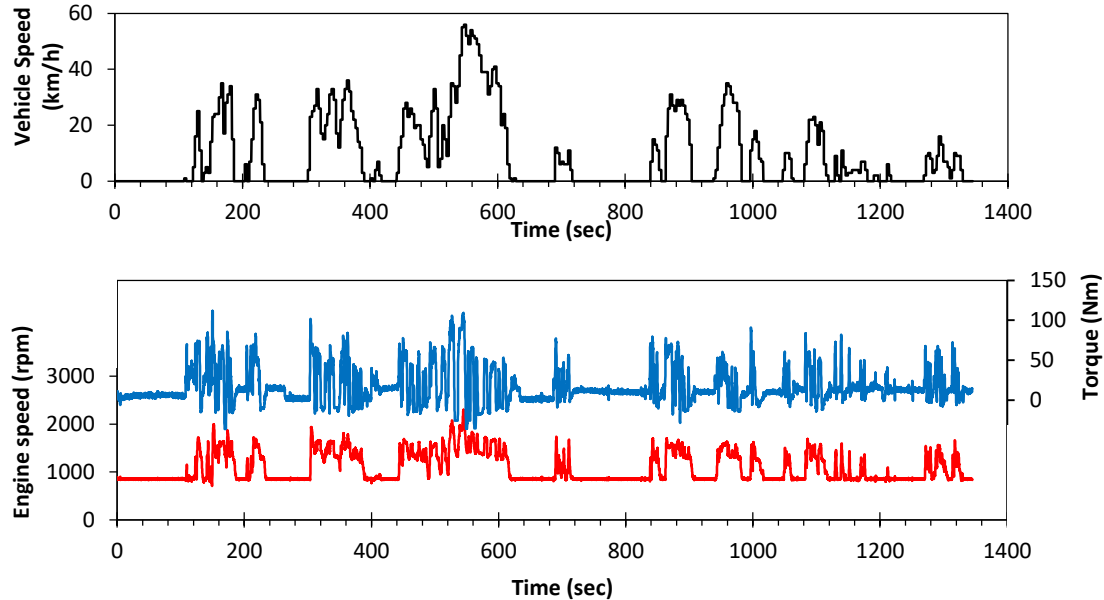


Figure 2. Vehicle speed (top) and speed-load demand (bottom) against time for drive-cycle simulation.

Table 2. Simulation Cases

Case	Description
Case A	Baseline engine (NA)
Case B	Baseline engine + Stop-start
Case C	Baseline engine + CDA
Case D	Downsized turbocharged

Case B is the baseline engine model with a stop-start system. The stop-start modelling strategy for this model is simple in that fuel will be cut-off (engine stops with zero fuel flow) whenever the torque demand and the vehicle speed are both zero at points along the driving route. This is an ideal case where there will be no set time delay for the engine to automatically stop. It is also assumed that the automatic stops and restarts are seamless and swift without any impact on fuelling and are not influenced by temperature requirement for catalyst light-off and battery charging or other auxiliary constraints. Simulation model Case C refers to the baseline engine with CDA capability which cuts off air-fuel supply to two cylinders. This is achieved by imposing zero-lift profiles on the intake cams of two out of the four engine cylinders. The strategy adopted for this engine was that CDA engaged whenever the transient speed-load point fell below the maximum steady-state full load torque values of the engine when operating with only two cylinders, as shown in Figure 3. This is achieved by way of cam profile switching mechanism in which two profiles are made on the intake cam allowing it to operate in either lifting or non-lifting modes. An additional procedure has to be put in place for the GT-Power model whereby the intake valves of two cylinders are switched to the non-lifting cam profile,

allowing the cylinders to be shut-off whenever torque demand falls below the pre-set speed-load values.

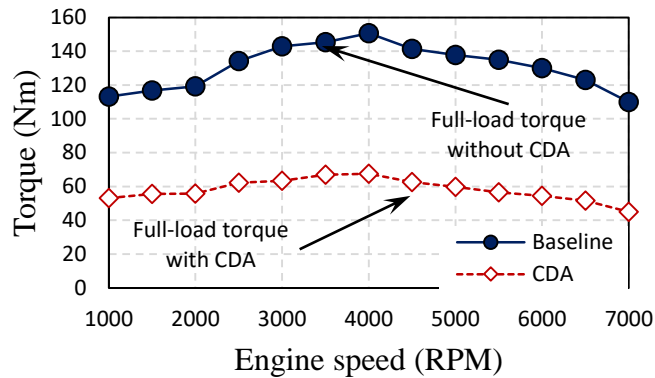


Figure 3. Torque characteristics at full-load for baseline engine and with deactivated cylinders.

The fourth case for the simulation (Case D) is a 1.3-litre turbocharged engine used to represent a turbocharged downsized engine. The basic engine specifications are shown in Table 1. This engine employs a single scroll turbocharger with 51mm and 55mm turbine and compressor wheel diameters, respectively. A waste-gate valve is used to regulate the boost pressure based on target engine torque. This allows boost pressure to be adjusted such that the 1.3-litre engine achieved the same full-load torque characteristics as the baseline engine. Figure 4 shows the torque output from the downsized engine (Case D) compared to the 1.6-litre baseline engine characteristics (Case A).

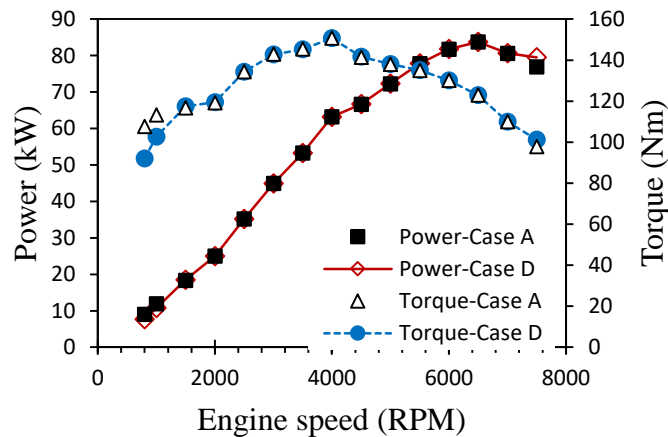


Figure 4. Full load torque characteristics of the turbocharged engine (Case D) compared to those of baseline engine (Case A).

The torque matched well across the entire RPM range except at very low engine speeds. The lack of low-end torque seen here was typical of a turbocharged engine and attributed to the turbines being inefficient at low engine speeds. Furthermore, the presence of the turbocharger turbine restricted the exhaust flow and introduces higher back-pressure, hence requiring the engine to produce more torque to maintain positive pressure through the cylinder. The turbocharged engine in Case D requires control of another

element namely the turbocharger waste-gate valve. This valve enables the flow of exhaust gasses to bypass the turbocharger turbine for boost control and avoid turbine over-speeding. A PID type waste-gate controller element was used in the turbocharged engine model to adjust the transient opening and closing of the waste-gate valve. This waste-gate model assumed that for a given pressure ratio, the instantaneous mass flow during opened valve condition is the sum of mass flow through the turbine and the waste-gate valve.

RESULTS AND DISCUSSION

Figure 5 compares the calculated fuel consumption profile over the drive cycle for all simulated cases with the cycle vehicle speed superimposed on the graph. As expected, the cumulative fuel consumption increased over time and their profiles were seen to be influenced by the corresponding vehicle speed. The baseline naturally aspirated engine without fuel-saving technologies consumed approximately 414.5 grams of fuel over the cycle. Figure 5 shows that Case B and Case C obtained the final fuel consumptions lower than that of the baseline engine in Case A. Case C which represents the stop-start feature shows the most substantial fuel-saving by as much as 27.5%. This was contributed by the engine shut-offs at several stops encountered throughout the drive cycle. Several plateaus in the fuel consumption profile can be observed in the figure with zero gradients of fuel flow indicating zero fuel flow.

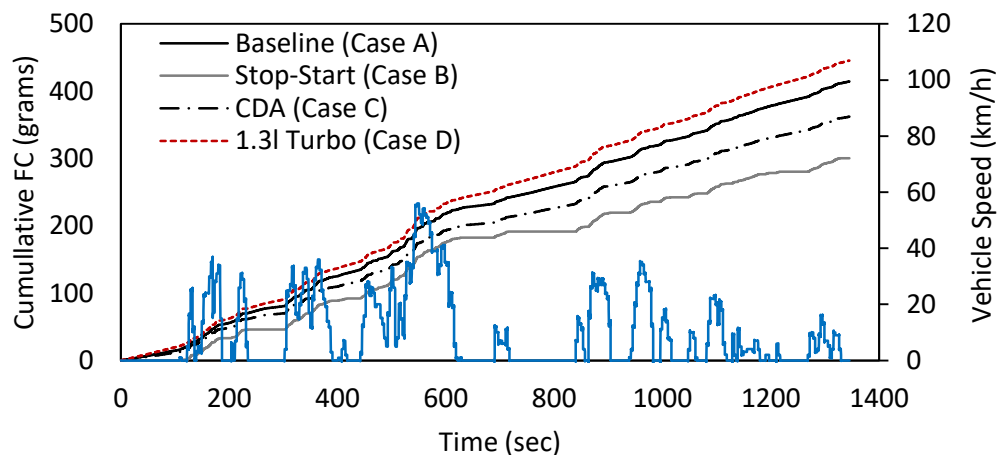


Figure 5. Comparison of cumulative fuel consumption for four engine cases.

In practice, the actual benefit of the start-stop system is expected to be less than predicted here due to several reasons. First of all, there would normally be a prescribed time delay for the engine to automatically shut when the vehicle stops which was not modelled in this study. Secondly, the need to operate the auxiliary systems such as the air-conditioning and alternator recharging may also cut short the automatic stop event. Another challenge for stop-start systems was the need to maintain sufficiently high temperatures for catalyst light-off for emission controls. This requirement may also prevent the vehicle control system to allow automatic shut-off of the engine during idle. The advantage of the CDA engine is apparent in this simulation. At the end of the cycle, 12.6% fuel consumption reduction was achieved by the engine over the baseline value. The comparison of fuel mass flow rate for Case C with the baseline engine (Case A) is given in Figure 6 along with the corresponding torque input profile. It can be seen that at the fuel flow rate corresponds well with the torque input and that the CDA-equipped

engine (Case C) is seen to consume less fuel compared to its baseline counterpart (Case A).

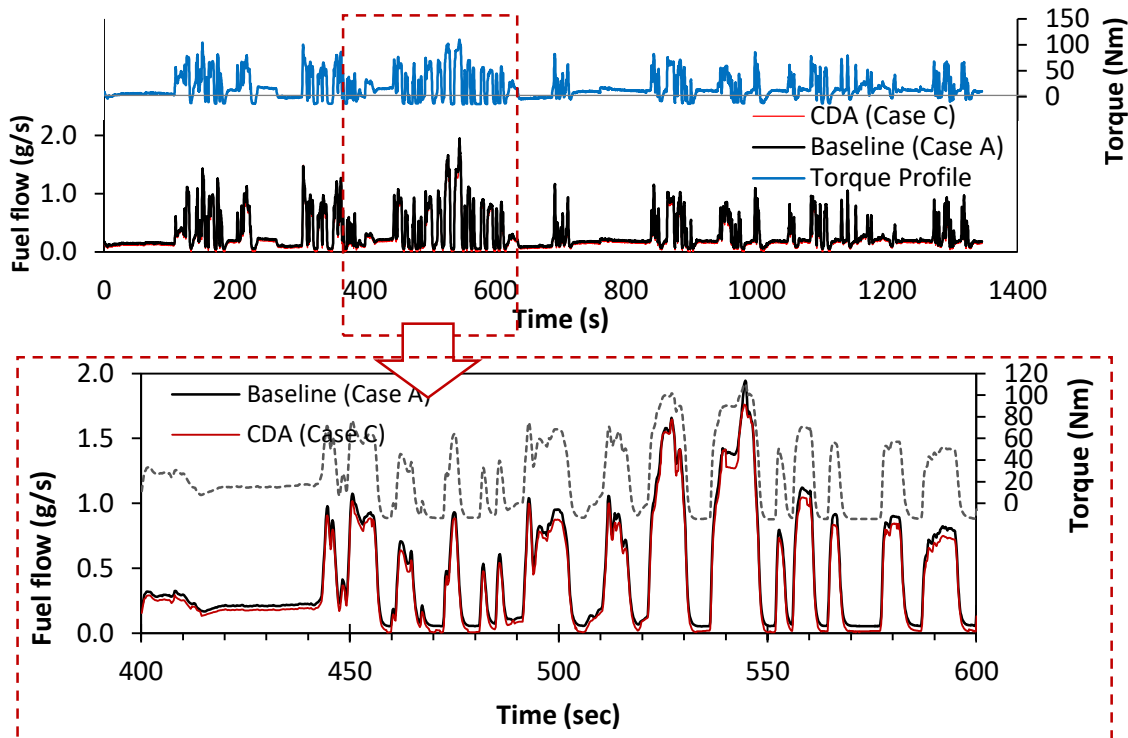


Figure 6. Comparison of fuel mass flow rate for baseline engine (Case A) with CDA-equipped engine (Case B) plotted with corresponding torque demand (with profiles zoomed view for 400-600 seconds).

Over the driving route, the engine operated mostly at inefficient low-speed and low-load points as indicated in Figure 7. Here, only $\approx 7\%$ of the total torque resident points were above beyond the CDA engine full-load curve, which allows the fuel economy to benefit from CDA implementation. The benefit of this technology can also be expected at the high-speed low-load regions. The turbocharged engine (Case D) in this simulation yields the worst fuel consumption with 7.5% increase over the baseline total cycle fuel consumption. This can attribute to several factors which include high engine back-pressure and low turbine efficiency. The engine was required to run at the higher torque at low engine loads to overcome the high back-pressure introduced by the presence of the turbocharger turbine in the exhaust pipe. Higher fuel flow needed to maintain sufficient torque during idling conditions also contributed the poor cycle fuel consumption. In addition, the turbocharger was not operating in its efficient region at low-speed and low-load points as encountered by the engine in this simulation.

The transient operating point of the turbocharger compressor in Figure 8 shows that only a very small region of the turbocharger map was occupied by the transient points. This took place at low-pressure ratios and low mass flow rate regions where the efficiency of the turbocharger was low. The simulation reported an average of $\approx 44\%$ and $\approx 34\%$ turbine and compressor efficiencies, respectively throughout the drive cycle and that the engine has never encountered turbocharger efficiency greater than 50% throughout the driving cycle. As such, further optimisation has to be done on the turbocharger engine if

it is to offer fuel economy benefits over the present drive cycle. This may include matching the engine to smaller turbochargers (which may involve trading-off maximum power output) or having multi-stage boosting systems to extend the effective range of operation. The limitation of current boosting systems and challenges in systems matching of downsized engines were demonstrated and discussed by Turner et al (2015) in [14]. For this, highly adaptable boosting systems are needed to further enhance the potential of downsized engines as a reliable solution.

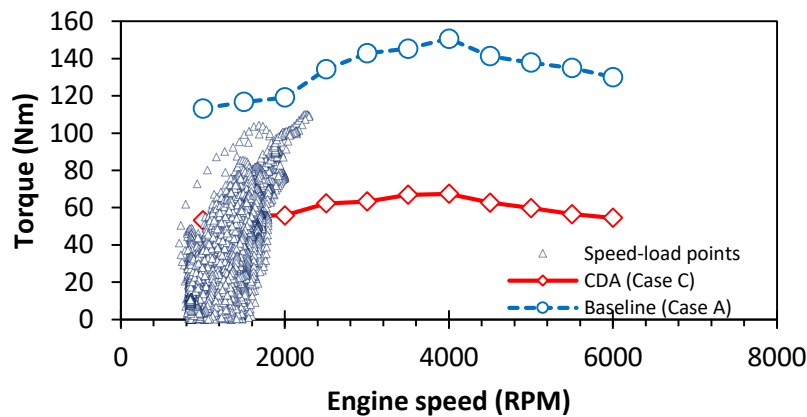


Figure 7. Driving cycle engine torque resident points on full-load torque characteristics of Baseline (Case A) and CDA (Case C) engines.

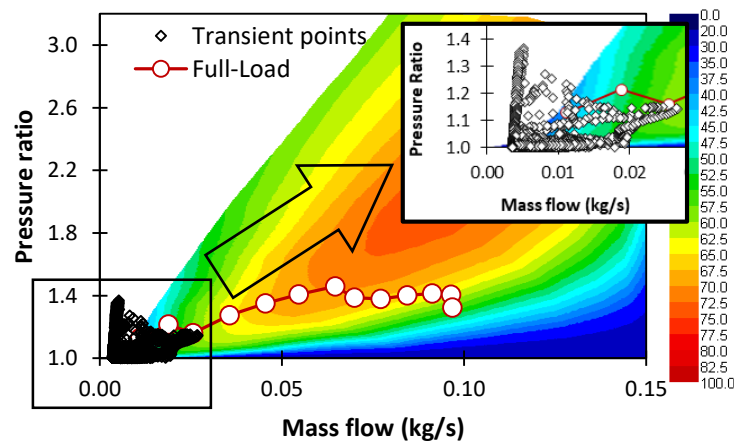


Figure 8. Transient and full-load turbocharger operating points plotted on the compressor map (Case D).

CONCLUSIONS

The aim of the study is to model engines for the transient part-load operation of an engine over an actual vehicle driving pattern. The transient characteristics of the model are based on the speed and torque profiles which are obtained from actual road tests. These are imposed as transient speed-load points on the engine model in GT-Power. Three fuel-saving systems in their simple forms were evaluated over the cycle namely the stop-start, CDA, and turbocharged systems. Of the systems evaluated, the stop-start offered the most benefits in terms of fuel economy over the prescribed drive cycle, giving a 27.5% reduction in cycle fuel consumption compared to the baseline model. The CDA system

exhibited a significant improvement in terms of fuel consumption (by 12.6%) over the prescribed drive cycle due to a large amount of torque resident points in the low load regions of the engine operating points. The turbocharged engine produced the worst fuel consumption (7.5% higher than the baseline engine value) due to the higher back pressure and high idling fuel consumption. In addition, the turbocharger was also found to be operating at inefficient regions over the majority of the cycle and further impacting the fuel economy. These findings are expected to be valid for an urban driving cycle consisting of similar driving profiles based on the operating load residency points over the transient driving profile. The study serves as the basis for future investigations on transient drive-cycle-based simulations. For this, the following recommendations are proposed:

- Highway mode driving-patterns can be included in future studies to investigate the various cycle characteristics and its effect on engine fuel consumption to enable selection and optimisation of various fuel-saving systems.
- A more realistic stop-start system incorporating stop-start event delays, auxiliary, and catalyst requirement can be modelled and evaluated.
- The used of the downsized engine can be further improved by implementing multi-stage and highly adaptable boosting systems as well as through incorporation of other enabling technologies such as the gasoline direct injection and variable valve timing systems.
- The vehicle fuel consumption of advanced powertrains such as hybrid vehicles and range-extenders can be included in the future.

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