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Effects of Intake Valve Lift Form Modulation on Exhaust Temperature and Fuel Economy of a Low-loaded Automotive Diesel Engine

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Abstract

Exhaust after-treatment (EAT) systems on automotive vehicles cannot perform effectively at low loads due to low exhaust temperatures ($T_{exhaust}$ < 250ºC). Conventional late intake valve closure (LIVC) technique - a proven method to improve diesel exhaust temperatures - generally requires the modulation of the whole valve lift profile. However, an alternative method - boot-shaped LIVC - only needs partial lift form modulation and can rise exhaust temperatures significantly. Therefore, this study attempts to demonstrate that boot-shaped LIVC can be an alternative solution to improve exhaust temperatures above 250ºC at low-loaded operations of automotive vehicles.

A 1-D engine simulation program is used to model the diesel engine system operating at 1200 RPM engine speed and at 2.5 bar brake mean effective pressure (BMEP) engine load. Boot-shaped LIVC is achieved via keeping the valve lift constant (at 4.0 mm) for a while during closure and then closing it at different closure angles. The method results in up to 55ºC exhaust temperature rise through reduced in-cylinder airflow and thus, is adequate to keep EAT system above 250ºC at low loads. The longer the boot is kept during closure, the lower the air-to-fuel ratio is reduced and the higher the exhaust temperature flows at turbine exit. Similar to conventional LIVC, boot-shaped LIVC improves fuel consumption as pumping losses are decreased in the system. Despite aforementioned improvements, EAT warm-up is affected negatively due to the significant drop-off on exhaust mass flow rates. The need to modify only some parts of the lift profile is a technical advantage and can reduce production costs.

Keywords: Intake valve lift modulation, Late intake valve closure, Thermal management, Exhaust temperature, Fuel efficiency.

Research Article

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1. Introduction

On-road automotive vehicles are generally equipped with diesel engines due to the cost-effective, fuel-efficient and reliable performance during operation. However, strict emission regulations issued by environmental authorities pose a serious threat for their widespread use on land transportation [1,2]. Those agencies particularly demand a significant reduction on the emission rates of nitrogen oxides (NO_x) and particulate matter (PM) for automotive vehicles using diesel engines. For instance, environmental protection agency (EPA) in the US require NO_x and PM emission rates for heavy-duty diesel vehicles to remain below 0.27 g/kWh and 0.013 g/kWh, respectively [2]. Therefore, engine manufacturers and researchers continue to develop new methods in order to meet those aforementioned stringent emissions norms [3,4]. One recent method is to use alternative fuels for gasoline and diesel on internal combustion engines [5-8]. Exhaust gas recirculation (EGR) is another effective method for low emission rates on diesel engine systems [9,10]. Researchers examine advanced combustion techniques to improve emission rates as well [11-13]. As aforementioned on-engine methods are generally inadequate to keep emission rates within permissible limits at all operating conditions, automotive vehicles are mostly outfitted with EAT systems [14] so as to meet strict emission regulations.

Automotive manufacturers generally use Three-Way Catalytic Converter (TWC) systems to limit criteria pollutants on highway vehicles. A typical TWC system consists of Diesel Oxidation Catalyst (DOC), Diesel Particulate Filter (DPF) and Selective Catalytic Reduction (SCR) subsystems, respectively. In this system, DOC is responsible to reduce unburned hydrocarbons (UHCs) and carbon monoxide (CO), DPF operates to decrease PM and finally SCR performs to curb NO_x emission rates. As long as the temperature remains above a certain degree (generally 250ºC), TWC systems work highly efficiently on automotive vehicles and distinctly reduce emission rates [15-17]. During intercity transport, operating temperature can be kept above 250ºC without any modulation as the vehicles generally perform at high loads. However, during inner-city transport, vehicles mostly operate at low loads due to the traffic congestion or the need to work on a stop-and-go schedule (such as public buses or goods distribution vehicles). Exhaust temperatures at those cases mostly fall below 250ºC [18-20] which is inadequate to keep TWC systems at effective levels. Therefore, particularly at light loads, there is a continuing search to improve diesel exhaust temperatures [21].

Previous studies generally focus on two main strategies to rise exhaust temperatures on diesel engines: fuel-path and air-path methods [22]. One of the effective fuel-path method is to implement early exhaust valve opening (EEVO) [23]. EEVO results in a significant exhaust temperature rise since exhaust flow through the turbine starts at a time not long after the combustion process [24]. However, expansion work is shortened in EEVO mode and thus, the system needs additional fuel in order to keep engine load constant [25]. Basaran shows that both EEVO and late exhaust valve opening (LEVO) can elevate exhaust temperature of a diesel engine up to 55ºC at a low-loaded operating condition [26]. It is also shown that high fuel penalty (up to 20 %) is a significant disadvantage which needs to be considered [26]. Another energy-inefficient on-engine technique is to apply internal exhaust gas recirculation (IEGR) [27]. IEGR can be achieved via negative valve overlap and exhaust temperature can be improved up to 50ºC at low loads. However, high in-cylinder residual gas deteriorates combustion and thus, the method requires fuel penalty [27]. Researchers examine the effects of the main fuel injection timing, post-fuel injection timing and post-fuel quantity on exhaust temperature as well [28,29]. Postponing main injection timing or utilizing extra fuel injection after top dead center (TDC) - post injection - generally rises exhaust temperatures with a reasonable fuel penalty. However, the improvement is generally limited and insufficient to boost exhaust temperature above 250ºC. Using afterburners, heat storage components or electrical heating can also be regarded as fuel path techniques to improve EAT effectiveness [30-32]. Since those engine-independent methods require both extra energy and equipment of additional devices on the engine system.

Unlike fuel-path methods, air-path techniques focus on the control of the total airflow into the cylinders [33]. One of the practical air-path method is to implement intake throttling [34, 35]. Partial opening of the intake throttle valve decreases airflow and elevates exhaust temperatures, however, it noticeably increases fuel consumption [35] and significantly rises NO_x and smoke emissions [36]. Similar to intake throttling, reducing waste-gate valve opening is effective to achieve high exhaust temperatures on diesel engine systems [37]. Another recent air-path technique is to apply intake valve closure (IVC) modulation [38,39]. It is experimentally demonstrated at a low-loaded diesel engine test stand that either delayed or advanced IVC timing (close to 125ºCA ABDC or 40ºCA BBDC) causes a noticeable reduction on in-cylinder air induction and rises exhaust temperatures significantly [40]. IVC modulation also improves fuel efficiency at light loads through reduced engine pumping losses [41]. Those advantages make IVC modulation more preferable to intake throttling, which, just as IVC modulation, can reduce air intake, but has significant drawbacks [35,36]. Similar to IVC modulation, cylinder deactivation (CDA) method has a noticeable potential to increase exhaust temperatures at low loads [42]. In CDA mode, not all cylinders are active, mostly half of the cylinders or in some cases one third of the cylinders are disabled via shutting off all valves and in-cylinder fuel injection [43]. As passive cylinders do not produce power, operating cylinders need extra fuel injection to maintain total engine power constant. Decreased air-to-fuel ratio (AFR) on active cylinders causes a considerable exhaust temperature rise on the system [44]. CDA is also shown to improve exhaust temperatures at low-loaded gasoline engine operations [45].

Those aforementioned air-path methods are generally more effective than fuel-path methods at improving exhaust temperatures. This may be due to the fact that air-path methods generally require lower mass to be heated. However, there is mostly a need to modify all inlet valves or waste-gate valve or in some cases - such as CDA - modulation of both valves and fuel injection is needed. Increasing the number of parts to be controlled not only requires technical difficulty, but also rises production cost. Investigating alternative air-path methods with the need to modulate less engine components can be a solution for those challenges.

The objective of this work is to demonstrate that an alternative non-traditional LIVC method - boot-shaped LIVC - can be as effective as conventional LIVC at improving both exhaust temperatures and fuel efficiency of diesel engines at low loads. At first, the method is applied for two-intake valves per cylinder. Then, it is implemented for single-intake valve per cylinder. Both double-valve and single-valve modulations can rise T_{exh} above 250ºC at low loads. Not only is exhaust system heated, but also BSFC is improved through reduced pumping losses. Numerical analysis shows that compared to conventional LIVC, less valve lift modification and less technological difficulty can be sufficient to improve both fuel consumption and EAT effectiveness at low loads through boot-shaped LIVC methods.

2. Methodology

2.1 Engine Properties and Simulation Model

Specifications for the engine used in the study - a compression-ignition (CI) engine - are given on Table 1. The four-stroke CI engine is designed for heavy-duty (HD) operations and has six cylinders. Air-intake is handled via utilizing a turbocharger in the system. Public buses, airport shuttles and delivery trucks mostly use those types of engines during urban transport. Those vehicles generally need to stop many times until they reach their final destination. Therefore, exhaust systems at those vehicles cannot always be kept at high temperatures. At those low-temperature-operating cases, thermal management is needed to improve exhaust temperatures and thus, EAT effectiveness.

The diesel engine model is shown on Figure 1. It is built via using Lotus Engine Simulation (LES) program [46,47]. Six cylinders are placed at the center of the model and connected to the intake ports and intake valves on the left and to the exhaust ports and exhaust valves on the right. Every cylinder has total four valves - two intake valves for the air inlet and two exhaust valves for the exhaust gas discharge -. Direct injection of diesel fuel is applied in the system. Every cylinder has a firing order as well. Considering the number of the cylinder at the top is 1 and the one at the bottom is 6, there is a firing order of 1-5-3-6-2-4 in the system. The features listed on Table 1 mostly define the main design parameters of cylinders and valves in the model. The low-loading operating condition of the diesel engine model examined in the study is given on Table 2.

The mathematical formulations for the model on Figure 1 can be found on a previous work which uses the same model and attempts to show that EVO timing modulation can considerably improve EAT warm-up at low loads [26]. Reasonable control of EVO timing has a significant potential to accelerate EAT warm-up on highway vehicles. However, it results in a noticeable fuel consumption rise (up to 20 %) which is mostly not desired during urban transport. Unlike Ref. [26], this work uses boot-shaped (BS) LIVC technique and mainly considers the exhaust temperature rise without a need to rise fuel consumption penalty. It also attempts to show that double-valve (DV) BS-LIVC and single valve (SV) BS-LIVC can have technological advantages compared to conventional LIVC technique.

Table 1. Engine specifications.

Model	Four-stroke diesel engine
Number of cylinders	6
Stroke (mm)	124
Bore (mm)	107
Connecting rod length (mm)	192
Compression ratio	17.3
Calorific value of diesel fuel (kJ/kg)	42700
Air-intake	Turbocharged
Cylinder firing order	1-5-3-6-2-4
EVO	20°CA BBDC
EVC	20°CA ATDC
IVO	20°CA BTDC
IVC	25°CA ABDC
Exhaust & Intake valve max. lift (mm)	10.0 and 8.5
Max. Engine Speed (RPM)	2800
Max. Engine Load (as BMEP) (bar)	19.0

Table 2. Low-loaded operating condition of the diesel engine.

Operating Engine Speed (RPM)	1200
Operating Engine Load (as BMEP) (bar)	2.5

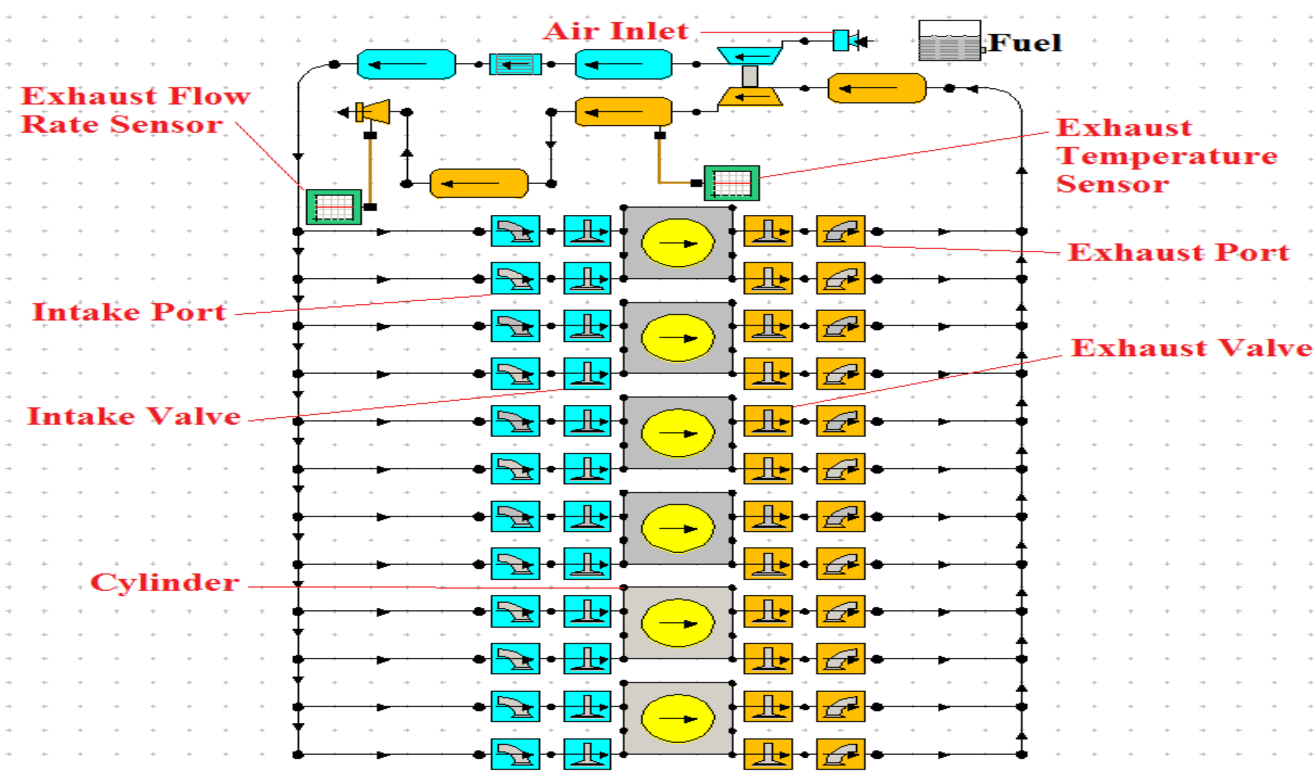

Fig. 1. Diesel engine model.

The model shown on Figure 1 focuses on the management of the turbine-out temperature (TOT) at 1200 RPM engine speed and 2.5 bar BMEP engine load. Turbine-out exhaust gases move directly through the catalytic converter systems (generally through a TWC system) on automotive vehicles. The temperature at turbine exit can be considered as a critical parameter for the performance of a TWC system which highly depends on temperature. Therefore, an exhaust temperature sensor is put on the model at turbine exit. This sensor is responsible for measuring the exhaust temperature at that point when IVC timing is changed in the system. Nominal TOT generally remains below 250°C at low loads. However, TWC systems can perform effectively on highway vehicles as long as TOT is maintained above 250°C. IVC timing is retarded through different techniques in the study so that TOT can exceed 250°C. Effects on exhaust flow rate is also considered in the analysis. Similar to exhaust temperature sensor, exhaust flow rate sensor illustrated on Figure 1 calculates the exhaust mass flow rate (kg/min) when nominal IVC timing - 25 °CA ABDC - is moved further from the BDC.

2.2 Boot-shaped Intake Valve Lift Profiles

The application of conventional LIVC is shown on Figure 2 below. As shown, there is no change on exhaust valve profile. EVO and EVC timings are kept constant. IVO timing is also kept fixed on Figure 2. However, IVC timing is shifted from its nominal position to the right in all intake valves. It is steadily retarded from the base timing. As seen, conventional LIVC requires the expansion of the intake valve lift profile. In nominal mode, intake valve lift ascends and descends in a sharp manner. This is due to the requirement to achieve the same maximum lift - 8.5 mm - at a shortened intake valve total opening timing. However, total opening timing is much longer at retarded IVC cases. Thus, the rise and fall of the intake valve lift is relatively smooth in LIVC mode. Although the valve motion is slow and seems advantageous at first, valve system is required to operate at a longer time and there is also the need to modify the whole intake valve lift profile which is not an easy technological task..

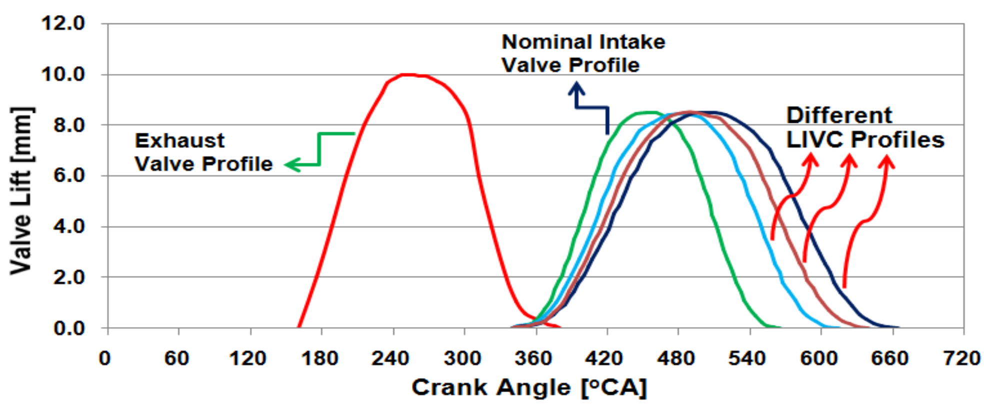

Fig. 2. Conventional LIVC profiles at different closure angles.

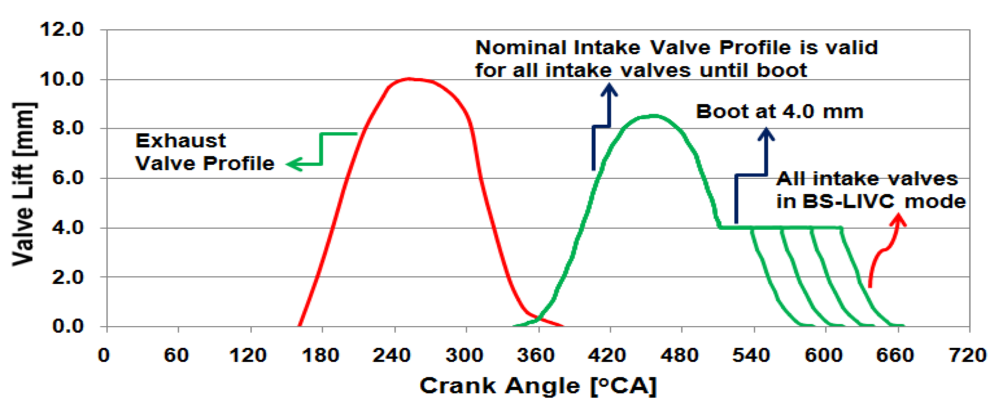

Fig. 3. Double-valve boot-shaped LIVC profiles at different closure angles.

An alternative LIVC technique is illustrated on Figure 3. Similar to conventional LIVC, DV-BS-LIVC requires the modulation of all intake valves in all cylinders. However, unlike conventional LIVC, there is no need to modify the whole valve lift profile. Rise of valve lift until 8.5 mm -maximum lift - and the lift fall from 8.5 mm to 4.0 mm is kept fixed. The change starts at 4.0 mm. At this height, valve lift is maintained constant for some degree (°CA) and then is closed similar to nominal intake valve profile. It is called boot-shaped as the closure part of the valve lift profile looks like a "boot". The boot can be determined either lower or higher than 4.0 mm. In the study, it is primarily intended to choose a random boot height (4.0 mm) and compare the results with the conventional

LIVC method. In DV-BS-LIVC mode, it is seen that partial adjustment of the lift profile is sufficient to delay IVC timing. The possibility of limited alteration on lift may be beneficial for the LIVC-aimed valve rocker arm production.

Conventional LIVC and DV-BS-LIVC methods need the control of all intake valves - total 12 valves for all cylinders - in the system. However, SV-BS-LIVC technique seen on Figure 4 requires the rearrangement of only one valve per cylinder. This single valve is modulated similar to the valves in DV-BS-LIVC method - boot at 4.0 mm - and other valve remains unchanged. In other words, while one valve per cylinder in the system goes through a boot-shaped modification, other one still performs in its nominal mode. SV-BS-LIVC not only decreases the need to modulate the entire valve lift profile, but also reduces the number of total valves - only 6 instead of 12 - that need to be controlled. This can be considered more practical compared to both DV-BS-LIVC and conventional LIVC methods. Therefore, the study primarily addresses the comparison of the effects of all three aforementioned LIVC techniques on diesel exhaust temperatures and fuel efficiency.

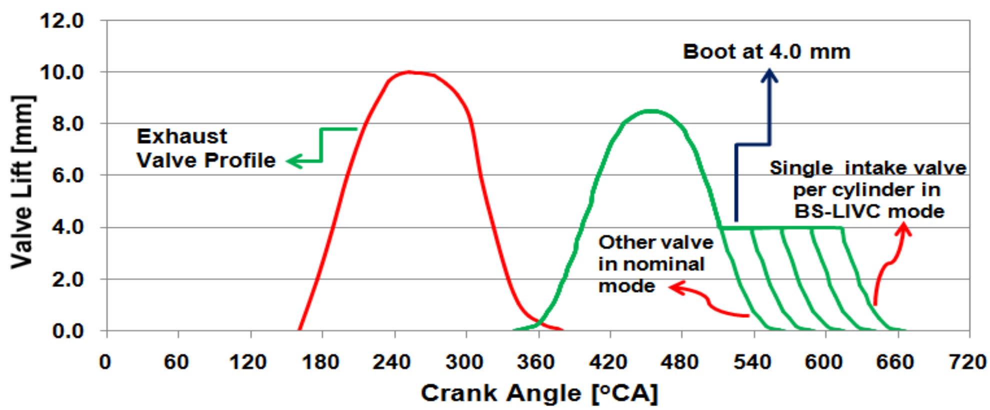

Fig. 4. Single-valve boot-shaped LIVC profiles at different closure angles.

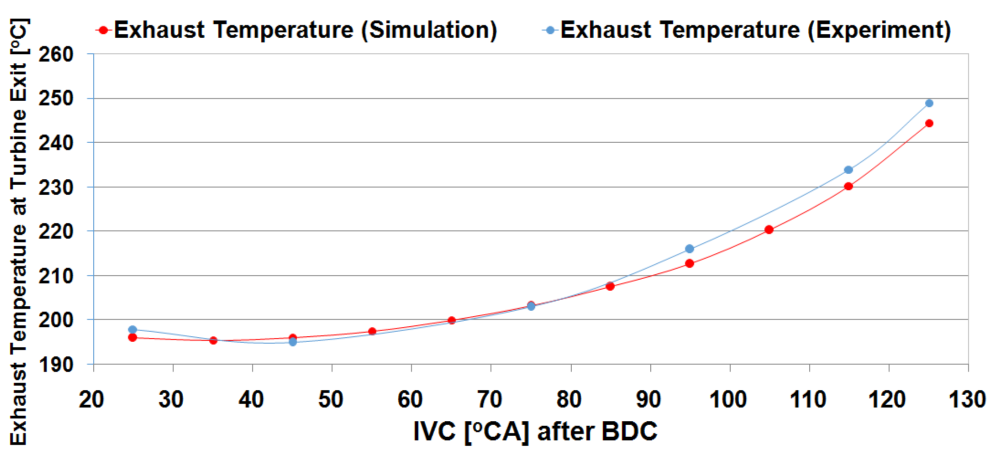

Fig. 5. Model validation with experimental results in conventional LIVC mode.

2.3 Validation of the Model in Conventional LIVC mode

Experimental results of a similar diesel engine at 1200 RPM engine speed and 2.5 bar BMEP constant engine load are found in the literature search [40]. In Ref. [40], IVC is modulated similar to the valve lift adjustment - conventional LIVC - seen on Figure 2. The model on Figure 1 operates under the same diesel engine condition as in Ref. [40] as previously stated on Table 2. It is validated with the exhaust temperature results of Ref. [40] along retarded IVC timings.

The comparison between model & experimental results of exhaust temperatures is illustrated on Figure 5. Nominal IVC timing - 25 °CA ABDC - is delayed up to 100 °CA from the starting position - until 125 °CA ABDC - with the aim of exhaust temperature rise in both studies. As shown on Figure 5, the results of the model are mostly similar with the experimental results. The difference remains below 5 % along all LIVC timings. Also, in both works, exhaust temperature can be raised to a point very close to 250ºC at most retarded IVC timing. The method shows identical potential to improve thermal management in both analyzes. Therefore, the simulation on Figure 1 can be considered as a reliable model for numerical analysis of diesel exhaust temperatures.

3. Results and Discussion

As shown on Figure 5, at a low-loading operating case - 1200 RPM and 2.5 bar BMEP -, diesel engine system performs with exhaust gas temperature much below 250ºC at base IVC timing - 25 ºCA ABDC - on Figure 5. Conventional LIVC is shown to be a feasible method to improve exhaust temperature at this condition. In this section, alternative LIVC techniques (shown on Figures 3 & 4) are compared with conventional LIVC technique considering the effects on both exhaust gas temperature and engine fuel consumption. Engine load is maintained at 2.5 bar BMEP in all calculations via fuel injection rate modulation.

Effect of both conventional and alternative LIVC methods on exhaust temperature at turbine-exit is demonstrated on Figure 6. As stated previously on Introduction section, 250ºC is generally considered as a threshold temperature for EAT systems for efficient performance. At nominal IVC timing, exhaust temperature seems to be highly inadequate - close to 195ºC - to maintain active EAT management. This is a serious threat for the engine system to keep NO_x and PM at low levels. However, as seen on Figure 6, once IVC is adequately delayed from its base point in all LIVC methods, exhaust temperature rises above 250ºC and thus, effective EAT operation can be maintained.

It is seen on Figure 6 that DV-BS-LIVC requires lower and SV-BS-LIVC needs higher IVC retardation compared to conventional LIVC in order to reach 250ºC exhaust temperature. Particularly, there is an explicit closure difference - approximately 11 ºCA - between DV-BS-LIVC and conventional LIVC.

The closure difference on IVC timing in Figure 6 can be attributed to the faster and slower reduction on volumetric efficiency at different methods on Figure 7. Due to the dramatic airflow reduction, a similar decrease on AFR in all techniques is also seen on Figure 8.

IVC timing is generally designed to obtain high volumetric efficiency on internal combustion engines. Inducting more air into the cylinders enable the system to combust more fuel and thus, more power is produced. This is highly beneficial during inter-city transport since vehicles generally operate at high loads. However, at low-loaded operations - mostly during inner-city transport -, there is no need to generate high power and thus, the system does not need that much air induction. It is seen on Figures 7 & 8 that LIVC considerably decreases in-cylinder airflow in all techniques. Yet, the system can still yield the same power and keep load constant. It can be derived that excess air is discharged back into the intake ports via delayed IVC.

At low-retarded IVC timings - until 75 ºCA ABDC -, exhaust temperature rise on Figure 6 is negligible since the reduction on volumetric efficiency is not significant at those timings. However, at high-retarded IVC timings - between 95 ºCA and 125 ºCA ABDC - temperature rise speeds up as more in-cylinder air flows back to the intake ports and AFR is substantially lowered in the system. It can be deduced that change of exhaust temperature is inversely proportional with both volumetric efficiency and AFR.

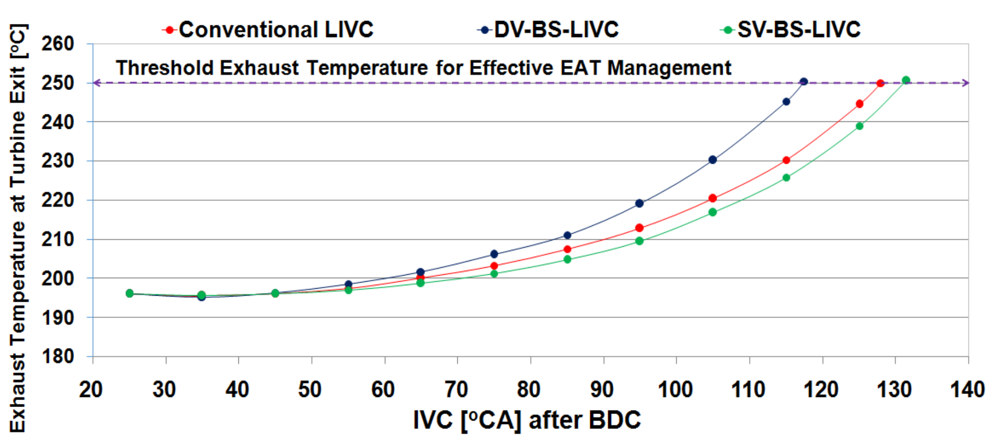

Fig. 6. Effects of different LIVC methods on exhaust temperature along retarded IVC angles.

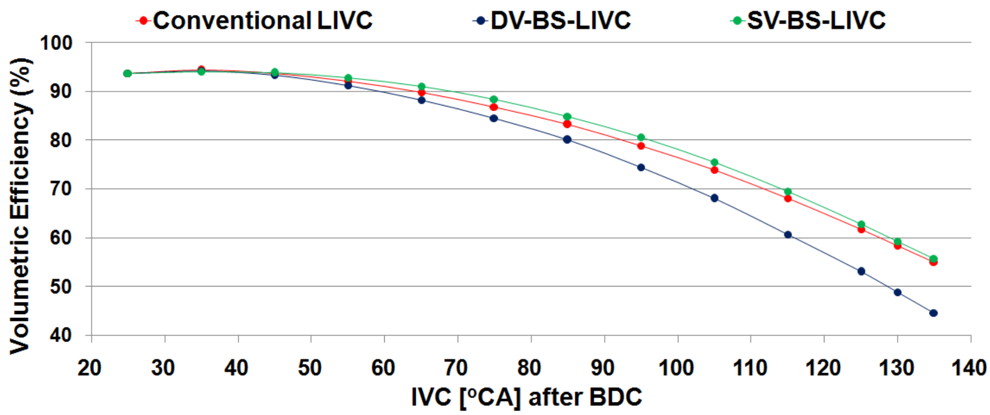

Fig. 7. Effects of different LIVC methods on volumetric efficiency along retarded IVC angles.

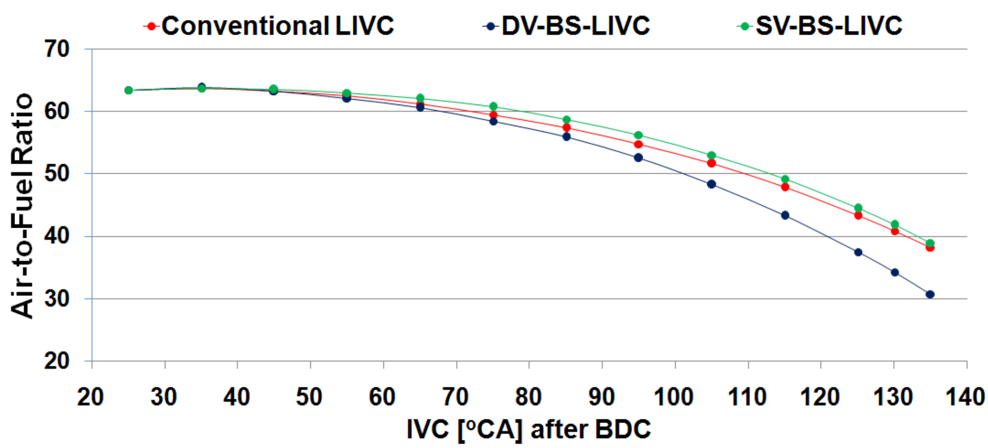

Fig. 8. Effects of different LIVC methods on air-to-fuel ratio along retarded IVC angles.

As seen on Figure 3, DV-BS-LIVC keeps all intake valve lifts at a significant height (boot at 4.0 mm) for a considerable time during compression stroke. The same is valid in SV-BS-LIVC method - on Figure 4 - for only half of the intake valves. Also, in conventional LIVC mode - on Figure 2 -, valve lift steadily decreases during compression phase. The faster volumetric efficiency reduction in DV-BS-LIVC mode on Figure 7 is due to the more available opening area for air discharge during compression stroke. It is seen that DV-BS-LIVC can discharge almost 10 % more air at high-retarded IVC timings compared to other LIVC techniques. Therefore, as shown on Figure 6, it can boost exhaust temperature above 250°C at a much earlier IVC timing.

Exhaust temperature can exceed 250°C in SV-BS-LIVC mode as well. However, it requires a higher IVC timing retardation due to the slower volumetric efficiency reduction. Half of the valves still operate in nominal mode and there is not a sufficient opening area for a fast air discharge.

Another important engine performance parameter needs to be considered is brake specific fuel consumption (BSFC). Effect of LIVC strategies on BSFC is illustrated on Figure 9. It is seen that BSFC is improved in all methods up to a certain IVC timing - 115 °CA ABDC -. After that timing, there is an increasing trend in all techniques - particularly in DV-BS-LIVC method -. Similar to the faster airflow reduction on Figure 7, DV-BS-LIVC also results in higher BSFC improvement on Figure 9 compared to other LIVC methods. This may be due to its more effective performance on in-cylinder air discharge during piston's movement towards top dead center (TDC). SV-BS-LIVC is also found to be as effective as conventional LIVC on Figure 9. It is even more effective at some IVC timings. Using only half of the valves shows a similar BSFC change with conventional LIVC at low-retarded IVC timings. However, as IVC is delayed above 95 °CA, intake valve boot remains longer at 4.0 mm and SV-BS-LIVC obtains a more advantageous in-cylinder media for movement of air back to intake ports. Therefore, it can reach threshold exhaust temperature on Figure 6 slightly more fuel-efficient than conventional LIVC method.

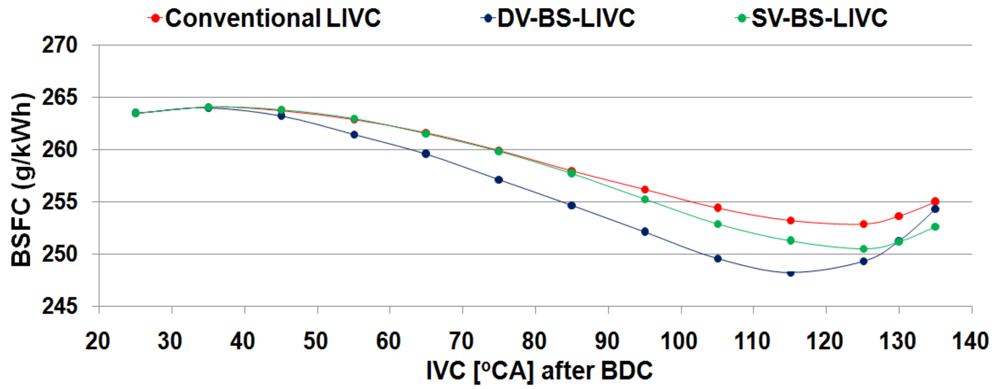

Fig. 9. Effects of different LIVC methods on BSFC along retarded IVC angles.

The change in BSFC along IVC timings can be evaluated through analyzing engine open and closed cycle efficiencies. Open-cycle efficiency (OCE) shows how effective in-cylinder air or exhaust exchange occurs in the system. During engine open cycle, both intake & exhaust valves can be open or at least one of them is kept open in the system for gas exchange. OCE can be defined as [48]:

$$\eta_{OCE} = \left[1 + {}^{PMEP}/_{IMEP_{power}}\right] \quad (1)$$

where PMEP is pumping mean effective pressure - pumping loss of the system - and $IMEP_{power}$ shows the indicated mean effective pressure - a measure for the effectiveness of the gross power production - in the system.

Unlike OCE, all intake & exhaust valves are closed during engine closed cycle. There is no gas exchange within the cylinder. Closed cycle efficiency (CCE) can be calculated with the formula given below [48]:

$$\eta_{CCE} = \left[IMEP_{power} / \left({}^{\dot{m}_f Q_{LHV}}/_{N * V_d} \right)\right] \quad (2)$$

where N is the engine speed, V_d is the displaced volume, Q_{LHV} is the lower heating value of the diesel fuel and finally $\dot{m}_f$ shows the fuel injection rate. CCE is a measure of the effectiveness of the conversion of in-cylinder diesel fuel energy into piston work. In other words, it evaluates the power-generation effectiveness of the total energy supplied to the system.

At first, the effect of LIVC methods on OCE is examined on Figure 10. It is seen that OCE is increased in all techniques. OCE directly depends on PMEP as stated previously in equation (1). Therefore, the improvement on OCE is due to the reduction on engine pumping loss shown on Figure 11. Decreased PMEP rises OCE particularly at high-retarded LIVC timings.

As LIVC strategies are compared on Figures 10 & 11, DV-BS-LIVC outstands as the most successful method to improve OCE in the system. As seen previously on Figure 7, it is the fastest method to decrease volumetric efficiency. That rapid air reduction facility decreases engine PMEP the most on Figure 11 among all LIVC techniques. Therefore, at most of the delayed-IVC timings, it is more fuel-saving than other methods on Figure 9. The improvement on BSFC through DV-BS-LIVC starts to wane after a certain - after 115 °CA - intake closure. This may be related to the change on engine CCE at those timings. SV-BS-LIVC is found to have a similar potential on OCE improvement - worse than DV-BS-LIVC but slightly better than conventional LIVC - although it only utilizes half of the valves in the system. Unlike SV-BS-LIVC, the reducing trend of valve lift during intake closure in conventional LIVC mode cannot keep the discharge area constant for a certain period of time - less favorable environment for air discharge -. Therefore, airflow reduction is achieved with marginally higher pumping losses. Those higher PMEP causes lower OCE improvement and thus, slightly lower fuel-efficiency in conventional LIVC method on Figure 9. Similar to DV-BS-LIVC, the improvement on BSFC in other LIVC methods deteriorates as IVC is moved beyond 115 °CA ABDC. This worsening case is also considered to depend on the change in CCE in the system. However, overall, non-traditional LIVC methods have promising results to decrease BSFC at low loads.

Effect of all LIVC techniques on CCE is seen on Figure 12. At low-retarded IVC timings, CCE does not change that much in all methods. As shown on Figure 13, in all strategies, a significant change on $IMEP_{power}$ is not observed at those IVC timings. Considering the CCE of the system mainly relies on $IMEP_{power}$ - stated on formula (2) -, a noticeable change on CCE is not predicted for those low-retarded IVC timings. However, as IVC moves further from the BDC and gets closer to the TDC - particularly 105 °CA after BDC -, all techniques have a decreasing trend in CCE. In fact, this is the area on Figure 9 where the improvement on BSFC comes to an end and even shifts towards a negative direction. It is also seen on Figure 13 that the reduction on $IMEP_{power}$ starts to accelerate at those timings. It can be derived that LIVC methods have a limit on BSFC reduction due to the inevitable fall of CCE in the system.

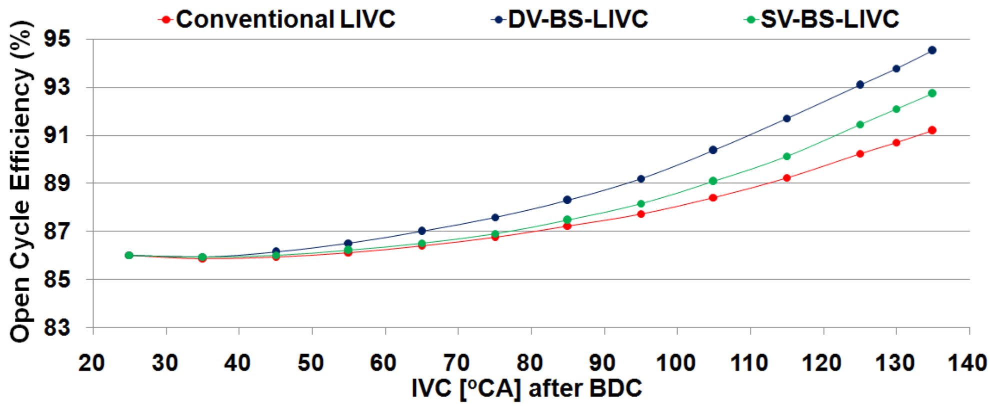

Fig. 10. Effects of different LIVC methods on OCE along retarded IVC angles.

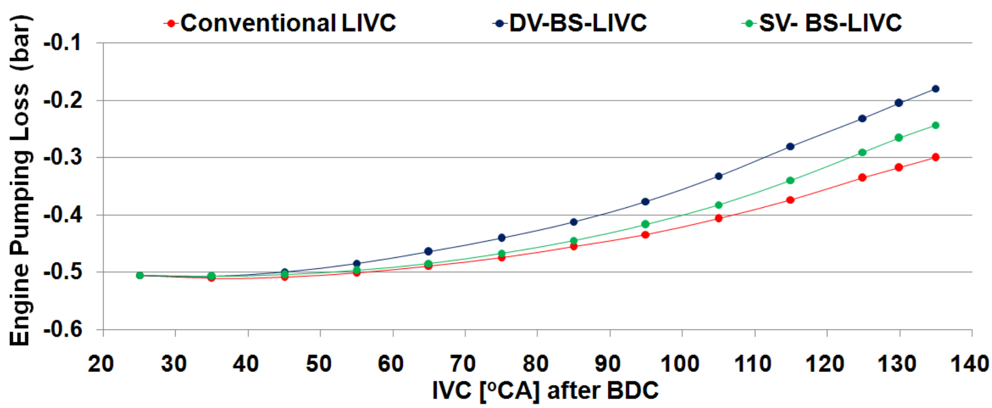

Fig. 11. Effects of different LIVC methods on engine pumping loss along retarded IVC angles.

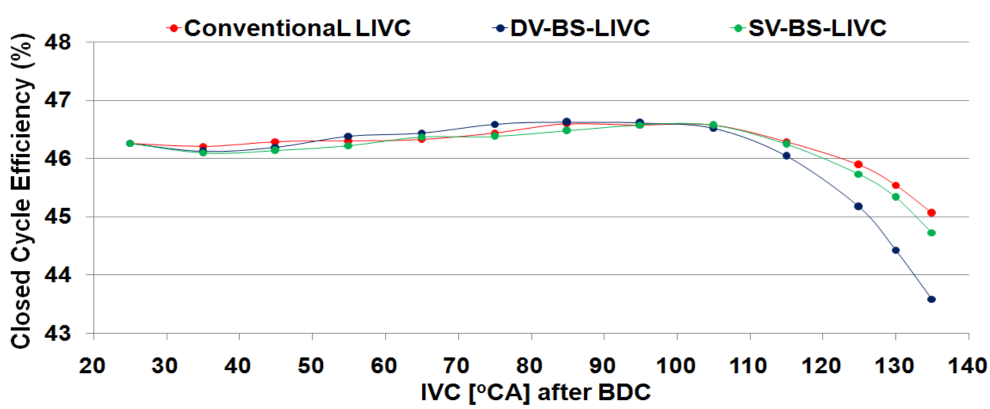

Fig. 12. Effects of different LIVC methods on CCE along retarded IVC angles.

The most dramatic reduction on CCE is seen in DV-BS-LIVC mode on Figure 12. As Figure 13 is examined, implementing boot-shaped retardation in all intake valves causes a sharper decrease on $IMEP_{power}$ compared to other LIVC techniques. This stems from the abrupt reduction on volumetric efficiency on Figure 7. All methods are faced with airflow reduction to some extent. However, keeping intake boot at 4.0 mm so long in all valves causes volumetric efficiency to remain below 50 % - noticeable reduction on Figure 7 - which is definitely not seen in other methods. The reduction on AFR in DV-BS-LIVC mode is also much sharper as illustrated previously on Figure 8. As seen on Figure 14, that much reduction on in-cylinder charge affects total fuel burn duration negatively. The higher reduction on CCE in DV-BS-LIVC mode is due to the late completed combustion compared to other techniques. The duration for the total fuel burning rises in conventional and SV-BS-LIVC methods as well. However, as IVC timing is shifted particularly over 115 ºCA ATDC, combustion begins to be completed at much longer periods and thus, the difference between DV-BS-LIVC and other strategies expands explicitly on Figure 14. This is the reason why a similar difference in CCE is observed at those IVC timings on Figure 12.

It is seen on Figure 14 that delay in combustion completeness is relatively low - up to 10 ºCA - in conventional LIVC and SV-BS-LIVC techniques compared to DV-BS-LIVC method - up to 18 ºCA -. Airflow change at those two strategies is highly similar as shown on Figures 7 & 8. Thus, on Figure 14, combustion effectiveness follows a similar direction. It can be derived that at light-loaded diesel engine operations, not all intake valves are required to be modulated - SV-BS-LIVC instead of conventional LIVC - in order to manage the in-cylinder airflow and thus, combustion completeness. SV-BS-LIVC necessitates only one valve lift profile per cylinder to be remodeled which is less difficult and can be cost-saving for the producers. It can still improve the OCE and keep the reduction on CCE at a low level at highly-delayed IVC timings. It also has the advantage of raising exhaust temperatures above 250ºC as illustrated on Figure 6. Those benefits can enable the SV-BS-LIVC method to be a considerable alternative for fuel-efficient EAT management on diesel engine systems.LIVC techniques have the advantage of high exhaust temperatures and reduced BSFC at low loads. However, those methods also lead to a significant reduction on exhaust mass flow rate as seen on Figure 15. The decreased exhaust flow rates can be attributed to the reduced volumetric efficiency in all methods on Figure 7. The lower the volumetric efficiency is, the lower the exhaust gas flows through the TWC system.

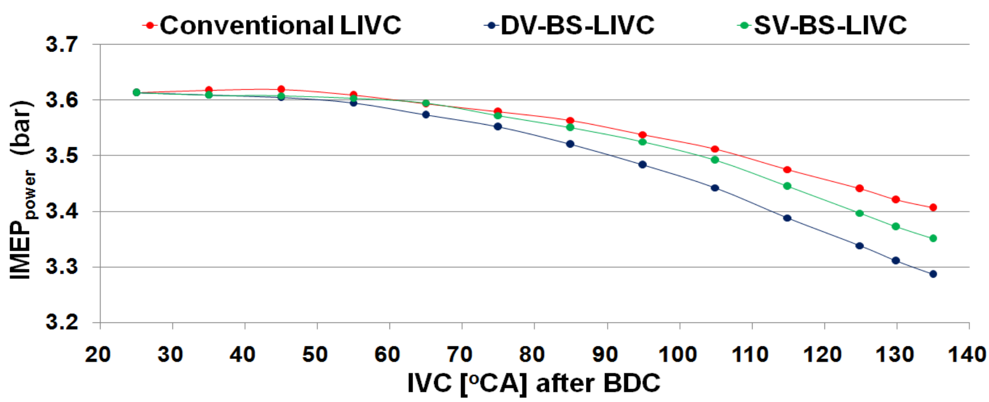

Fig. 13. Effects of different LIVC methods on $IMEP_{power}$ along retarded IVC angles.

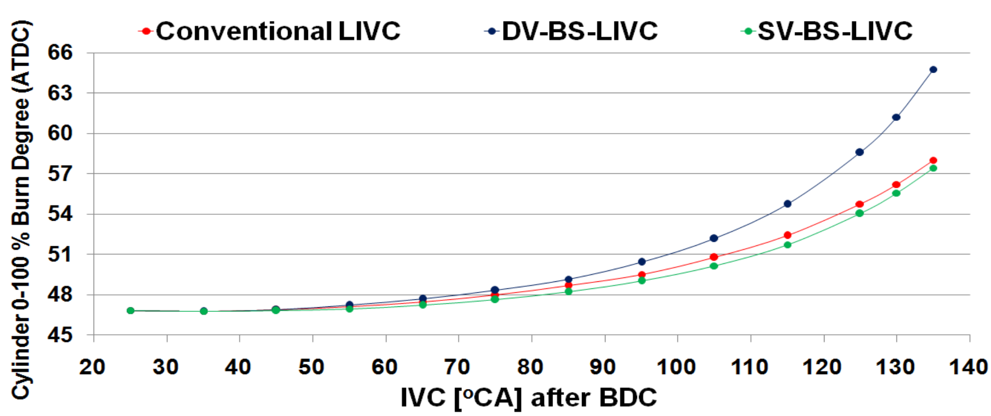

Fig. 14. Effects of different LIVC methods on cylinder 0-100 % burn degree along retarded IVC angles.

Aforementioned lowered exhaust flow rates can be a drawback for EAT heat-up. Therefore, effect of LIVC strategies on EAT warm-up is examined considering both the advantage of high exhaust temperatures and the disadvantage of low exhaust flow rates. Equation (3) below is utilized to calculate the approximate heat transfer rates from the diesel exhaust gas to the EAT system [49]:

$$\dot{Q} = C\left[\dot{m}_{exh}^{4/5}\right]\left[T_{exhaust} - T_{EAT\ catalyst\ bed}\right] \qquad (3)$$

where $T_{exhaust}$ shows the temperature of the exhaust gas - assumed as TOT in the analysis -, $T_{EAT\ catalyst\ bed}$ represents the EAT catalyst bed temperature and $\dot{m}_{exh}$ denotes the exhaust mass flow rate moving through the EAT system. $\dot{Q}$ - the heat transfer rate - is predicted considering those three parameters. C in equation (3) is a constant depending on the material and geometry of the EAT system. A specific EAT system - thus, a particular C - is not defined on Figure 1. Even if it is defined, C in formula (3) remains constant regardless of the method applied in the system. Therefore, as shown on Figure 16, the heat transfer rates are normalized and relative comparison of all LIVC methods is examined.

The normalized heat transfer rates for all LIVC techniques on Figure 16 are valid for IVC timing of 115 ºCA ATDC. In nominal case, IVC is taken as 25 ºCA ATDC. In the normalization process, the heat transfer rate for nominal case at 0ºC EAT temperature is taken as 1.0. Other heat transfer rates are proportioned based on this value between -50ºC and 450ºC EAT temperatures. Exhaust temperature and flow rate remain constant in both nominal case & LIVC strategies during steady-state operation. However, as EAT system warms up, temperature difference in equation (3) changes and thus, the heat transfer rate to the EAT catalyst bed differs on Figure 16.

As Figure 16 is examined, it is seen that it consists of two main parts divided with a "no heat transfer line" in the middle where $T_{exhaust}$ is equal to $T_{EAT\ catalyst\ bed}$. On the upper part - above zero heat transfer line -, heat transfer rates are positive since $T_{exhaust}$ is higher than $T_{EAT\ catalyst\ bed}$ in the system ($T_{exhaust} > T_{EAT\ catalyst\ bed}$). On this area, EAT catalyst bed is warmed up until the heat transfer rates cross the "no heat transfer line" where $T_{exhaust} = T_{EAT\ catalyst\ bed}$. DV-BS-LIVC seems to be the most successful method as it can heat the EAT system up to approximately 250ºC. This is predicted since the highest exhaust temperature rise is obtained in DV-BS-LIVC mode on Figure 6. Other LIVC methods warm up the EAT system up to 230ºC which is close to but still below the threshold temperature. In nominal case, $T_{EAT\ catalyst\ bed}$ can only reach 195ºC which is far from 250ºC. It is also seen that although LIVC methods can improve the heat transfer rates up to 66 % when $T_{EAT\ catalyst\ bed}$ is above 100ºC, nominal case is more effective at lower temperatures ($T_{EAT\ catalyst\ bed} < 100$ºC). This is due to the noticeable exhaust flow rate reduction shown previously on Figure 15. Nominal case has much higher exhaust flow rate and thus, is more advantageous for EAT warm-up along low catalyst bed temperatures.

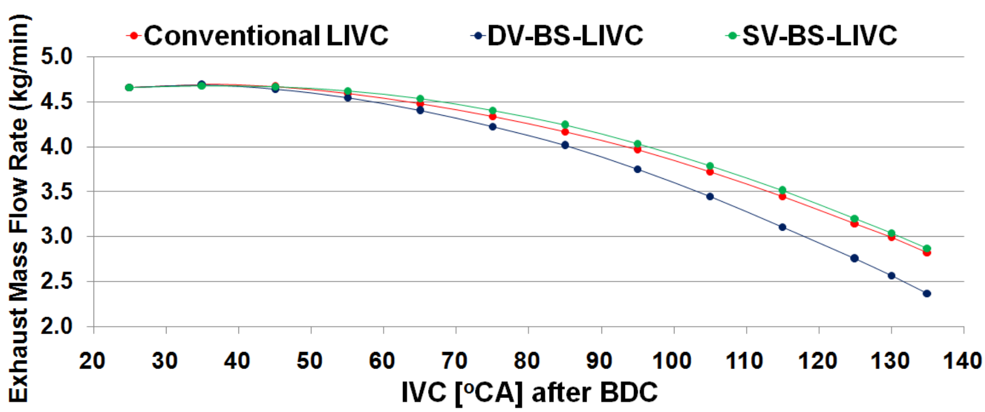

Fig. 15. Effects of different LIVC methods on exhaust flow rate along retarded IVC angles.

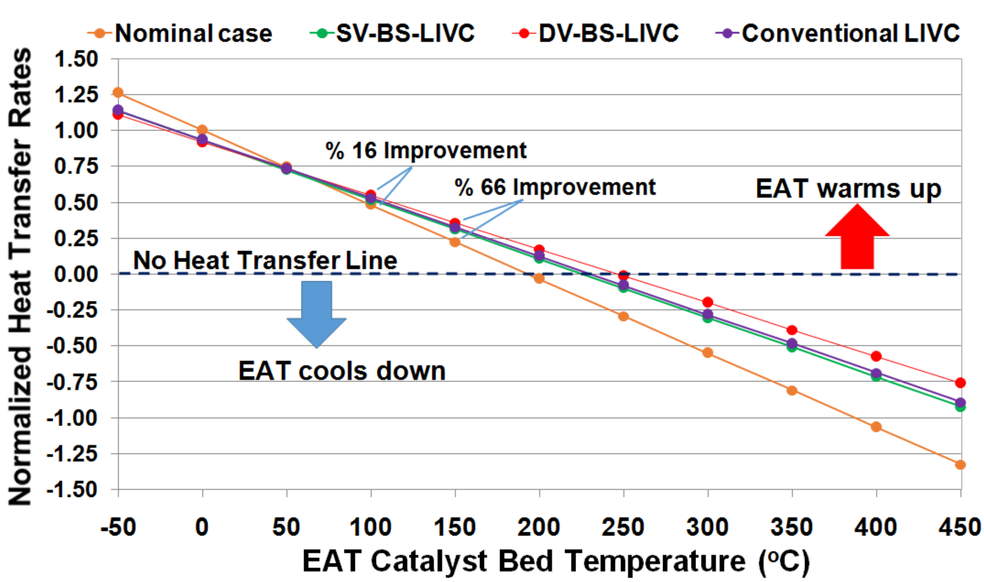

Fig. 16. Effects of different LIVC methods on EAT warm-up at 2.5 bar BMEP.

On the lower part of "no heat transfer line" on Figure 16, heat transfer rates are negative since on this case, unlike upper part, $T_{EAT\ catalyst\ bed}$ is hotter than $T_{exhaust}$ ($T_{EAT\ catalyst\ bed} > T_{exhaust}$). EAT system cools down on this area due to the reverse heat transfer rates. Low negative heat transfer rates are favorable in order to keep EAT system at high temperatures - particularly above 250ºC - for long periods. It is seen that DV-BS-LIVC has the least heat transfer loss when EAT system is hotter than 250ºC ($T_{EAT\ catalyst\ bed} > 250$ºC). Considering formula (3), high $T_{exhaust}$ and low $\dot{m}_{exh}$ are demanded for low negative heat transfer rates. DV-BS-LIVC mode meets those requirements better than other methods on Figures 6 & 15. Thus, it is more successful at delaying EAT cooling. The improvement in SV-BS-LIVC mode is lower yet close to DV-BS-LIVC mode. Considering it only needs half the complexity of total valve control compared to other two LIVC techniques, SV-BS-LIVC can be preferred in the region EAT cools down. Compared to aforementioned LIVC methods, nominal mode has the highest negative heat transfer rates and EAT is cooled the fastest in this mode. This can be attributed to the low $T_{exhaust}$ - 195ºC - and high $\dot{m}_{exh}$ - above 4.5 kg/min - which are opposite of what is desired for low heat loss in equation (3).

4. Conclusions

In this work, an alternative LIVC method is examined numerically on a diesel engine model in order to enhance both fuel consumption and exhaust temperature management at low loads. Instead of retarding IVC timing in a conventional manner, boot-shaped lift forms are used on intake valves for LIVC in the system. That non-traditional LIVC modulation is not only implemented for double intake valves per cylinder but also for single valves.

Both DV-BS-LIVC and SV-BS-LIVC are effective at improving exhaust temperatures (up to 55ºC temperature rise) at low loads. Compared to conventional LIVC, DV-BS-LIVC requires lower and SV-BS-LIVC needs higher retardation on IVC timing in order to reach 250ºC exhaust temperature. The difference stems from the fact that SV-BS-LIVC can control only half of the total intake valves and thus, it can reduce in-cylinder air and AFR slower than other two LIVC methods. The faster the AFR decreases, the faster the exhaust temperature rises in all methods.

Non-traditional LIVC methods improve engine fuel consumption as well. Reduced pumping loss through decreased air flow causes a noticeable rise on OCE and thus, the system can operate in a fuel-efficient manner. There is a lower BSFC improvement in conventional LIVC mode since pumping loss is decreased at a lower rate. However, it is also found that at high-retarded IVC timings (above 115 ºCA ATDC), the reduction on CCE is high in unconventional LIVC methods. Thus, BSFC improvement deteriorates at those timings.

All LIC strategies are ineffective at EAT warm-up compared to nominal case at cold catalyst bed temperatures (particularly below 100ºC) due to the significant decline on exhaust mass flow rate. However, after a certain temperature (particularly above 150ºC), LIVC techniques may be preferred for improved EAT heat-up. Reduced exhaust flow rates and elevated exhaust temperatures are beneficial to decrease negative heat transfer rates at hot catalyst bed temperatures (above 250ºC) as well.

The requirement to modify only a limited part of the valve profile in BS-LIVC methods is a technical advantage compared to conventional LIVC and can be cost-effective during production. Moreover, using only half of the valves in SV-BS-LIVC technique can be less challenging compared to conventional LIVC and DV-BS-LIVC methods.

On future works, alternative LIVC techniques can be examined both numerically and experimentally on diesel engine systems. It is seen that proper intake valve lift design has the potential to improve both EAT management and fuel efficiency at low loads. Therefore, the search on the effects of different lift modifications should be continued on further studies.

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Nomenclature

ABDC	: after bottom dead center
AFR	: air-to-fuel ratio
ATDC	: after top dead center
BBDC	: before bottom dead center
BDC	: bottom dead center
BMEP	: brake mean effective pressure (bar)
BSFC	: brake specific fuel consumption (g/kWh)
BTE	: brake thermal efficiency
CA	: crank angle (degree)
CCE	: closed cycle efficiency
CDA	: cylinder deactivation
DOC	: diesel oxidation catalyst
DPF	: diesel particulate filter
DV-BS	: double-valve boot-shaped
EAT	: exhaust after-treatment
EEVO	: early exhaust valve opening
IEGR	: internal exhaust gas recirculation
IMEP	: indicated mean effective pressure (bar)
IVC	: intake valve closure
IVO	: intake valve opening
LES	: lotus engine simulation
LEVO	: late exhaust valve opening

LIVC	:	late intake valve closure
$\dot{m}_{exh}$	:	exhaust flow rate (kg/min)
$\dot{m}_f$	:	fuel flow rate (g/h)
N	:	engine speed (RPM)
NO_x	:	nitrogen oxides
OCE	:	open cycle efficiency
P_{max}	:	maximum in-cylinder pressure (bar)
PM	:	particulate matter
RPM	:	revolution per minute
SCR	:	selective catalytic reduction
SV-BS	:	single-valve boot-shaped
T	:	temperature
TDC	:	top dead center
TOT	:	turbine out temperature
TWC	:	three-way catalytic converter
V_d	:	displaced volume

Conflict of Interest Statement

The author declares that there is no conflict of interest in the study.

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