FUEL SAVINGS AND COST REDUCTION OF START-STOP TECHNOLOGY FOR AN INTERNAL COMBUSTION ENGINE

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ABSTRACT

Global warming effects have forced the regulation on carbon dioxide (CO_2) emissions by vehicle to be tighter. European Union (EU) has set by 2015 the amount of CO_2 emitted must be below 130 g CO_2/km. Several technologies have been emerged to improve vehicle fuel efficiency which subsequently reducing the amount of CO_2 emission for instance engine downsizing, hybridization and alternative fuels for instance bio-fuel, fuel cell and hydrogen. Even though these technologies have been proven capable of improving fuel efficiency, the cost incurred to develop the technologies is very high and require longer payback period. Thus, Stop-Start (SS) technology has been seen as a promising solution due to its lower development cost, less complexity architecture, shorter payback period and capable to reduce fuel consumption.

The basic principle of start-stop operation is the vehicle's control system will switch the engine off when the vehicle is idling for example in a congested traffic condition or stop at traffic light. The engine is automatically switched on when the driver presses the clutch or accelerator pedal. Start-stop system can be a standalone system and directly applied to standard conventional vehicle.

This thesis presents the test methodologies and results for fuel consumption comparison between standard Persona and Persona equipped with start-stop system by using Proton Test Standard. Three different time settings were added for engine stop to evaluate the thermal cabin comfort. The data from the fuel consumption test was used to calculate the annual fuel and cost savings.

The annual fuel saving computed is 296 liter/100 km and the annual cost saving is RM562.40 with the assumption that the price of fuel is RM1.90/liter. However, during the

test, the battery performance showed some deterioration. Thus, it was recommended battery with higher performance needs to be used for start-stop application.

For thermal comfort, the passengers were not happy with the condition during engine stop where the air-conditioner was off. Therefore, additional device such as storage evaporator is required to ensure the thermal comfort inside the cabin.

This thesis also presents literature reviews on main components required when start-stop technology is integrated with conventional vehicle system. The components are enhanced battery, intelligent battery sensor, integrated starter-alternator and DC to DC converter. The control strategies for engine stop and start are covered in the thesis. The advantages and challenges of this technology are also presented.

ABSTRAK

Kesan pemanasan global telah menyebabkan peraturan pelepasan karbon dioksida oleh kenderaan menjadi lebih ketat. Kesatuan Eropah (EU) telah menetapkan menjelang 2015, jumlah karbon dioksida yang dilepaskan mesti di bawah 130 g CO_2/km. Beberapa teknologi telah muncul untuk meningkatkan kecekapan bahan api kenderaan yang seterusnya mengurangkan jumlah pelepasan karbon dioksida seperti pengecilan enjin, penghibridan, dan bahan tenaga alternative seperti bio-bahan api, hidrogen dan sel bahan api. Walaupun teknologi-teknologi ini telah terbukti mampu meningkatkan kecekapan bahan api, kos yang ditanggung untuk membangunkan teknologi adalah sangat tinggi dan memerlukan tempoh yang lebih lama untuk mendapatkan bayaran balik. Oleh itu, teknologi *Start-Stop* telah dilihat sebagai penyelesaian yang menjanjikan kerana kos pembangunan yang lebih rendah, kurang kerumitan seni bina, lebih pendek tempoh bayar balik dan mampu untuk mengurangkan penggunaan bahan api.

Prinsip asas operasi *Start-Stop* adalah sistem kawalan kenderaan akan memberhentikan enjin apabila kenderaan dalam keadaan statik contohnya dalam keadaan lalu lintas yang sesak atau berhenti di lampu isyarat. Enjin secara automatik akan dihidupkan apabila pemandu menekan klac atau pedal pemecut. Sistem *Start-Stop* adalam system yang berdikari dan boleh terus digunakan untuk kenderaan konvensional.

Tesis ini membentangkan kaedah ujian dan keputusan untuk perbandingan penggunaan bahan api antara Persona standaed dan Persona yang dilengkapi dengan sistem *Start-Stop* dengan menggunakan Standard Ujian Proton. Tiga kali tetapan yang berbeza telah ditambah untuk enjin berhenti untuk menilai keselesaan di dalam kabin kendereaan.

Data dari ujian penggunaan bahan api telah digunakan untuk mengira penjimaatan tahunan untuk penggunaan bahan api dan kos.

Penjimatan bahan api tahunan dikira adalah 296 liter/100 km dan penjimatan kos tahunan adalah RM562.40 dengan andaian bahawa harga bahan api adalah RM1.90/liter. Walau bagaimanapun, semasa ujian, prestasi bateri menunjukkan kemerosotan. Oleh itu, bateri dengan keperluan prestasi yang lebih tinggi disyorkan penggunaan system *Start-Stop.*

Untuk keselesaan termal, penumpang tidak gembira dengan keadaan semasa berhenti enjin di mana penghawa dingin ditutup. Oleh itu, peranti tambahan seperti penyejat penyimpanan diperlukan untuk memastikan keselesaan terma di dalam kabin.

Tesis ini juga membentangkan ulasan kesusasteraan pada komponen utama yang diperlukan apabila teknologi *Start-Stop* bersepadu dengan sistem kenderaan konvensional. Komponen-komponen yang dimaksudkan ialah bateri yang dipertingkatkan, , *intelligent battery sensor, integrated starter-alternator and DC to DC converter*. Strategi kawalan untuk menghentikan enjin dan menghidupkan enjin serta kelebihan dan cabaran teknologi ini juga dibentangkan.

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LIST OF ABBREVIATIONS

AGM	Absorbent Glass Mat
BSA	Belted Starter/Alternator
BSG	Belt-Driven Starter Generator
CFD	Computer Fluid Dynamics
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CS	Cost Saving
DC	Direct Current
DOC	Diesel Oxidation Catalyst
ECU	Engine Control Unit
EFB	Enhanced-Flooded Battery
EPA	Environmental Protection Agency
EU	European Union
FC	Fuel Consumption
FLA	Flooded Lead-Acid
FS	Fuel Saving
HC	Hydrocarbon
HLT	Hydraulic Locking Tensioner
IBS	Intelligent Battery Sensor
ISA	Integrated Starter-Alternator
ISG	Integrated Starter Generator
NA	Naturally Aspirated
NDA	Non-Disclosure Agreement

NEDC	New European Driving Cycle
NHMC	Non-Methane Hydrocarbon
Nox	Nitrogen Oxide
NRDC	Natural Resource Defense Council
NVH	Noise, Vibration And Harshness
SoC	State Of Charge
StARs	Starter Alternator Reversible Systems
UDDC	Urban Delivery Drive Cycle
VMT	Vehicle Miles Travelled
VRLA	Valve-Regulated Lead-Acid

CHAPTER 1.0 - INTRODUCTION

1.1 OVERVIEW

Global warming, if not being aggressively restrained, would impose disastrous impacts on human communities, health and economy in various ways. According to Natural Resource Defense Council (NRDC) United States, for over 50 years, the average global temperature has rapidly increased and the fastest rate recorded in history (NRDC, 2011). Global warming is caused by carbon dioxide (CO_2) and other pollutants that form layers in atmosphere. These layers become a blanket that causes heat to trap and hence increases the global temperature.

One of the solutions to curb global warming effects is by improving the fuel efficiency of vehicles and thus reducing the amount of emitted CO_2. Due to this awareness, European Union (EU) has reinforced tighter regulations for CO_2 emission. By 2015, CO_2 emission permissible is going to be 130 g CO_2/km (Albers et al., 2011).

1.2 PROBLEM STATEMENT

Various technologies that are capable to increase vehicle fuel efficiency have been developed for example engine downsizing, hybridization and alternative fuels for instance bio-fuel, fuel cell and hydrogen. However, these technologies require high development, manufacturing and infrastructure costs. On the other hand, there is one technology called Start-Stop which is able to reduce fuel consumption and generate fuel saving with low additional cost and less complex vehicle architecture.

The basic principle of start-stop operation is the vehicle's control system will switch the engine off when the vehicle is idling for example in a congested traffic condition or stop at traffic light. The engine is automatically switched on when the driver presses the clutch or accelerator pedal. Start-stop system can be a standalone system and directly applied to standard conventional vehicle.

1.3 OBJECTIVES

It is essential to understand the basic concept of start-stop operation, how the system can reduce the fuel consumption and the impact on the passenger comfort. The objectives of this thesis are:

1) To study the start-stop technology
2) To calculate fuel savings associated with the start-stop technology
3) To estimate cost reduction associated with the start-stop technology
4) To evaluate cabin thermal comfort when the start-stop system is enabled

1.4 SCOPE AND LIMITATION

The tests conducted were the first tests related to start-stop system initiated by Proton**.** The methodologies used were intended for standard conventional vehicles. Therefore, the standard methodologies were slightly modified to suit start-stop operation system. There was no exclusive methodology developed for start-stop system due to inadequate knowledge on thorough information on start-stop system and limited budget for part development and vehicle validation test. Only actual on-road tests were carried out due the tests represented the real condition of start-stop application on the congested road. There was no simulation cycle being developed for dynamometer to simulate the start-stop driving patterns due to the reasons mentioned above. The rest of the writing related to the components, control strategies, advantages and challenges were based on studies and comparisons from several literature reviews only.

CHAPTER 2.0 - LITERATURE REVIEW

There are four main topics covered in this chapter which are the descriptions of the main components for start-stop system, the operation strategies, the advantages and the challenges.

2.1 MAIN COMPONENTS

In order for the start-stop system to operate effortlessly without comprising on the drivability and comfort, few standard components are recommended to be improvised and certain components are added into the standard production vehicles. The components are battery, intelligent battery sensor (IBS), integrated starter-alternator (ISA) and DC to DC convertor.

2.1.1 BATTERY

Unlike hybrid vehicles that use high-end nickel-metal hydride or lithium-ion battery, start-stop vehicles use more modest and cost effective energy storage for example flooded lead-acid (FLA) battery, enhanced-flooded battery (EFB) and absorbent glass mat (AGM) battery.

2.1.1.1 Flooded Lead-Acid Battery (FLA)

FLA is a standard type of battery used in conventional vehicles. The battery is the ultimate option in term of cost-performance ratio. However, based on (Albers et al., 2011), FLA is not suitable for start-stop application since the technology demands for higher cycling ability and requires higher specification against acid stratification. FLA battery is only capable for limited number of stops and only can last for few weeks (Weissler, 2012)

2.1.1.2 Enhanced-Flooded Battery (EFB)

EFB was developed to have a better performance compared to FLA with respect to cycling performance and ability to withstand acid stratification (Albers et al., 2011). Its cycling performance is two times higher than FLA and the charge acceptance is enhanced. EFB application is recommended for economy vehicles with low feature contents for example European version of Toyota Yaris, Ford Fiesta ECOnetic and Fiat 500 (Weissler, 2012). The battery functions well in short-distance urban driving condition. The construction of EFB produced by BOSCH is shown in Figure 2.1. It has thicker plates and additional polyester scrim that holds additional lead alloy (Albers et al., 2011).

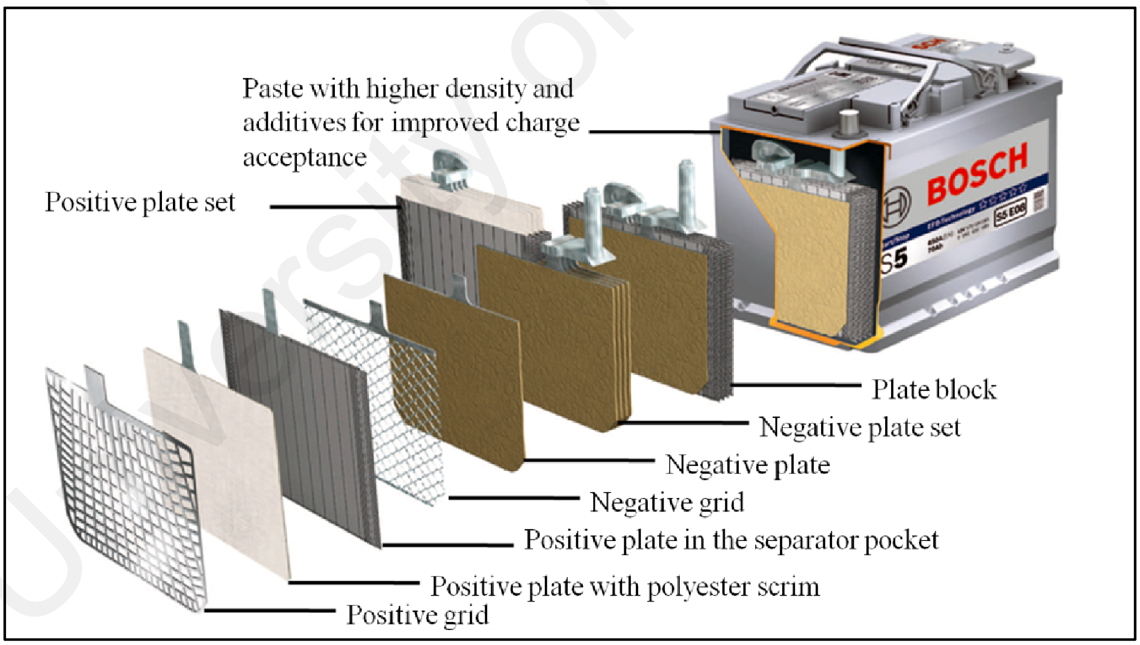

Figure 2.1: EFB configuration (BOSCH, 2011)

2.1.1.2 Absorbent Glass Mat Battery (AGM)

The AGM battery has four times higher deep-cycle resistance compared to FLA and does not show any acid stratification (Albers et al., 2011). Although the cost is 100% higher than the conventional battery, it dominates 70% of European start-stop vehicle market (Weissler, 2012). Figure 2.2 displays the configuration of AGM battery. The micro-glass fleece bounds the acid completely and the design is so robust against mass shedding and acid stratification. It also has a pressure relief valve called valve-regulated lead-acid (VRLA) that opens when the battery is overpressure (Weissler, 2012).

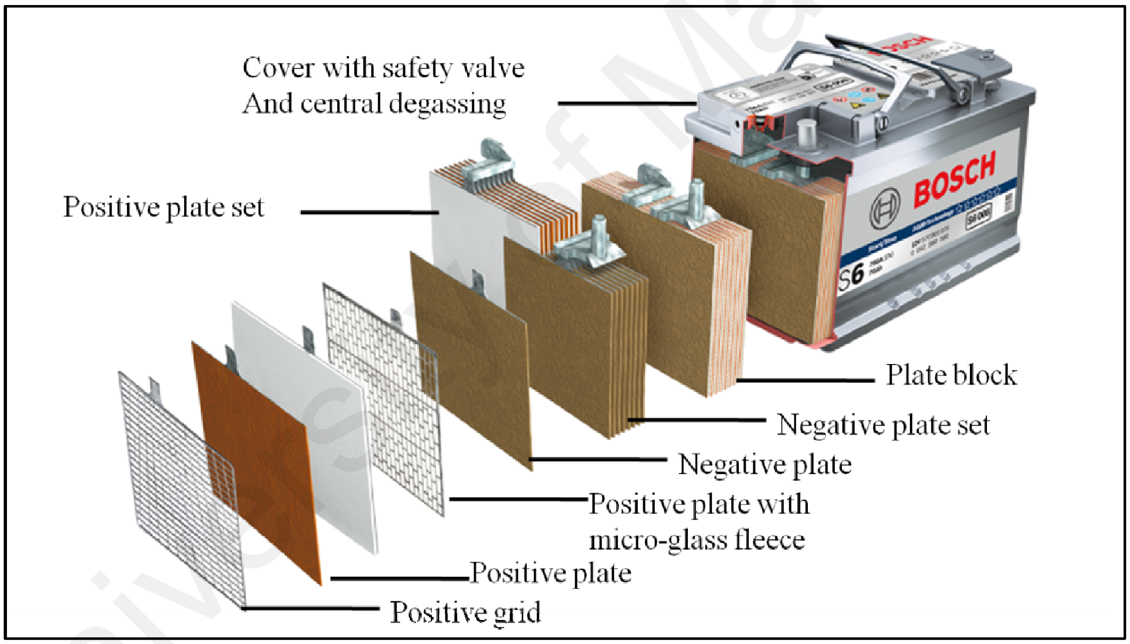

Figure 2.2: AGM configuration (BOSCH, 2011)

(Albers et al., 2011) had conducted Dynamic Pulse Cycling (DPC) test to simulate start-stop application and to compare the performance of FLA, EFB and AGM batteries. The fail criterion were either the batteries capacity fall below 50% of its nominal value or the voltage during 50 A discharge drops below 10 V. The cycling phase consists of 50 cycles, each with state of charge (SoC) swings from 80% down to 70%, up to 90% and back to 80%. The results are shown in Figure 2.3. FLA displays a substantial decrease of capacity in initial cycling units. The performance of EFB is in between AGM and FLA and reached the failure line at 110 capacity turnovers. AGM shows an excellent performance and way far better from EFB performance.

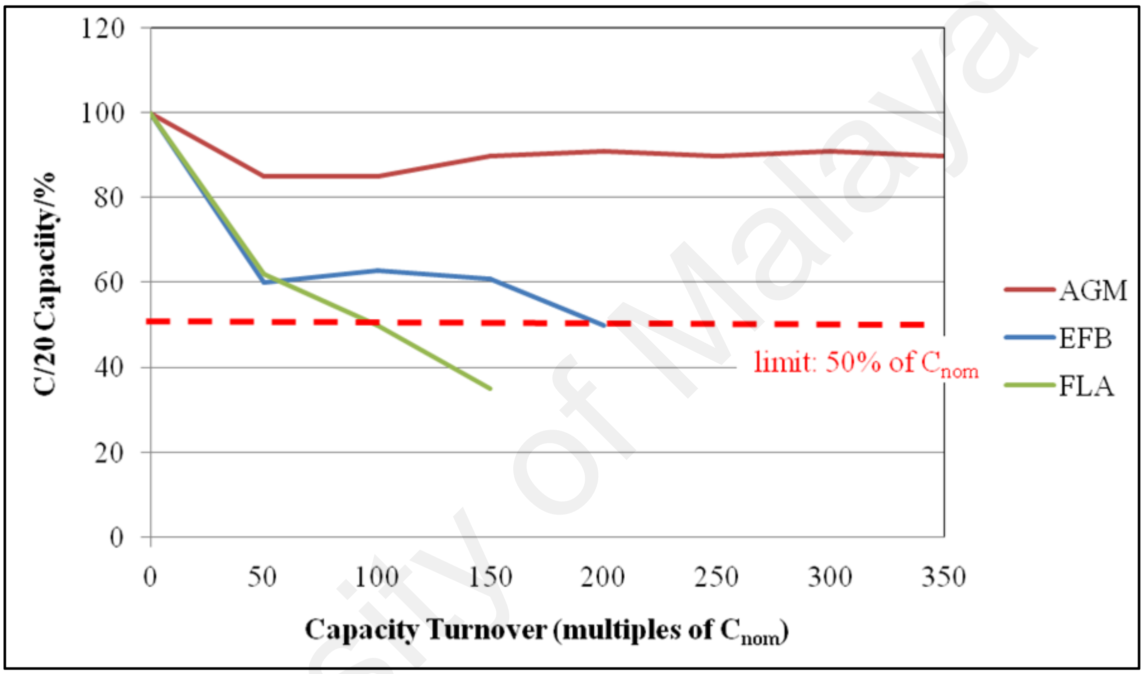

Figure 2.3: Results of dynamic plus cycling (Albers et al., 2011)

2.1.2 INTELLIGENT BATTERY SENSOR (IBS)

In standard conventional vehicles without start-stop system, the electrical power system is designed such that the battery charge balance is maintained at positive value during normal driving condition (Lakshminarasimhan et al., 2012). For the case of start-stop, during engine off, the battery takes the primary role to supply power to electrical loads. Thus, the battery can undergo progressive discharge as shown in Figure 2.4. The battery SoC is reduced by 5% after 20 km drive when undergo 30 – 60 seconds idle period for every 1 km. The prolonged condition of low SoC may deteriorate the life of the battery such that there will be progressive sulphation and permanent capacity loss (Lakshminarasimhan et al., 2012).

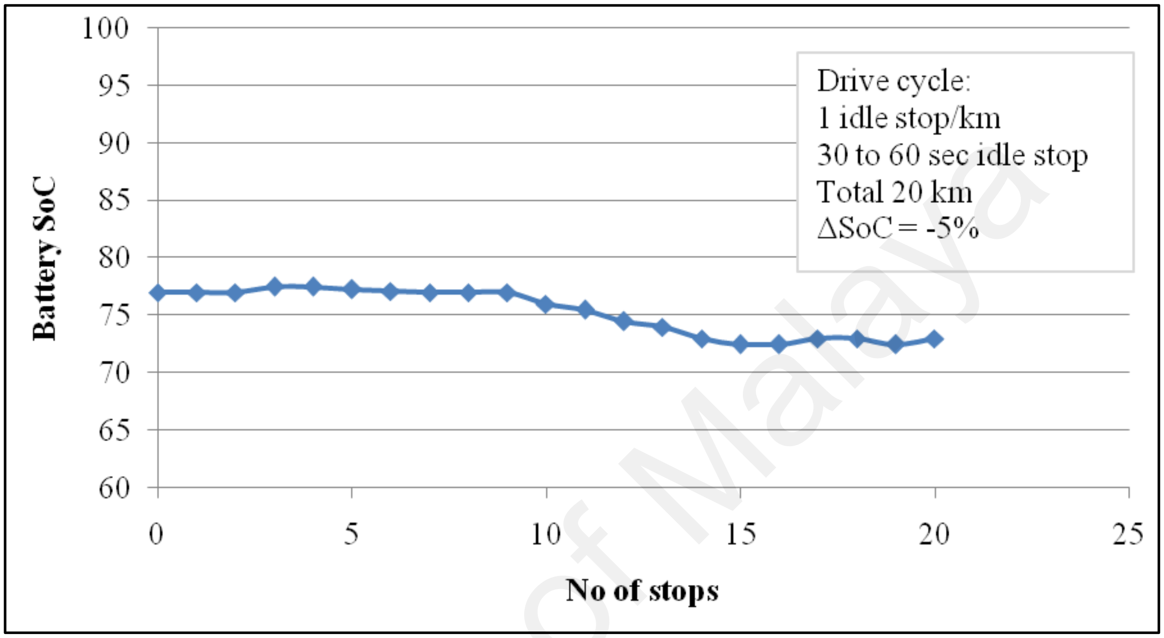

Figure 2.4: Battery SoC during start-stop drive cycle (Lakshminarasimhan et al., 2012)

In order to solve the problem, technology in battery monitoring and state detection are required to predict future operation conditions (Meissner and Richter, 2005). Hence, intelligent battery sensor (IBS) was introduced. IBS plays a vital role in start-stop battery management system. IBS is installed in the negative terminal of the battery as shown in Figure 2.5. The function of IBS is to register the operating data for example power, voltage and temperature (BOSCH, 2011). Thus, it provides accurate estimation of current status of battery charge and health and transfers the information to the engine control unit (ECU).

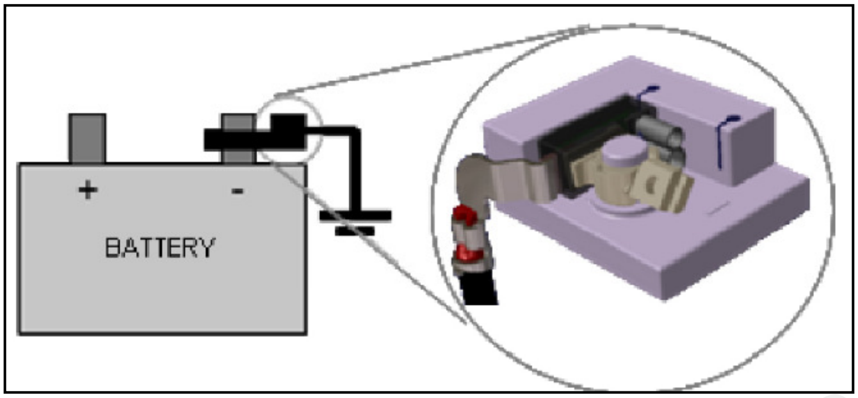

Figure 2.5: Intelligent battery sensor (Lakshminarasimhan et al., 2012)

2.1.3 INTEGRATED STARTER ALTERNATOR (ISA)

Due to increasing occurrences in start and stop events, the standard components must be enhanced and improvised to cope with the high requirements.

According to (BOSCH, 2011), the starter bearings durability must be increased due to heavy loading. The fork and pinion must be stronger with larger brushes for longer life. For the alternator, the cooling must be optimized and voltage regulator is controlled digitally.

An innovative design of new concept of starter-alternator has been introduced to provide more efficient operation in start-stop system. It enables a quicker and smoother start and stop without jeopardizing the vehicle noise, vibration and harshness (NVH) (Canova et al., 2007). The integration of starter and alternator enable the vehicle to both independently restart the engine and drive the accessories during engine stop. There are several terms given for this system but in the nutshell, serve the same function. Some of terms given are Integrated Starter Generator (ISG), Belt-driven Starter Generator (BSG), Integrated Starter Alternator (ISA), and Belted Starter Alternator (BSA).

Figure 2.6 shows the different segments of belt-driven starter-alternator for diverse hybrid applications which are micro, mild and full hybrid. Micro-hybrid vehicle is defined as a vehicle equipped with start-stop system and regenerative braking system. System complexity, cost and fuel consumption (FC) increase as the degree of hybridization increase. Thus, the introduction of micro hybrid equipped with start-stop system is the best option for the market where the cost is very critical.

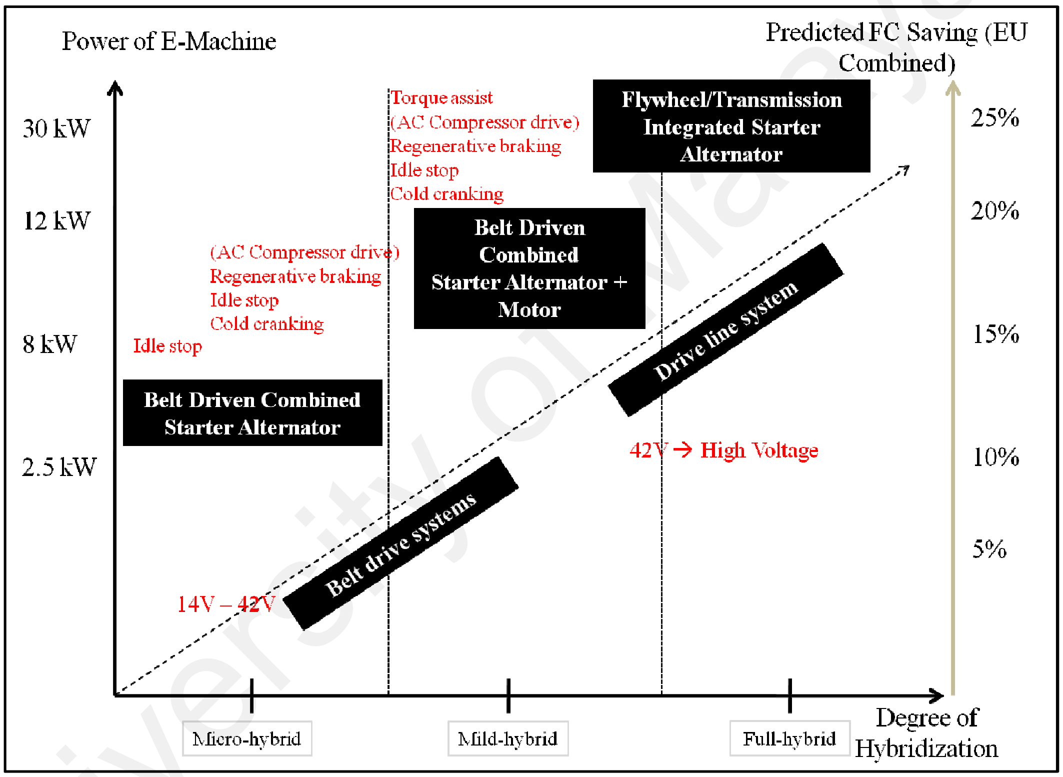

Figure 2.6: Alternative hybrid solutions (Cluett, 2007)

Valeo Electrical System has developed an inverter which is a 14 V BSA assembled on standard engine. The inverter was installed between a traditional belt driven claw-pole three phases synchronous machine and 12 V battery connected by power cables as shown in Figure 2.7. The system is called Starter Alternator Reversible System (StARS). Valeo has been producing this system since end of 2004 (Pfiffer et al., 2006).

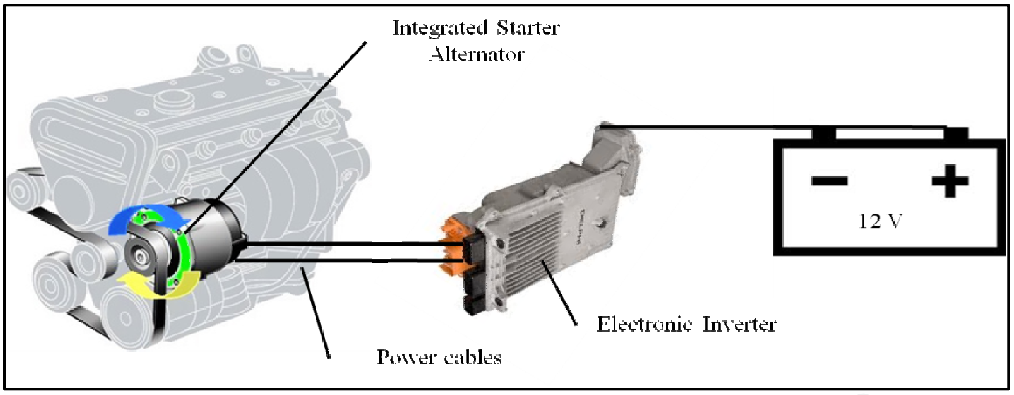

Figure 2.7: Description of 14 V StARS (Pfiffer et al., 2006)

In the alternator mode, the system functions as a standard alternator by converting mechanical power from the engine into DC for electrical loads at a constant voltage. In starter mode, it has two operations which are initial starts (cold engine) and restarts (warm engine). The starter mode converts electrical power to mechanical power via belt to crank the engine. The high power is required in order to start the engine. The acceptable duration for engine start is between 300 ms to 800 ms. In contrast, a conventional starter takes up between 1second to 2 seconds to crank the engine.

Figure 2.8 shows the machine speed and battery current versus time during cranking in hot conditions. The system is able to start half the time of standard starter.

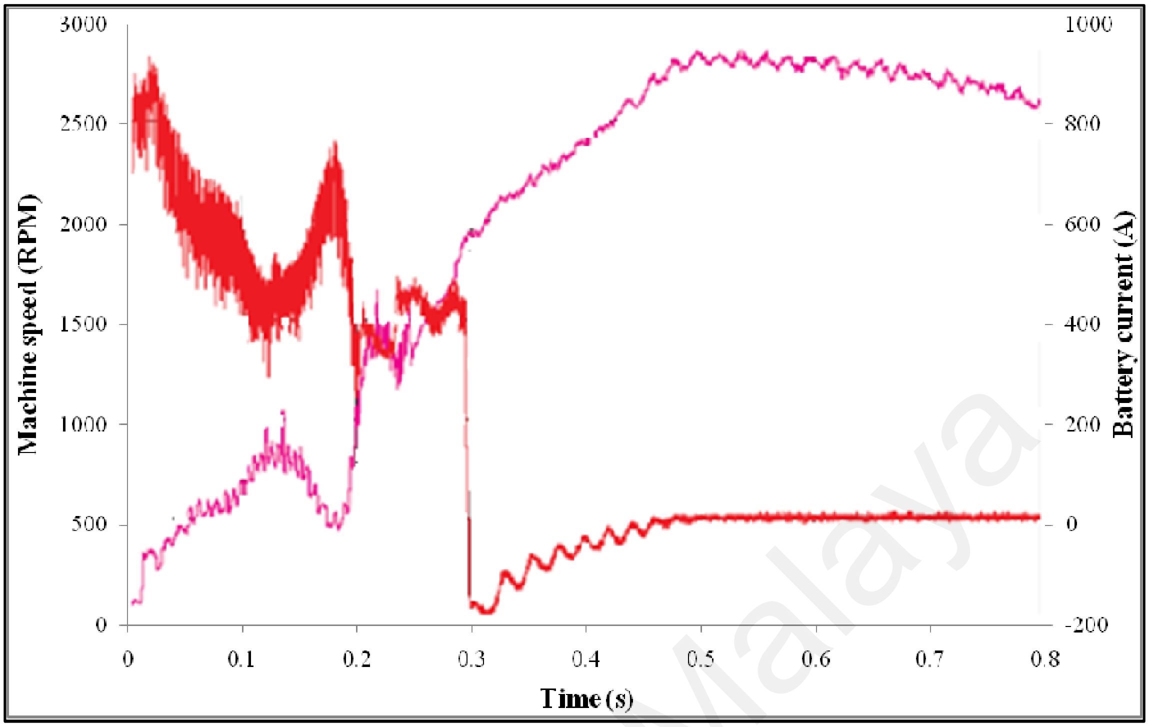

Figure 2.8: Machine speed and battery current vs. time during cranking in hot conditions (Pfiffer et al., 2006)

(Prucka, 2005) has adopted StARS for his project to demonstrate an engine start-stop system at idle state. The study was done to evaluate on hardware adaptation on standard production vehicle, control development, drivability implications and impact on fuel economy and emission. The vehicle selected was a 2003 Neon 2.0L engine with 4 speed automatic transmission.

In term of hardware adaptation, the BSG was controlled by an external ECU. The belt was upgraded to six groove belt and drive pulley. A dual side tensioner was installed to control the tension in belt and higher performance of battery was used that has a deeper discharge cycle. The system architecture is shown in Figure 2.9.

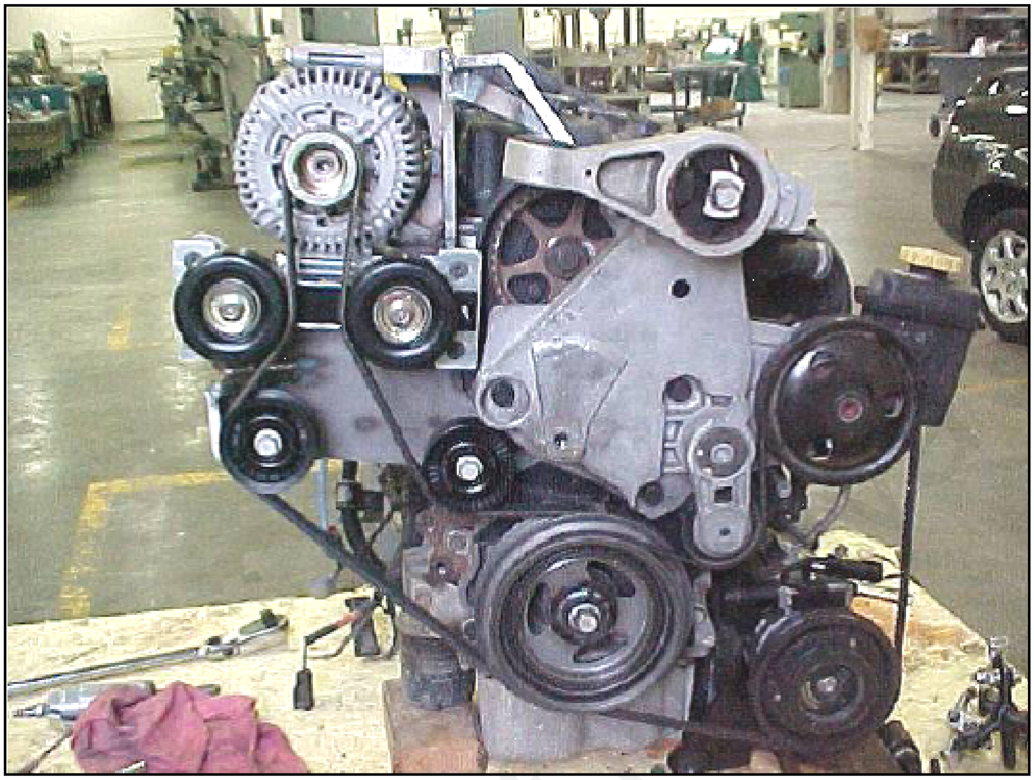

Figure 2.9: BSG installed on engine (Prucka, 2005)

The calibration and control strategy was divided into three phases; start-stop enable logic, start-stop sequencing and emission controls (Prucka, 2005). The first phase would activate related sensors to give signals to determine whether the engine was suitable to shutdown and the succeeding to restart. The second phase managed the operation of start-stop for example throttle opening, spark ignition, fuel injection and others. The last phase coordinated the emission control during the event.

Figure 2.10 displays the response for engine restart from the 2.0L engine with start-stop system. It took approximately 500 ms to restart. According to (Prucka, 2005), the 500 ms delay was objectionable by the evaluators and the restart time should be reduced to 300 ms. The proposal made by the author was to use a higher torque of BSG or increased the system voltage.

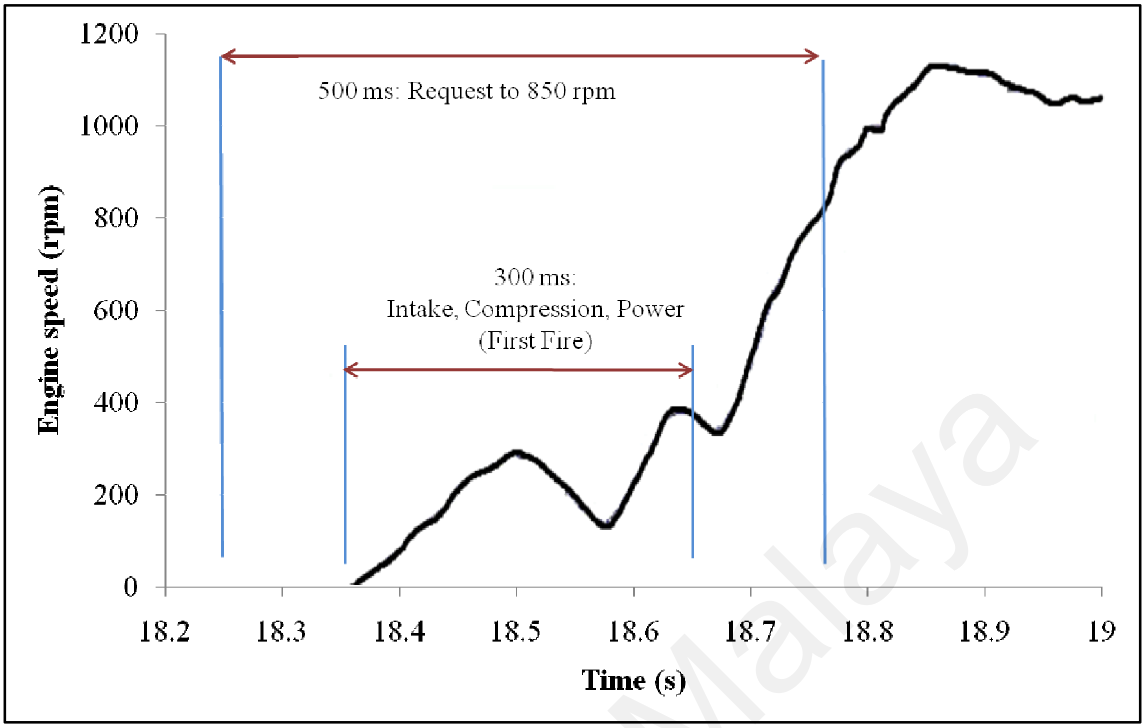

Figure 2.10: Engine restart time (Prucka, 2005)

The fuel saving recorded for this project was 2.6% and emission level of carbon monoxide (CO), nitrogen oxide (NO_x) and non-methane hydrocarbon (NHMC) were negligible.

2.1.4 DC TO DC CONVERTER

DC to DC converter functions as a voltage stabilizer especially during engine restart. When starter motor is cranked, the battery voltage suffers sudden voltage drop. This condition interrupts electrical auxiliaries operations temporarily for example radio reception interruption or loss in navigation signal (BOSCH, 2011). Thus, DC to DC converter helps to stabilize the voltage supply to other electrical components during engine restart.

Figure 2.11 presents the condition between the stable and unstable power range for a conventional 12 V system as s function of subnet power (Rosenmayr et al., 2012).

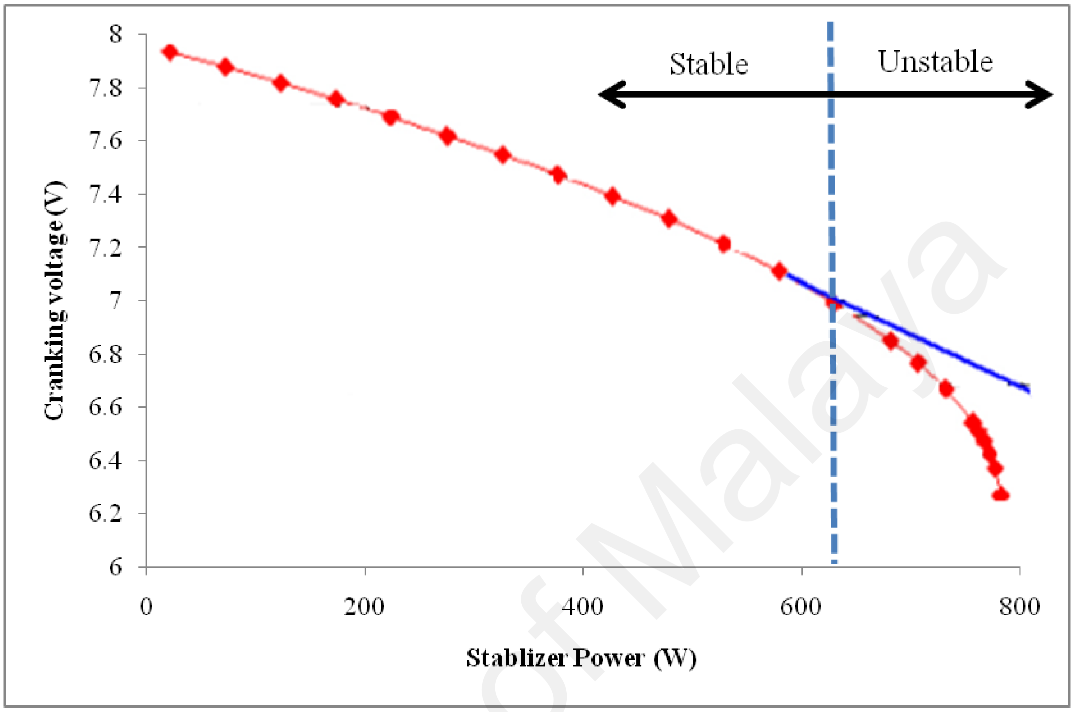

Figure 2.11: Voltage drop during warm cranking (Rosenmayr et al., 2012)

(Gao et al., 2009) have integrated DC to DC converter with BISG for micro-hybrid vehicle development program. The component connected the high and low power networks in the vehicle. It has two operation modes. The first mode was the forward mode. It provided energy from a high voltage sink to a low voltage sink. This mode charged the 12 V battery and supported other electrical loads. The second mode was the reverse mode. In this mode the supply of energy was from the low to the high voltage side by using the 12 V battery to charge ultracapacitor pack when its voltage was too low to crank the engine. Figure 2.12 illustrates the vehicle packaging for (Gao et al., 2009) development program which included DC to DC converter, BSG and IBS.

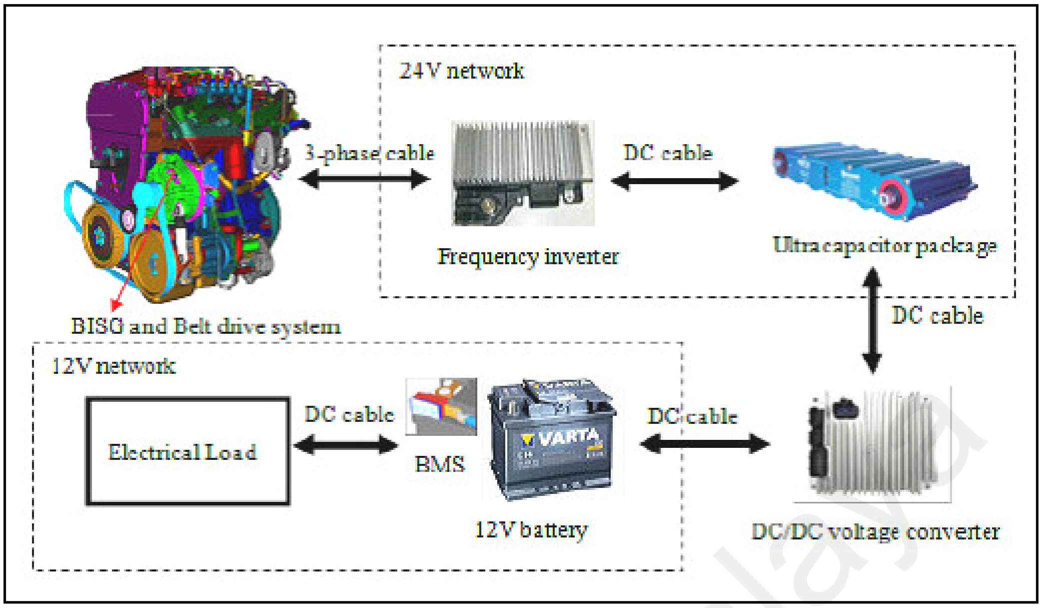

Figure 2.12: Vehicle packaging (Gao et al., 2009)

2.2 OPERATION STRATEGIES

The basic principal in the operation of start-stop is the engine is stopped when power is not required to propel the vehicle and automatically restarted when power is requested.

2.2.1 ENGINE STOP

Engine stop can only be initiated by the driver. In order for the engine to stop, the vehicle speed must be below a certain threshold and the accelerator pedal is released (Müller-lerwe et al., 2008). The engine is stopped after a small delay *(y-sec)* if the gear is engaged and a different delay *(x-sec)* if the car is in neutral as shown in Figure 2.13 (as for a manual transmission vehicle).

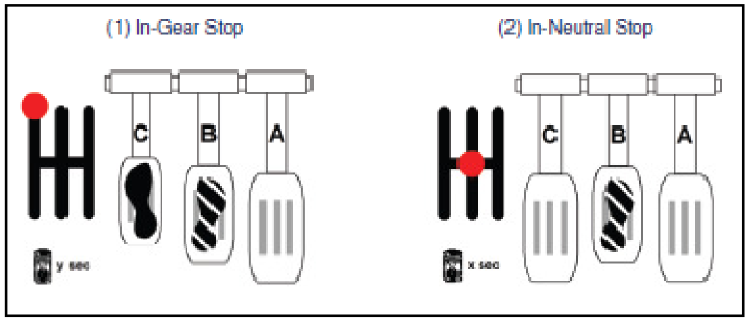

Figure 2.13 : Engine stop conditions (Müller-lerwe et al., 2008)

2.2.2 ENGINE STOP INHIBITORS

However, in the control strategies, stop inhibitors are identified to ensure that the vehicles are not stopped under undesirable conditions which relates to safety, comfort, durability and other factors (Dhand et al., 2009). The inhibitors are described below:

2.2.2.1 Battery Temperature Limit

The control strategies disallow the engine to stop when the temperature of the battery is below a defined threshold. The strategy objectives are to ensure that the SoC of the battery is within the limit and to prevent any failure on the durability and performance of the battery.

The assumption made is the temperature of the battery is equal to the ambient temperature. The criteria and the function graph are shown in Figure 2.14.

$$Assumption: T_{ambient} = T_{battery} \quad (2.1)$$

$$Inhibit\ criteria: T_{ambinet} < T_{threhold\_battery} \quad (2.2)$$

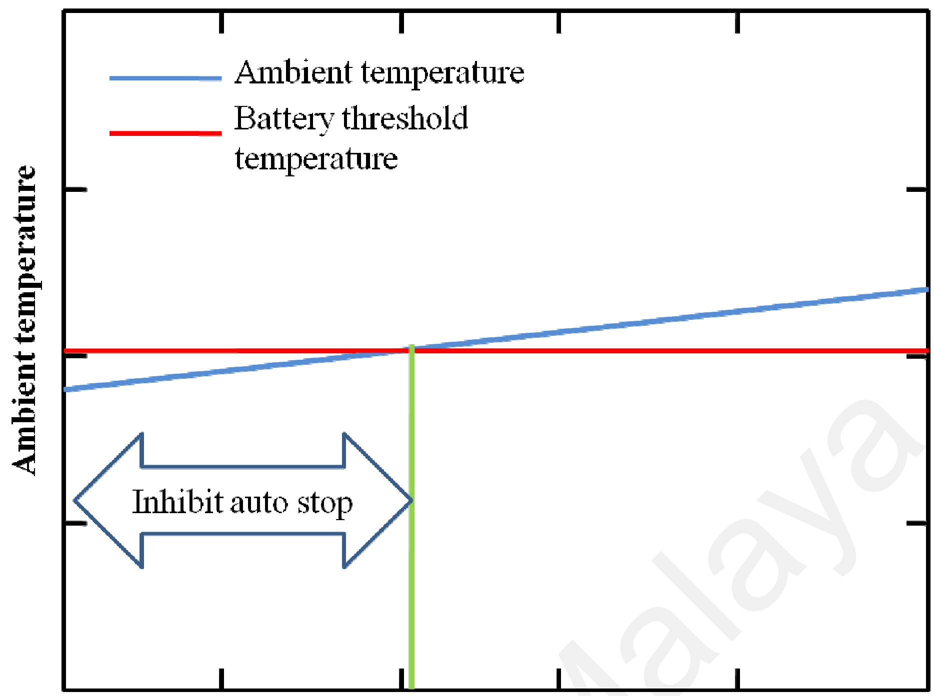

Figure 2.14 : Battery temperature inhibitor (Dhand et al., 2009)

2.2.2.2 Cabin Cooling and Heating

Cabin comfort is substantial to the passengers and engine is not going to shutdown if the air-conditioning or heater is activated. Otherwise, the vehicle must be equipped with extra devices to maintain the comfort as of a standard vehicle. An example of the device is a storage evaporator. Then, a reliable calibration needs to be done to ensure the comfort. The detail descriptions of these devices are presented in Section 2.4.4.

2.2.2.3 Vehicle Slow After Start

A speed threshold must be determined to enable a next stop. The strategy is required to prevent the engine stop when the vehicle is in slow speed conditions for example parking maneuver or very slow moving traffic (Dhand et al., 2009). The vehicle speed must exceed the threshold value so that the inhibitor can be disabled to prepare for the next stop.

2.2.2.4 Engine Stop Delay/Pre-Launch Start

Engine stop delay and pre-launch start are implemented at the same time. The engine stop delay function is to improve drivability by avoiding engine stop for very short vehicle stops (Dhand et al., 2009). The pre-launch time is a virtual time programmed to display the engine start time since the formula is based on vehicle speed (Dhand et al., 2009). Engine stop is disabled when the vehicle stop time is less than the sum of predefined times.

2.2.3 ENGINE START

Engine start can be invoked via the driver or by the vehicle system.

2.2.3.1 User Activation

Engine start by the driver is determined by the interactions between the driver and the pedals or the gearbox. The following actions described here can contribute to the engine start (Müller-lerwe et al., 2008). The engine can restart when the brake pedal is released or the accelerator and brake pedal are pressed at the same time or clutch pedal is depressed if it was pressed on released beforehand. Figure 2.15 illustrates these three actions respectively (manual transmission).

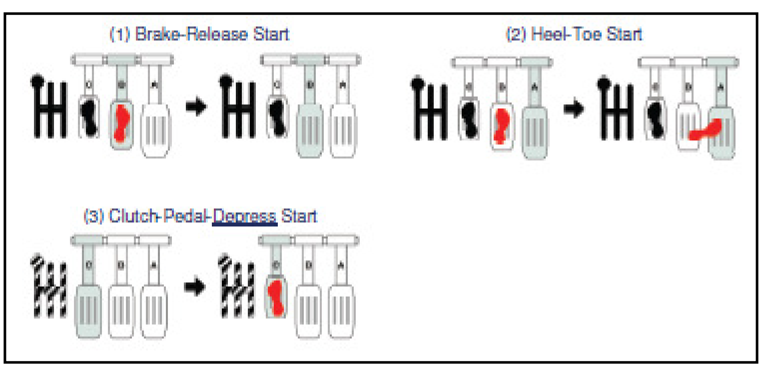

Figure 2.15 : Engine start driver induced (Müller-lerwe et al., 2008)

2.2.3.2 System Activation

Engine start by the system includes the followings (Müller-lerwe et al., 2008); air conditioning activation, battery state of charge is below a threshold, brake assist vacuum depletion and vehicle rolling.

2.3 ADVANTAGES

The main purposes of developing start-stop technology are for fuel economy and to reduce CO_2 emission. This technology has lower development and installation cost compared to mild or full hybrid. Besides, the vehicle architecture is not complex and can be integrated in standard mass production vehicles. It also provides more revenue to the workshop since the service of the battery must be done with proper devices and trained personnel.

2.3.1 FUEL ECONOMY (FE)

Start-stop system is designed to reduce unnecessary fuel consumption. There are several tests conducted either via dynamometer simulation or actual on-road driving to validate the start-stop system.

George et al., (2001) had conducted dynamometer test to evaluate fuel economy on a Ford Explorer equipped with 42 V ISG. The first phase of the test was carried out on an unmodified 2001 Mercury Mountaineer which has a similar powertrain configuration with Ford Explorer. This was done to familiarize the testers with the powertrain and throttle response. The next phase was done on the ISG Explorer with the production alternator supplied 12 V electrical current as per current production vehicle. By this strategy, the two tests were equivalent and could be compared. The difference was the ISG Explorer experienced a mass penalty of extra weight due to the ISG system. The test cycles were implemented on both city and highway conditions based on Environmental Protection Agency (EPA) standard.

Table 2.1 tabulates the fuel economy test results. The results showed that the fuel efficiency was increased by 2.8% for city driving. However, for highway driving, the efficiency was minimal. This was due to less start-stop events and the vehicle experienced weight penalty by 5.64%. Thus, the start-stop system does not provide additional fuel benefit for highway driving (George et al., 2001).

Table 2.1: Fuel Economy by function in miles per gallon (mpg) (George et al., 2001)

Cycle	**EPA City**		**EPA Highway**	
Vehicle Type	Mountaineer	ISG Explorer	Mountaineer	ISG Explorer
Vehicle Mass (kg)	1932	2041	1932	2041
Baseline (mpg)	17.18	17.55	26.80	26.90
Start-stop (mpg)	-	18.04	-	26.95
% Over Base	-	2.80	-	0.19

Wishart et al., (2012) were a team from ECOtality North America, part of United State Department of Energy's Advance Vehicle Testing had tested three different European vehicles equipped with BSA. The selected vehicles were 2010 Smart Fortwo, 2010 Volkswagen Golf TDI Bluemotion and 2010 Mazda 3 DISI. The evaluations were conducted by means of dynamometer test to measure the start-stop efficiency in laboratory setting and on the road test to demonstrate the efficiency of this technology in the real world condition.

Table 2.2 presents the fuel economy results for the dynamometer test according to EPA standard and on-road test. The 'SS' indicates that the start-stop system was enabled and 'No SS' means the system was disabled. The dynamometer results display similar pattern as tests conducted by (George et al., 2001). The percentage difference between the vehicles with and without start-stop technology is between 2.1% to 7.8% for city driving. However, the system has no impact for highway driving for all vehicles. The on-road test result is inconclusive since Volkswagen result shows negative fuel efficiency. According to the authors, several variables might contribute to such result for instance the start-stop system might not properly function, driver behavior and route differences.

Table 2.2: Dynamometer and on-road fuel economy test results (Wishart et al., 2012)

Vehicle	**Smart**			**Mazda**			**Volkswagen**		
Condition	**SS**	**No SS**	**%Δ**	**SS**	**No SS**	**%Δ**	**SS**	**No SS**	**%Δ**
EPA City (mpg)	43.8	40.5	7.8	28.6	27.7	3.2	42.9	42.0	2.1
EPA Highway (mpg)	40.0	40.0	0.0	44.0	44.0	0.0	63.5	63.5	0.0
On-road	36.3	36.2	0.3	29.6	29.1	1.7	41.2	41.5	-1.2

Goodfellow et al., (2005) have conducted simulation based on actual measurements of urban delivery vans equipped with start-stop and regenerative braking systems. The authors have developed two Urban Delivery Drive Cycle (UDDC) cycles which are UDCC1 that represented door-to-door delivery pattern (i.e. mail or grocery) and UDDC2 that represented neighborhood-to-neighborhood delivery (i.e. domestic parcel). The authors also carried out the simulation using New European Driving Cycle (NEDC) as a comparison.

During the simulations for the start-stop, the regenerative braking was disabled. The assumptions made were the van was using 36V, 50 Ah VRLA battery and 4kW ISA. The simulations were programmed in order that the engine would stop one second after the vehicle came to standstill and in a neutral gear position. The prediction of the fuel savings are summarized in Table 2.3. The results proved that the introduction of start-stop system manage to save fuel with UDDC1 shows the highest percentage due to more stop and idle events.

Table 2.3: Predicted fuel consumption savings with start-stop (Goodfellow et al., 2005)

Cycle	UDDC1	UDCC2	NEDC
Idle content	64%	26%	25%
Average running mechanical power	9.0kW	5.7kW	9.2kW
Fuel savings due to START-STOP	18.0%	4.9%	2.2%

2.3.2 CO_2 EMISSION REDUCTION

According to (Albers et al., 2011), by 2015, EU has set a target of 130g CO_2 emission per km. In order to achieve the new regulation within a short period, start-stop technology is the best solution.

Fonseca et al., (2011) have carried out actual on-road test on two diesels Land Rover Freelander2, to measure the CO_2 emissions when start-stop system was applied. One of the vehicles was a conventional car (9MY) and the other one was installed with start-stop system (10MY) which the system could be turned on and off. The test was conducted on two circuits that have been identified to be the most congested traffics in the city of Madrid. The results are shown in Figure 2.16 as a function of speed.

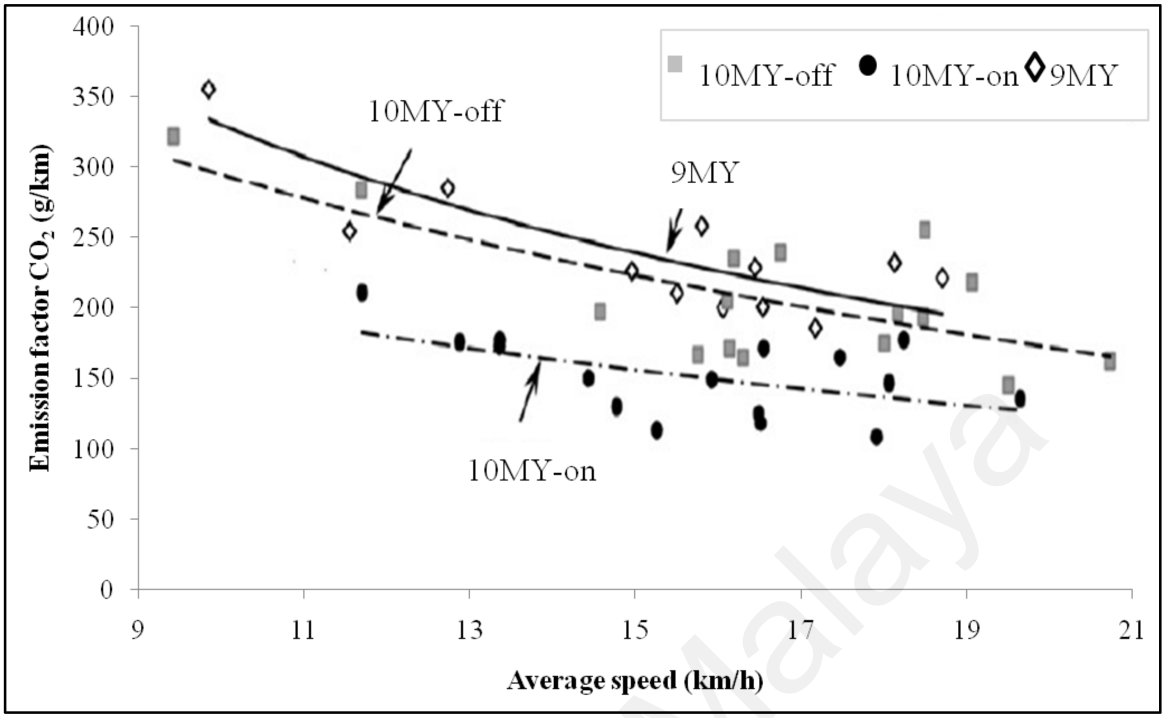

Figure 2.16: Trends and measured data of CO_2 emission versus average speed (Fonseca et al., 2011)

The emission factor CO_2 depended on the driving style, street conditions, average engine oil temperature and traffic conditions. Based on Figure 2.16, 10MY-on displays the lowest trend of emission factor and a reduction by more than 20%.

Silva et al., (2007) focused on low complexity technologies analysis and conducted simulation to validate these technologies contribution toward CO_2 emission reduction. The technologies identified were regenerative braking, fuel cut while coasting, engine start-stop and engine downsizing with turbocharging.

For start-stop system, the standard production starter motor was replaced by ISG. The battery voltage was increased to 14-42 V instead of standard 12 V. The vehicles used were categorized by five classes which were small, lower medium, medium, upper medium and large. The specifications summary of the vehicles and the value of fuel consumption and CO_2 emission using NEDC cycle as a guideline are shown in Table 2.4. In addition to NEDC, IC19 and ME01 cycles were also chosen to emulate the congested traffic condition. IC19 was a typical Lisbon freeway and ME01 was based on University California Riverside that was intended to validate all engine capabilities (Silva et al., 2007).

Table 2.4: Vehicle specification with fuel consumption and CO_2 emission for the NEDC (Silva et al., 2007)

Class	Small	Lower medium	Medium	Upper medium	Large
Weight (kg)	980	1158	1375	1540	1683
Displacement (l)	1.2	1.4	1.6	1.8	4.0
Consumption in NEDC (l/100km)	5.8	6.5	7.2	8.2	9.0
CO_2 (g/km)	139	159	163	187	206

The percentage of fuel consumption saving and CO_2 emission for start-stop are displayed in Table 2.5 which both show similar value. The average value for CO_2 reduction and fuel consumption saving for NEDC is 8% and the other cycles are up to 15%. The simulation also predicted other emission reduction, which hydrocarbon (HC) recorded to be from 7% to 26% and less than 3% for CO and NO_x (Silva et al., 2007).

Table 2.5: Total fuel saving and CO_2 reduction (Silva et al., 2007)

	Vehicle classes				
Driving Cycle	**Small**	**Lower medium**	**Medium**	**Upper medium**	**Large**
ME01	1	1	1	1	1
IC19	13	13	12	12	15
NEDC	7	6	6	6	8

2.3.3 LOW COST TECHNOLOGY

Start-stop technology is considered to be a low cost technology compares to full and mild hybrid. The addition of extra components, validation and verification tests, and modification on standard vehicles are not intricate and does not consume lengthy development period. Table 2.6 shows the comparison in term of feature contents, market segment, cost and vehicle benchmarks for full hybrid, mild hybrid and micro-hybrid (start-stop system with or without regenerative braking).

Table 2.6: Hybrid categories comparison (Gao et al., 2009)

Features		Full Hybrid	Mild Hybrid	Micro-Hybrid
Functions	Electric Drive	Yes	No	No
	Torque Assist	Yes	Yes	No
	Start-Stop	Yes	Yes	Yes
	Regenerative Braking	Yes	Yes	Yes (limited)
Hardware	Electric Machine	High power electric motor	CISG, BISG	BISG, ESM
	Power Source	High voltage NiMH or Li-Ion battery pack	High voltage NiMH or Li-Ion battery pack	FLA, EFB, AGM, or Ultracapacitor
Hybridization Cost		High	Medium	Low
Market		High end	High and middle end	Entry level
Benchmark		For Escape Toyota Prius Lexus RX400h	Honda Civic GM VUE	Cintroen C2 BMW 1 Series

Rosenmayr et al., (2012) have considered the concept of the total cost of the ownership, which the effort could be quantified by the premium cost versus the fuel saving which is the benefit. The premium cost defined by (Rosenmayr et al., 2012) is the cost that need to be paid for the additional functionality added on the vehicle. The topologies considered by (Rosenmayr et al., 2012) were micro-hybrid, mild hybrid and full hybrid. The micro-hybrid evaluated was a combination of start-stop with regenerative braking functions. Consequently, the payback period was calculated to determine which topology would be the most economical for the vehicles' owners. The payback period represented the number of miles required to drive in order to counter the premium costs with saved fuel.

Table 2.7 shows the comparison of the average payback periods in Vehicle Miles Traveled (VMT) for different hybrid topologies.

Table 2.7 : Average payback periods in Vehicle Miles Traveled (VMT) for different hybrid topologies (Rosenmayr et al., 2012)

30 mpg/$3.50 per gallon	Fuel Efficiency Increase (%)	Typical Premium Cost ($)	Average Payback Period
Micro-Hybrid	8	300	35, 000
Advanced Micro-Hybrid	15	600	39, 000
Mild-Hybrid	25	1, 500	64, 000
Full-Hybrid	44	6, 000	168, 000

The calculation from the Table 2.7 based on an average fuel consumption of 30 mpg (without hybrid technology) and fuel cost of $3.50 per gallon. Micro-hybrid shows the shortest payback period. The data displays a trend whereby the fuel economy with lower premium cost provides the most benefit. However, the trend also shows that the higher the fuel efficiency, the longest the payback period.

Besides the above data, (Silva et al., 2007) have also tabulated the range of additional cost required when a conventional vehicle is fitted with different technologies as shown in Table 2.8.

Table 2.8 : Comparison of additional cost required for different technologies (Silva et al., 2007)

No	Technologies	Price range ($)
1	Regenerative braking	600 – 2,600
2	Fuel cut while coasting	50 – 100
3	Start-stop	200 – 500
4	Engine downsizing with turbocharging	500 – 600
5	Combination: fuel cut + start-stop + engine downsizing	700 – 1,200

Silva et al., (2007) also mentioned that National Alternative Fuel Trainings Consortium (NATFC) of West Virginia University estimated that the additional cost for start-stop was $300 to $400 which is consistent with their estimation.

It can be concluded that the additional cost required to equip a standard vehicle with start-stop system is not substantial and has a short return of investment.

2.3.4 INCREASE REVENUE FOR WORKSHOP

The battery plays the primary role in the start-stop system. The progressive number of vehicles with start-stop system has changed the way the car batteries are sold and serviced (BOSCH, 2011).

The replacement of the battery cannot be done by the owners or unauthorized workshops. It requires a trained professionals and any change in the battery needs to be notified to the control unit which links to the diagnostic device. According to (Camahan, 2010), in 2010 the sales of micro-hybrid vehicles was 3 million worldwide and it is expected to be 34 million by 2015. Thus, it will drive a strong demand for the workshop service corresponding to the battery replacement and hence increasing its revenue.

2.4 CHALLENGES

The operation of start-stop should not be perceptible by the passengers. The passengers must behave as normal as possible as it the system is not exist in the vehicle. Besides that, start-stop system must not interferes with other functions and deteriorate the performance of affected components. There are mainly four major challenges in integrating start-stop system which are noise, vibration and harshness (NVH), the impact of after-treatment process, the belt slippage due to high frequency of start-stop events and thermal cabin comfort.

2.4.1 NOISE, VIBRATION AND HARSHNESS (NVH)

Start-stop operation must be imperceptible to the passengers. The engine start-stop produces undesirable vibrations and if it was not rightly managed, the vibrations would cause vehicle motions that eventually would be felt by the passengers. Therefore, the events must be very smooth to achieve standard satisfaction and comfort. One of the challenges when start-stop system is enabled is the NVH issues due to frequent start.

Kuang (2006) and Robinette and Powell (2011) have conducted investigation to analyze the root cause of start-stop NVH, developed methodologies and proposed practical countermeasures to overcome the issues. Robinette and Powell (2011) focused on optimizing standard 12 V start-stop systems and utilized the conventional starter instead of using BSA. Meanwhile, Kuang (2006) conducted his study based on Ford Escape Hybrid which was equipped with start-stop system.

Robinette and Powell (2011) have come out with basic source-path-receiver diagram for a conventional powertrain setup as presented in Figure 2.17. The source was engine torque pulsation from combustion or compression process. The path was vehicle sensitivity determined by the ratio of driver seat track acceleration to the engine mounts torque.

Figure 2.18 and Figure 2.19 show the vibration/harshness during engine start in neutral condition and engine stop respectively. In Figure 2.18, there were two phases where the vibration was detectable by the driver, which were engine cranking and initial combustion. During the first phase, the vehicles would move backward and forward with fore/aft oscillation. In the second phase, the vehicles jerked forward. Figure 2.19 also showed that the driver would feel the vibration during engine ramping down or engine stop.

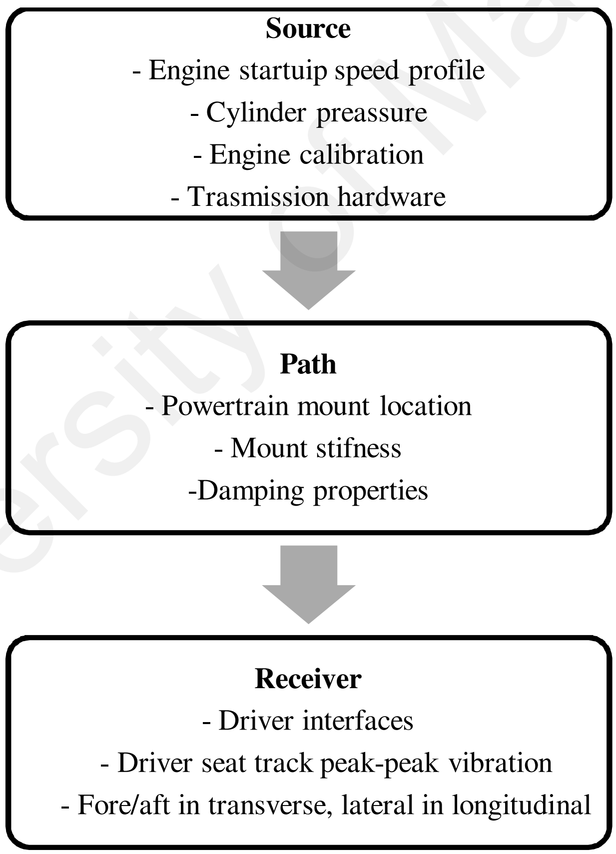

Figure 2.17: Source-path-receiver model for 12 V auto start (Robinette and Powell, 2011)

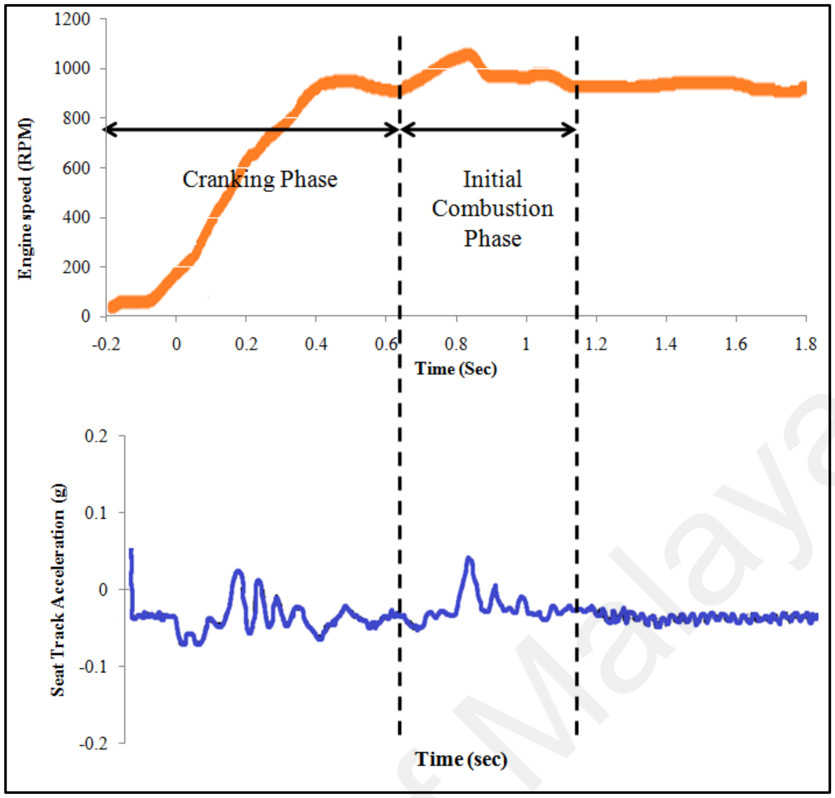

Figure 2.18: Engine speed and seat rack acceleration during engine start (Kuang, 2006)

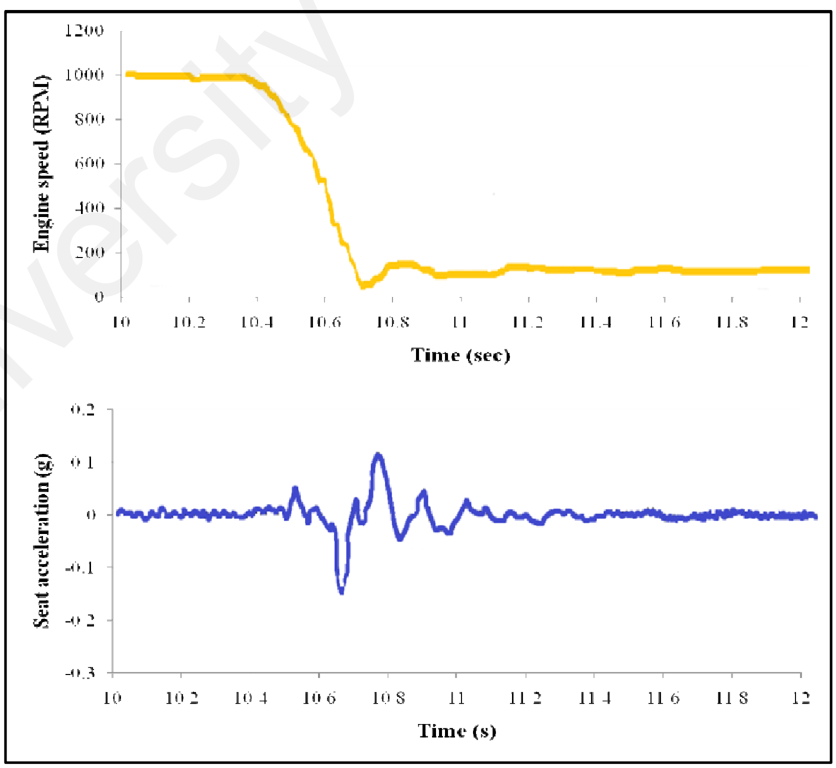

Figure 2.19: Engine speed and seat rack acceleration during engine stop (Kuang, 2006)

In order to reduce the NVH, either the sources or the path sensitivity could be reduced. Furthermore, calibration management for example firing timing, engine spark position, and cylinder pressure must be properly done. The focus areas are during engine ramping up and down. Besides that, materials and components selection must be rightly chosen to get a suitable frequency during vibration.

The application of BSG can also improve the NVH. BSG can restart faster compared to conventional starter motor (Gao et al., 2009). BSG is installed permanently engaged to the engine and thus can restart the engine independently unlike the standard starter motor that requires the engine to completely stop. Figure 2.20 shows the performance comparison between BSG and conventional starter motor. The BSG restarts the engine faster than thus will reduce the NVH.

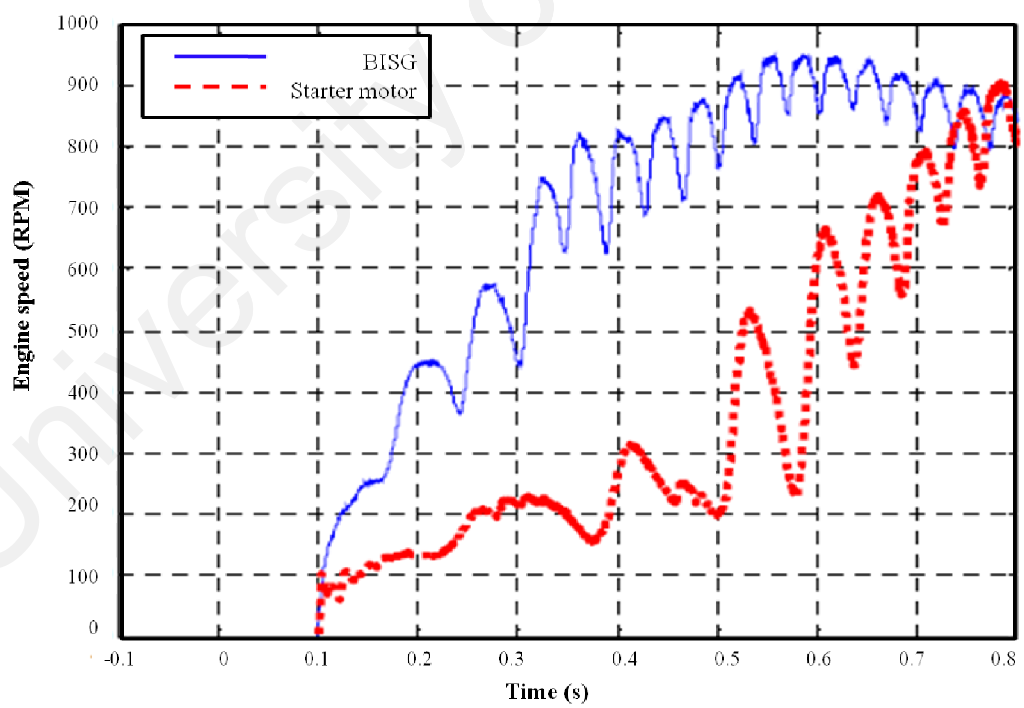

Figure 2.20: Engine start performance (Gao et al., 2009)

2.4.2 IMPLICATION ON CATALYTIC CONVERTER FUNCTION

Due to periodic engine starts and stops, hence several cooling-downs conditions occur in the exhaust system. The cooling period in the catalytic converter may result in temperature decrease. If the temperature dropped below the temperature threshold value, it would deactivate the after-treatment function in catalytic converter. Thus, it would result in the amount of emission produced by the vehicles which will impact the regulation requirement.

Koltsakis et al., (2011) have performed numerical simulation via Computer Fluid Dynamics (CFD) software and experiments to measure the thermal losses when the engine was shut off. The vehicle configuration used in the study was a diesel hybrid equipped with start-stop system.

Figure 2.21 displayed the comparison of measured gas temperature at Diesel Oxidation Catalyst (DOC) entrance between the conventional and hybrid vehicles. The plot shows that the temperature of the hybrid vehicle is significantly lower than the conventional one. This implies that there is a high potential that catalyst operation would be below the light-off or threshold temperature.

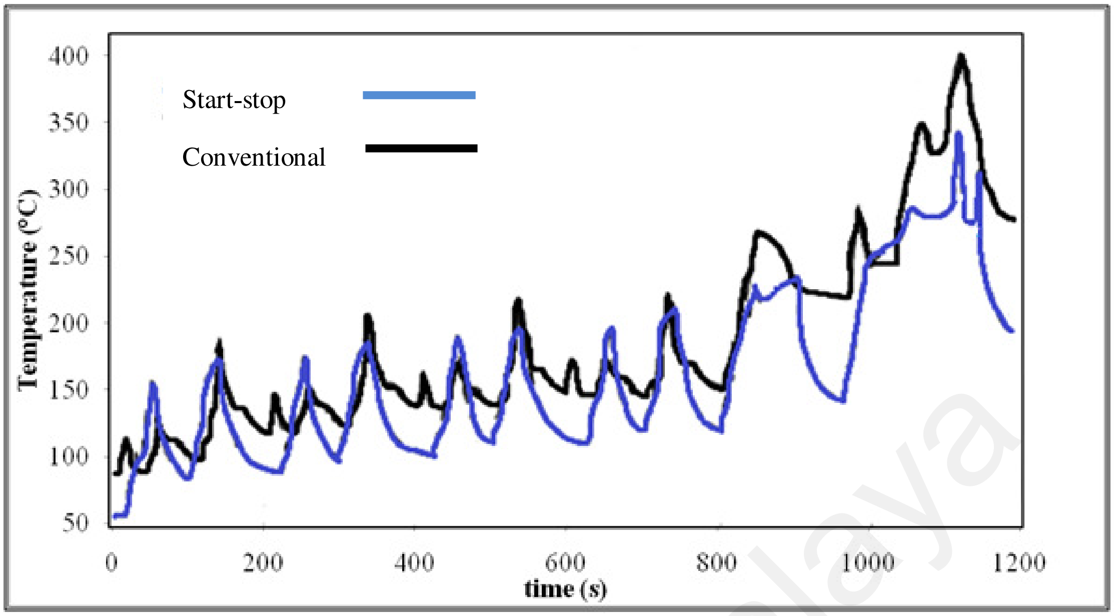

Figure 2.21: Measured gas temperature at DOC entrance for conventional and hybrid mode operation (Koltsakis et al., 2011)

Figure 2.22 and 2.23 plot the cumulative CO and HC emission at DOC entrance respectively as similar condition in Figure 2.21. Even though the engine was turned 42% off from the NEDC cycle, the amount of CO was higher in hybrid mode. According to (Koltsakis et al., 2011), it was observed that the high CO emissions occurred immediately after restarting. However, the amount of HC in hybrid mode was substantially lower compared to conventional mode.

Koltsakis et al., (2011) highlighted that the common assumption of adiabatic condition at the front and rear faces of substrate was no longer valid in zero-flow condition. Convection and radiation must be taken into account when doing the analysis on thermal management when developing the catalyst.

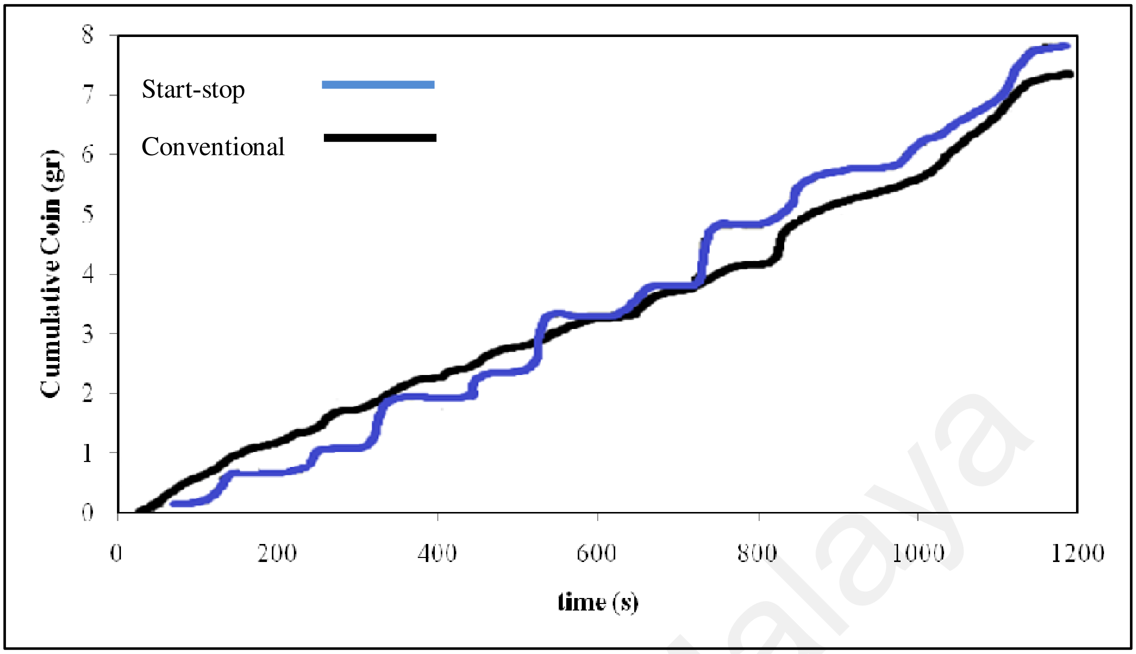

Figure 2.22: Measured cumulative CO emissions at DOC for conventional and hybrid operation mode (Koltsakis et al., 2011)

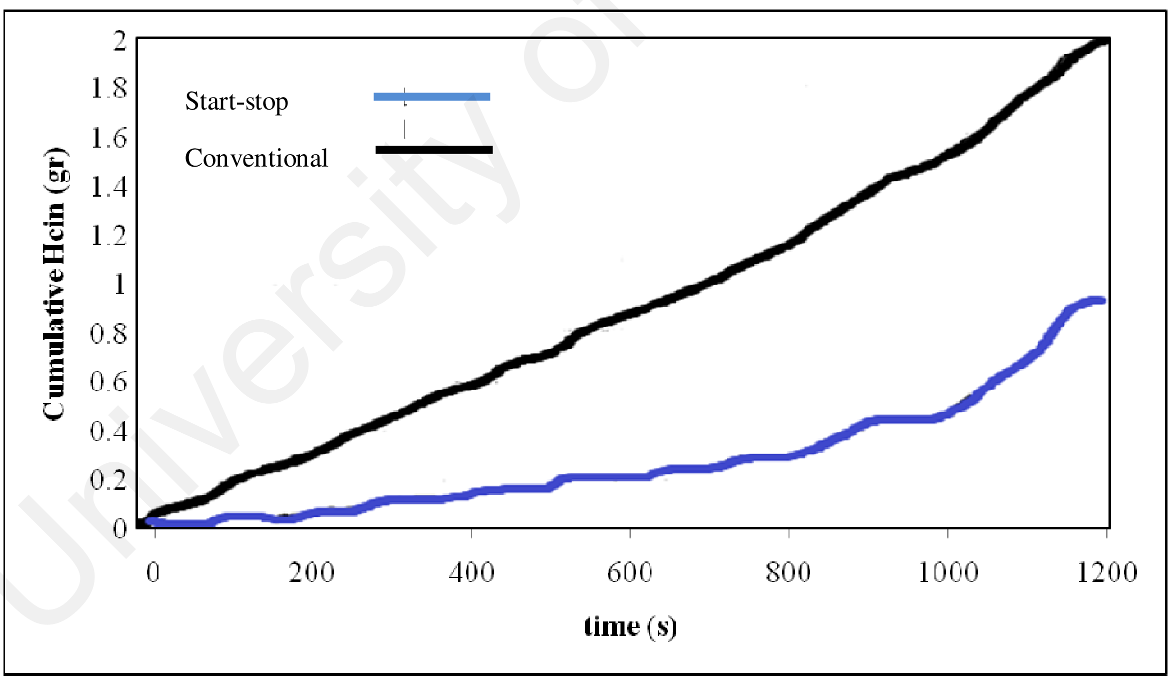

Figure 2.23: Measured cumulative CO emissions at DOC for conventional and hybrid operation mode (Koltsakis et al., 2011)

2.4.3 BELT DURABILITY

The function of the belt is to transmit torque from the starter motor to the crankshaft pulley. It is also must capable to drive the accessories. The engine will not restart if the belt failed to function. Due to high frequency of engine restart, the belt is exposed to the slippage and friction loss.

Gao et al., (2009) had identified that water splash/moisture that enters the engine compartment could cause belt slippage. The authors had conducted an experiment by directly sprayed a small amount of water on the belt. Figure 2.24 shows that the engine failed to start that was caused by belt slippage.

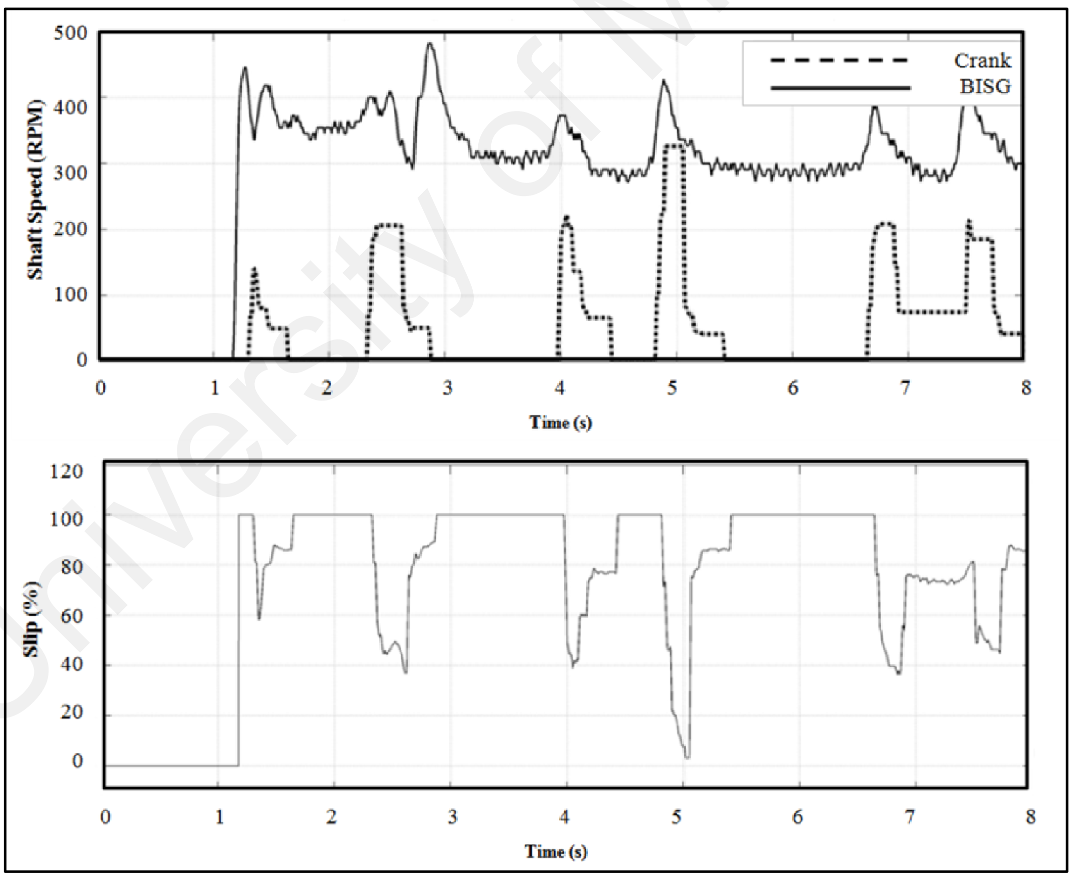

Figure 2.24: Failed engine start due to belt slippage (Gao et al., 2009)

According to (Gao et al., 2009), in order to overcome the issue, a cover or shield was required to protect the belt. In addition to that, a sensor could be added to detect the slippage and included in the calibration for engine start inhibitors.

Meanwhile, Okuda et al., (2006) focused on the belt layout and tension when ISG was added as part of start-stop system. Driving an ISG required higher tension in the belt compare to the conventional application. However, increasing the tension during the normal driving would cause additional load to the accessory bearings and the belt itself.

The friction loss torque due to belt tension at 1000 rpm was about 50% from the entire amount of friction loss. At high rpm, approximately 6000 rpm, the friction loss torque was 30%. Based on the authors, the increase in the belt tension would increase the friction loss torque which consequently increasing the fuel consumption.

Okuda et al., (2006) proposed an automatic tensioner that was capable to elongate and contract freely so that the tension in the belt could be automatically adjusted. The auto tensioner was called Hydraulic Locking Tensioner (HLT). The main feature in HLT as shown in Figure 2.25 is a solenoid valve that controls the closing and opening of fluid path. The fluid provides damping force during the elongation and contraction of HLT cylinder and piston.

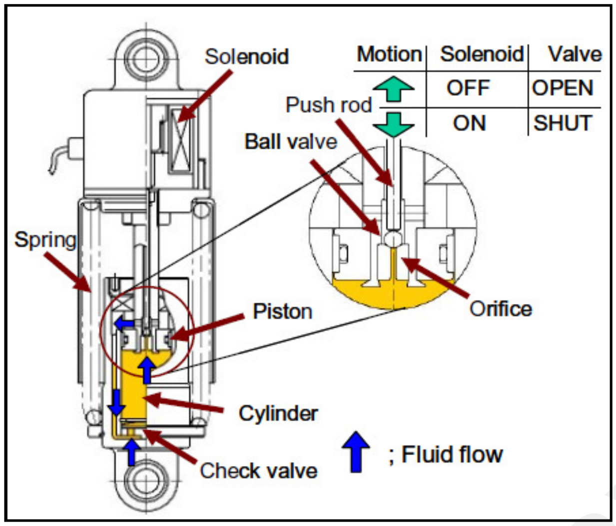

Figure 2.25: HLT configuration (Okuda et al., 2006)

2.4.4 CABIN COMFORT

During engine stop, all accessories are not functioning including air-conditioning compressor. Thus, temperature inside the cabin will increase and cause discomfort for the vehicle passengers.

Manski et al., (2006) have come out with an ingenious proposal by using a storage evaporator that could provide thermal comfort to the vehicle passengers. The configuration of the storage evaporator is shown in Figure 2.26. It consisted of two tubes, inner and outer. A latent storage media was put between the inner and outer tube. The inner tube contained refrigerant liquid. The heat from air would be absorbed by the fins and transferred by latent storage media. The refrigerant would evaporate to solidify the storage media.

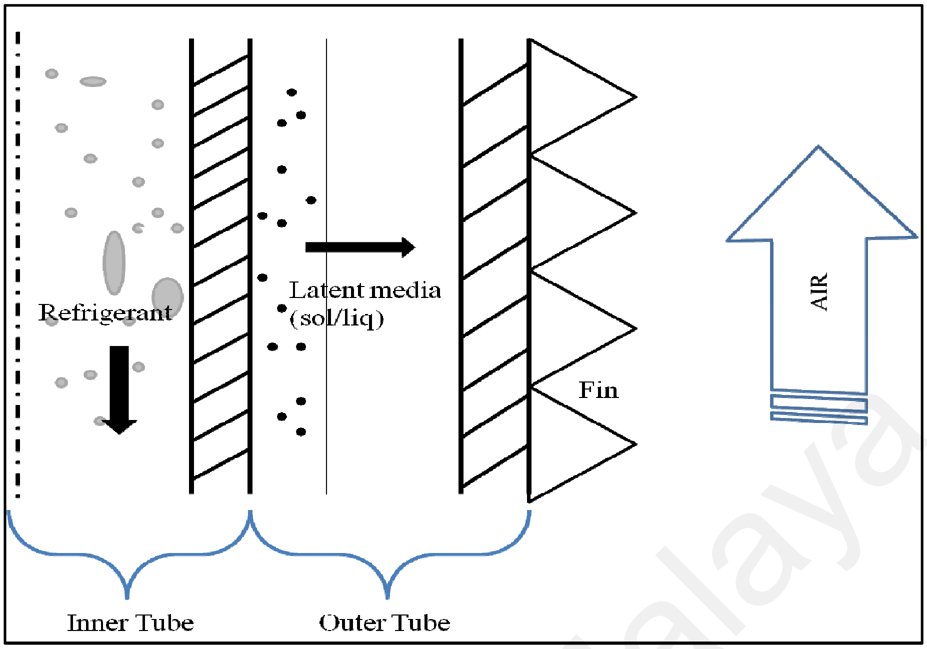

Figure 2.26: Storage evaporator configuration (Manski et al., 2006)

The layout of storage evaporator in the vehicle refrigerant loop is shown in Figure 2.27. The tubes were arranged in the evaporator block and were installed parallel to the standard evaporator. The loop consisted of a compressor, a condenser with integrated receiver and two evaporators which one was the standard and the other one was the storage evaporator. The function of the expansion valves was to turn off the storage evaporator if the latent storage media was frozen.

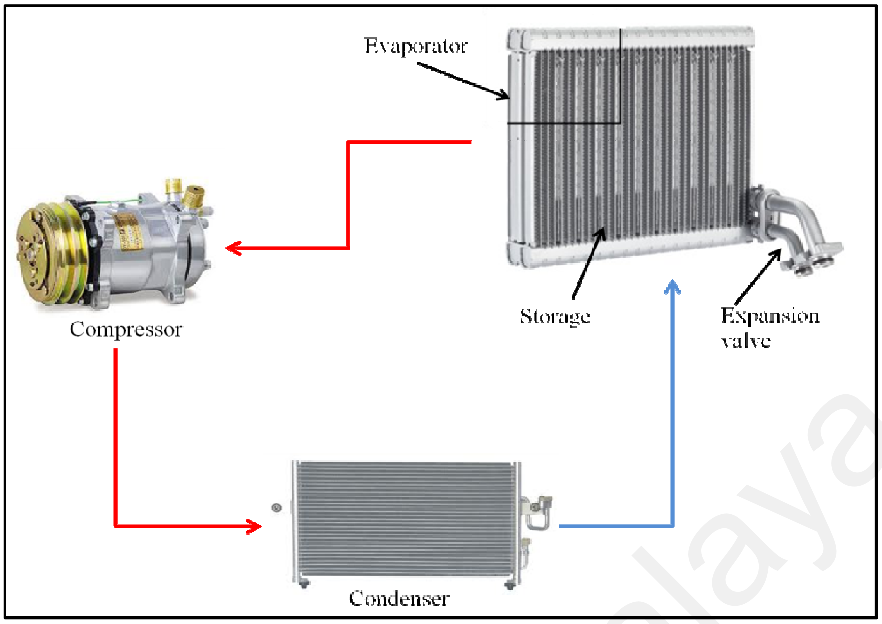

Figure 2.27: Storage evaporator in vehicle refrigerant loop (Manski et al., 2006)

Figure 2.28 shows the vehicle test results for the storage evaporator versus the standard evaporator. The results show that the storage evaporator was slightly better than the standard one the first few minutes.

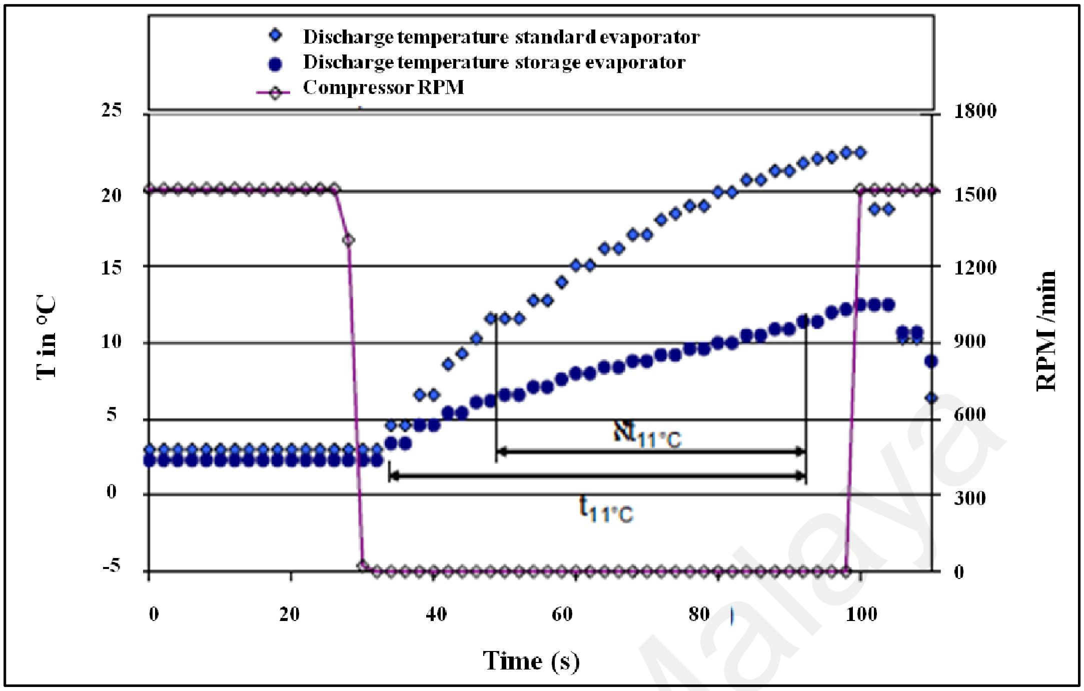

Figure 2.28: Vehicle test results (Manski et al., 2006)

Valeo has also come with similar concept to overcome this issue. The system was named STOPStayCOOL (Valeo, 2004). The cooling function was achieved by an evaporator which the material contained in it could store cold energy. When the engine was turned off, by this system, the air-conditioner fan would continue to operate, directing the air through the evaporator which was cooled before the air entered the cabin.

In summary, based on the literature reviews, start-stop technology is able to increase the vehicle fuel economy and hence reduce CO_2 emission with minimal investment. Additional components are required when start-stop system is applied to ensure the smoothness in drivability, the comfort for the passengers and to maintain the performance of the components. Control strategies must be thoroughly calibrated so that the start-stop operation is unnoticeable by the vehicle passengers and does not change driver's driving behavior.

CHAPTER 3.0 - METHODOLOGY

Two types of tests were conducted to evaluate fuel consumption for vehicle with start-stop system. The first test was a pre-test done at Proton semi-high speed test track to validate the functionality and the fuel consumption impact of the system. The second test was the actual on-the-road test in Kuala Lumpur which the routes were highly congested.

3.1 VEHICLES PREPARATION

The tests were done on two Proton Persona vehicles which one of it was equipped with start-stop system. The specifications of the vehicles are shown in Table 3.1.

Table 3.1: Vehicles specifications (Awang and Rasid, 2011)

Maker	Proton	
Model	Persona	
Engine	Campro IAFM (NA)	Campro IAFM (NA) with start-stop
Engine Capacity (cc)	1,600	
Transmission	5 speed manual MMC F5M41 (FDR:4:052)	
Max Torque (Nm) @ 4000 rpm	148Nm @ 4000 rpm	
Max Power (kW) @ 6500 rpm	82	
Curb Weight (kg)	1,200	

The start-stop configuration consisted of standard vehicle components integrated with additional parts which were a start-stop controller, an LED indicator, a hood switch and an activation switch at clutch pedal. The configuration layout is shown in Figure 3.1.

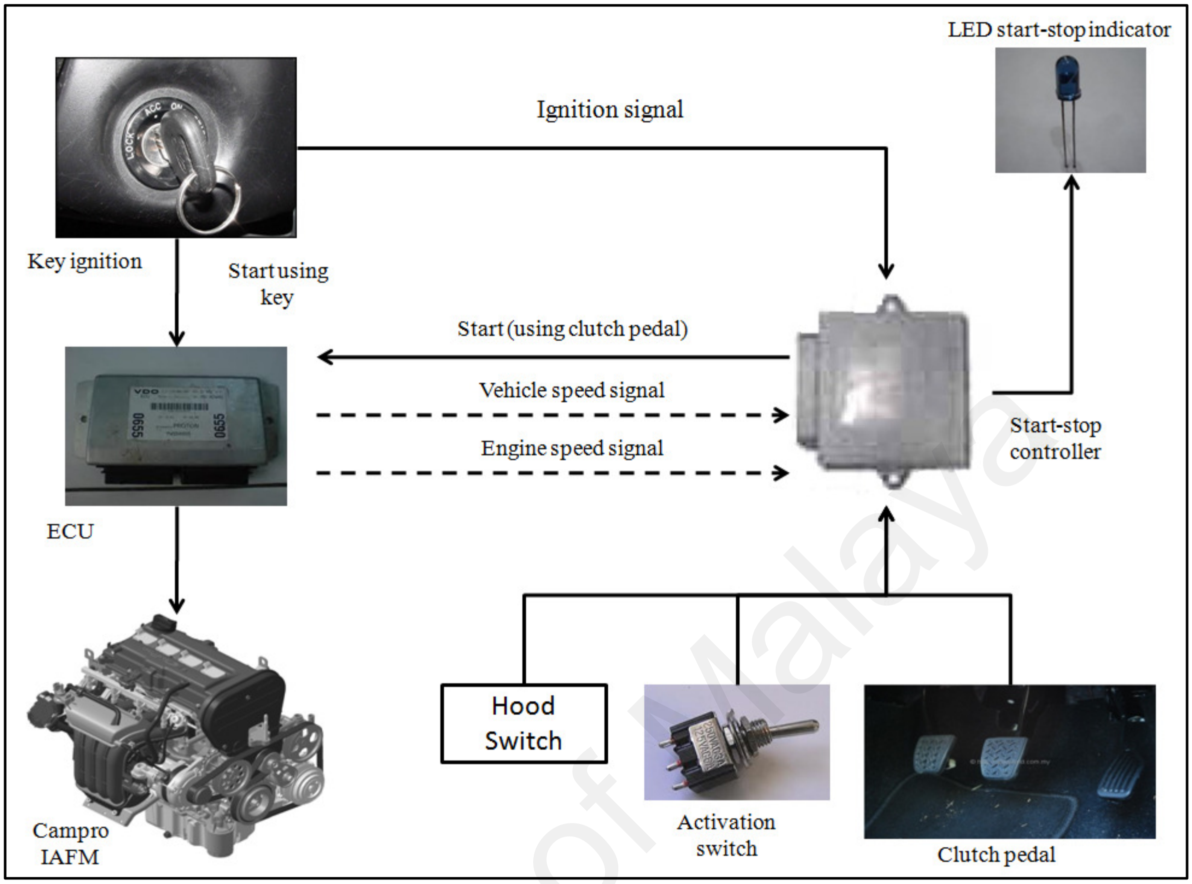

Figure 3.1: Persona start-stop component configuration

The start-stop controller is an engine control unit which incorporates start-stop operation software. The function of the controller is to analyze data from relevant sensors and to give signal to switch off or switch on the engine. Figure 3.2 shows the controller's inputs and outputs diagram. Detailed schematic diagram is treated confidential under Proton Non-Disclosure Agreement (NDA).

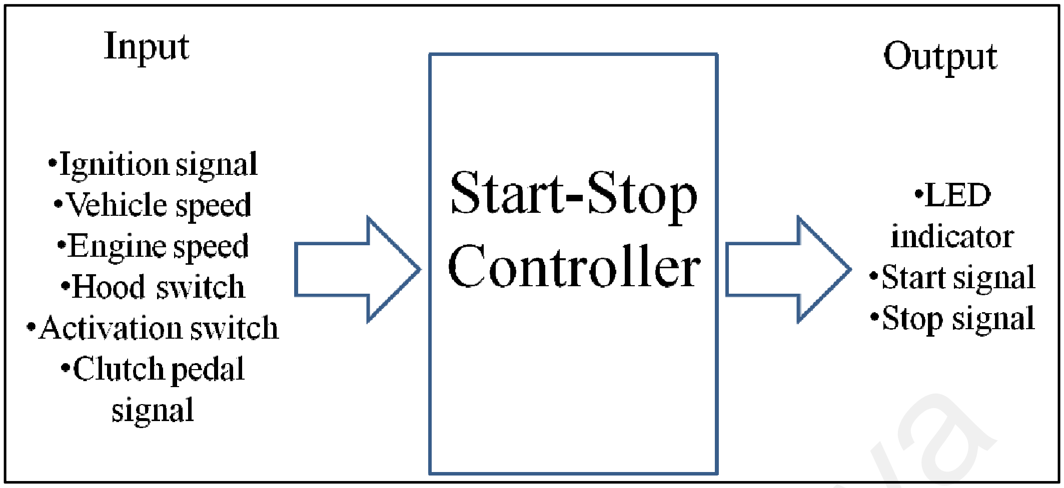

Figure 3.2: Start-stop controller inputs and outputs diagram

Due to lack of capability in conducting start-stop system test related to facilities, budget and manpower, those components mentioned in previous paragraph were the only additional parts that were integrated. The test vehicles were used standard FLA battery and conventional starter and alternator.

Three main devices were used in the on-road tests which were Ono Sokki Non-contact Speedometer, Ono Sokki Volumetric Fuel Flow Detector and WXT520 Vaisala Weather Transmitter. Table 3.2 shows the measurement range and accuracy for these devices.

Table 3.2: Description of equipments

Device Name	Function	Measurement range	Accuracy
Vaisala Weather Transmitter (Vaisala, 2012)	Wind Speed	0 to 60 m/s	±0.3 m/s
	Wind Direction	0 to 360°	±0.3°
	Temperature	-52 to 60 °C	±0.3 °C
	Relative Humidity	0 to 100% RH	±0.3 %RH
	Barometric Pressure	600 to 1100 hPa	±0.5 hPa
	Rainfall	0 to 200 mm/h	±0.5%
Ono Sokki Non-contact Speedometer (ONO_SOKKI, 2012a)	Speed	1.5 to 320 km/h	±0.5%
Ono Sokki Volumetric Fuel Flow Detector (ONO_SOKKI, 2012b)	Mass fuel rate	0.3 to 120 liter/h	±0.2%

The test vehicles' condition must be clean and the tires used must be specified by manufacturer and inflated to the specified pressure. The lubricants used must be recommended by the manufacture as well. Before the test begins, the vehicles must be running-in and driven at least 3,000 km to ensure the vehicles are in good mechanical conditions. Table 3.3 shows the items that are required to be inspected prior to the test.

Table 3.3: Checklist items before test (Proton, 2009)

No	Items	Check
1	Alignment	Camber, caster
2	Steering	Free-play
3	Tire	Type, condition, pressure (cold)
4	Engine speed	RPM
5	Ignition timing	Degree of advance
6	CO	Percent
7	Engine oil	Specification level

The vehicle weight must be measured before the test and the vehicle must be driven a minimum of 10 km at an average speed of 80 km/h immediately prior to the test.

3.2 CONTROL STRATEGY

In order for the engine to stop, five conditions must be fulfilled as displayed in Figure 3.3. The five conditions are; the activation switch must be switched on, the clutch pedal must be fully released, the hood is closed, the vehicle speed needs to be 0 km/h and the engine speed was less than 1,000 rpm. Three control settings which are 2 seconds, 6 seconds and 8 seconds were defined to determine passengers' behavior and comfort level. For instance, when the time setting of 2 seconds was chosen, it means that when the five conditions were fulfilled, the system required 2 seconds to automatically stop.

Engine start requires the clutch to be pressed and the flow is as shown in Figure 3.4. The sequence of the engine start by clutch operation is displayed in Figure 3.5. The clutch is pressed and the gear must be moved to neutral condition. Then, the clutch is released and subsequently repressed for the engine to automatically start.

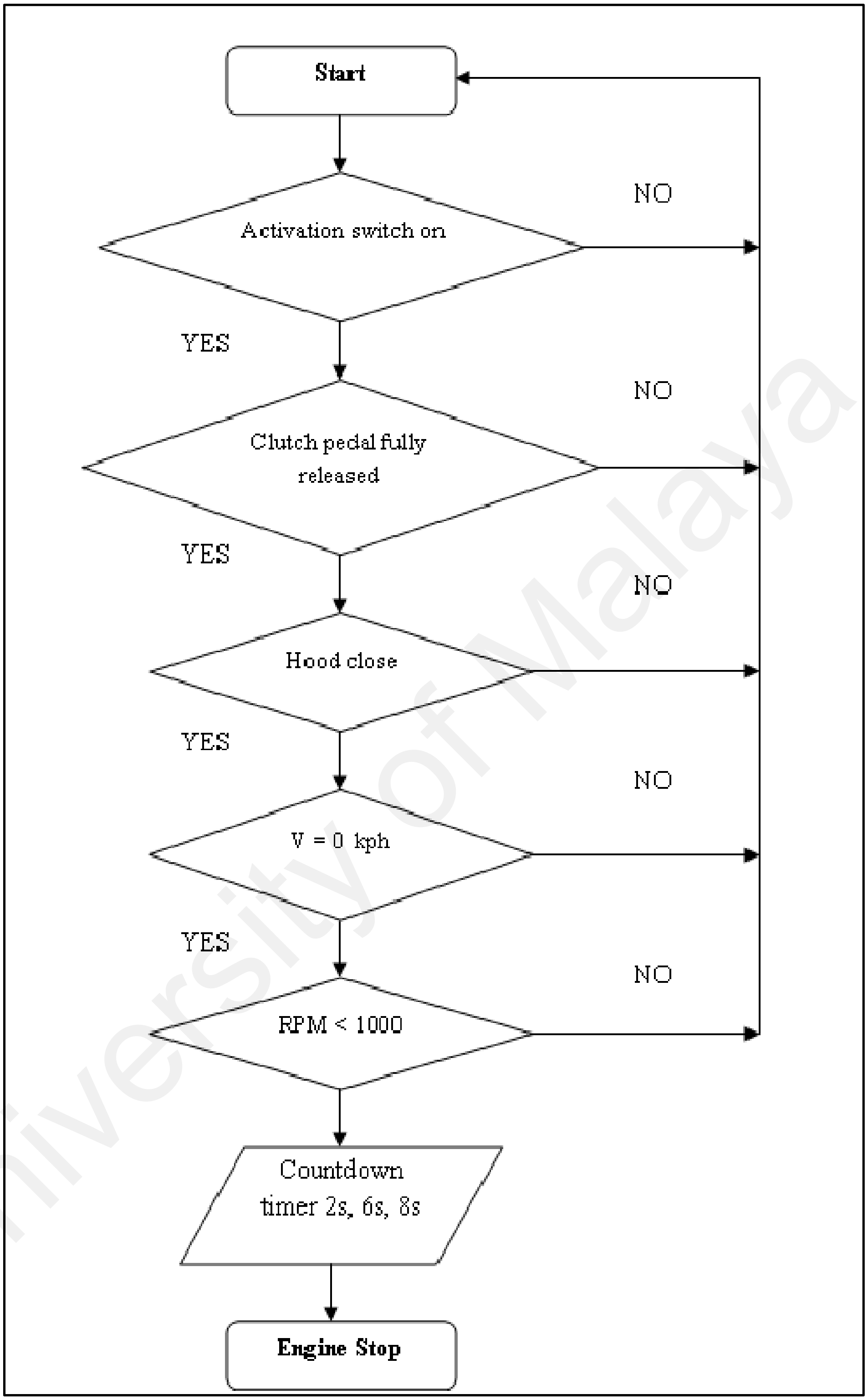

Figure 3.3: Control strategy - engine shuts down (Awang and Rasid, 2011)

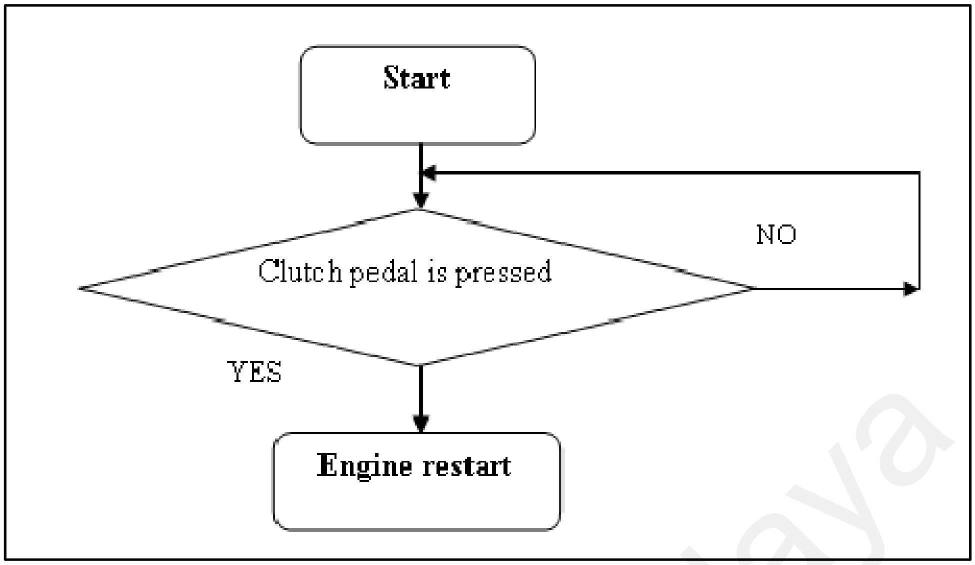

Figure 3.4: Control strategy - engine starts (Awang and Rasid, 2011)

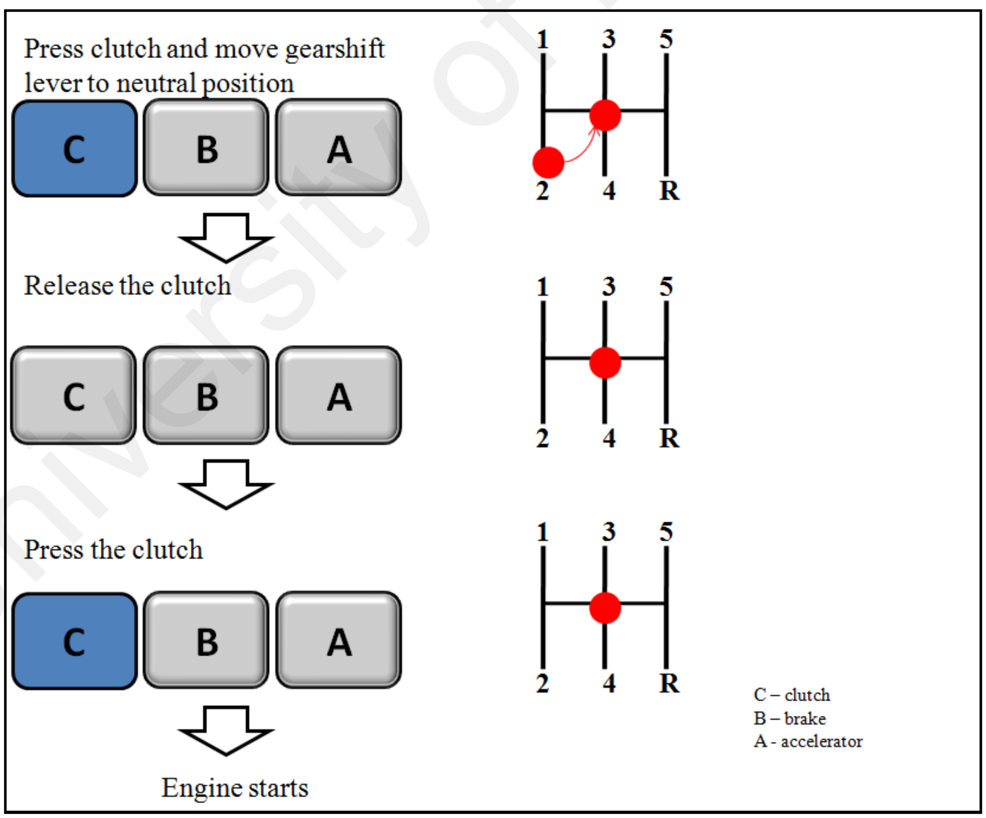

Figure 3.5: Clutch and gear condition for engine start (Awang and Rasid, 2011)

3.3 FUEL CONSUMPTION TESTING PROCEDURES

The testing procedures are based on Proton Standard, titled On Track Fuel Consumption Test produced by Vehicle Testing Section, Homologation and Testing (HNT) Department (Proton, 2009). The objective of the standard is to provide a guideline for conduction on track fuel consumption of vehicle on the actual road condition in constant speed mode. The scope of the application of the standard is applicable to all motor vehicles.

3.3.1 TEST CONDITION

The road must be in a dry condition. The road surface must be level and slope is constant to within ±0.1% and not exceeds 1.5%. The road gradient must be in a controlled condition so that less mechanical power is used to climb the slope which has an impact on the overall fuel consumption. In term of atmospheric conditions, the average wind speed must be less than 3 m/s with peak speeds less than 8 m/s. The crosswind must be less than 2 m/s.

3.3.2 TEST PROCEDURES

All the electrical accessories must be in OFF position. Windows should be closed during the test run. Any covers of air climatization systems, headlamps, etc, must be in non-operation position (Proton, 2009).

3.3.2.1 General on Track Fuel Consumption Procedure

The vehicle is driven at specified speed. Then, fuel flow meter sampling is started when the vehicle has achieved the specified constants speed. The vehicle must be kept driven at constant speed at least 100 m for the fuel meter to display the average fuel economy value. The test is repeated to cover at least 2,000 m to get minimum set of 20 data. The relevant data is then selected in term of correct constant speed (±2 km/h from desired speed and constant fuel economy reading). The test is repeated if there is other constant speed that has been set to be tested.

3.3.2.2 Pre-Test On Proton Test Track Procedure

The test procedures were according to the steps mentioned in section 3.3.2.1. Both cars were driven in the test track with constant speed of 40 km/h with the distance of 23 km. The test was done to simulate a congested traffic condition.

3.3.2.3 Actual On Road Kuala Lumpur City Driving Procedure

The test procedures were according to the steps mentioned in section 3.3.2.1. The test was conducted for 25 days with an average distance of 50 km per day. Both vehicles were driven at the same time and place to obtain accurate comparison.

3.4 FUEL AND COST SAVING CALCULATIONS

The fuel saving (FS) for each time setting was calculated by using Equation 3.1 and the percentage difference was from Equation 3.2 respectively. PersonaSS represents Persona with start-stop and PersonaStd represents standard Persona.

$$\boldsymbol{FS = PersonaSS\ FC - PersonaStd\ FC} \qquad (3.1)$$

$$Percentage\ difference = \frac{FS}{PersonaStd\ FC}\ x\ 100 \qquad (3.2)$$

The annual fuel saving is calculated based on assumptions that the annual mileage for the city driving was 20, 000 km and the fuel price for RON95 was RM 1.90/liter. The annual fuel saving equation is shown in Equation 3.3.

$$AnnualFS = FS\ x\ 20000 \quad (3.3)$$

The annual cost saving (CS) is then computed from Equation 3.4.

$$AnnualCS = AnnualFS\ x\ 1.9 \quad (3.4)$$

3.5 THERMAL CABIN COMFORT

Comfort level evaluation was conducted based on different timing controllers since the air-conditioning system was off during engine shutdown. The evaluation was measured by the standard subjective rating from the evaluators' responses. The rating is as follow.

Table 3.4: Standard subjective rating (Awang and Rasid, 2011)

Standard subjective rating	Description
1	Sweating
2	Hot
3	Warm
4	Slightly warm
5	Comfortable
6	Cold
7	Chill

Two thermostats were located at the center of the cabin and outside the vehicle to measure the inside temperature and ambient temperature respectively.

CHAPTER 4.0 - RESULTS AND DISCUSSIONS

The results presented in this section are the comparison of fuel consumption for pre-test on Proton test track, fuel consumption for actual city driving in Kuala Lumpur, the annual fuel cost saving and cabin thermal comfort.

4.1 FUEL CONSUMPTION RESULTS

Table 4.1 shows the result for pre-test conducted in Proton semi-high speed test track. Setting time chosen was 2 seconds. Based on the table, it can be seen that there is a reduction in the fuel consumption when start-stop system was used. The percentage difference was calculated by using Equation 3.1 and 3.2. The result is a reduction of 0.95% in fuel consumption which is equivalent to 0.08 liter/100 km.

Table 4.1: Pre-test test fuel consumption result

Persona SS (liter/100 km)	Persona Standard (liter/100 km)
8.31	8.39

Since the pre-test result shows a reduction in the fuel consumption, it can be concluded that the start-stop system was functioning as it was intended to be. Therefore, the on-road test was able to be carried out.

Table 4.2 shows the average results of the fuel consumption with three different time settings which are 2, 6, and 8 seconds respectively on the actual on road vehicle test.

Table 4.2: On-road test fuel consumption result

Setting time (sec)	Persona SS (liter/100 km)	Persona Standard (l/100 km)	Percentage difference (%)
2	11.43	13.73	16.75
6	10.72	11.76	8.84
8	12.00	13.10	8.34

As expected, the 2 seconds setting obtains the highest fuel reduction as the engine was shut down the earliest compared to the other settings. The second highest fuel reduction is 6 seconds setting followed by 8 seconds setting. Nonetheless, there is a big gap of the percentage difference between the 2 seconds setting and the others.

Factors that might contribute to the fuel consumption results were different road congestion condition, weather condition and driving behavior.

4.2 ANNUAL FUEL AND COST SAVINGS RESULTS

Table 4.3 displays the annual fuel saving when start-stop system is installed in the vehicle. The annual fuel saving was calculated by using Equation 3.3 and the annual cost saving was calculated by using Equation 3.4. The 2 seconds setting provides the highest fuel and cost savings. Nevertheless, in term of reduction in liter/100 km, the 8 seconds setting overrules the 6 seconds setting and thus has the second highest rating for fuel and cost savings. The average fuel saving for the three settings is 296 liter/100 km and the average for cost saving annually is RM 562.40.

Table 4.3 Annual cost saving

Setting time (sec)	2	6	8
Fuel saving (liter/100 km)	2.3	1.04	1.10
Annual fuel saving (liter)	460	208	220
Annual cost saving (RM)	874.00	395.20	418.00

During 25 days of actual on-road test, there was one occasion where PersonaSS had experienced of difficulty to crank the engine. Few attempts were made to crank the engine before it was able to restart. It was suspected that the performance of the standard of FLA battery was deteriorating and the SoC was reaching its minimum threshold value. The main tasks of the battery were not only to restart the engine via starter motor but also to supply power to electrical system while idling during engine stop. Therefore, there is a high possibility that the life of the FLA battery is shorter when start-stop is enabled compared to a conventional vehicle. The less capable of the battery, the fewer numbers of stop and start the engine can make.

A worst business case scenario was established where the battery was assumed needs to be changed twice a month to keep the battery performance at its standard. In a year, there are 52 weeks and thus the number of battery required for a year is 26 units. With the assumption that the cost of a battery is RM200, the total cost to purchase the battery annually is RM5, 200.

Therefore, having the start-stop system with FLA battery will impose a higher cost to the end user and not a favorable option even though the system has proven its capability to reduce the fuel consumption.

It is highly recommended that manufacturer to select higher performance of battery for instance EFB or AGM to provide convenience to the users in term of safety, serviceability and value-for-money product. Even though the recommended battery will cause higher vehicle price, the fuel economy improvement is about 5% - 10% compared to FLA battery application (Weissler, 2012).

Beside start-stop technology, there are few other technologies that can be considered and comparable to start-stop with respect to the premium cost and the improvement in fuel consumption. Table 4.4 displays the comparison made by (Silva et al., 2007) using IC19 driving pattern which simulates a highly congested road condition for lower medium class vehicle. The curb weight of the vehicle used in this simulation is 1,158 kg and Persona's curb weight is 1,170 kg.

Table 4.4: Comparison of fuel consumption saving (%) and premium cost ($) (Silva et al., 2007)

No	Technology	Fuel consumption saving (%)	Premium cost ($)
1	Downsizing plus turbo	10-20	500-600
2	Stop-start	15	200-500
3	Fuel cut	13	50-100
4	Combined	32-40	700-1,200

4.3 THERMAL COMFORT

Table 4.4 presents the average results of the subjective evaluation on the cabin comfort. It can be concluded that the passengers were not feel comfortable. There were few cases that the passengers were sweating during the evaluation due to temperature increase inside the cabin.

Table 4.5: Comfort level results

Controller timing	Subjective rating	Remarks
2 sec	2	Hot
6 sec	2	Hot
8 sec	3	Warm

The bar chart below shows the results of the average temperature inside the cabin and ambient for three different timing settings. The level of comfort must be below ambient temperature and the comfort benchmark was Persona Standard controlled temperature which was 25 °C. The temperature was chosen because it was the comfort temperature based on survey. Thus, it can be seen that the inside cabin comfort is not acceptable and fitting in timing controller has no impact on comfort level.

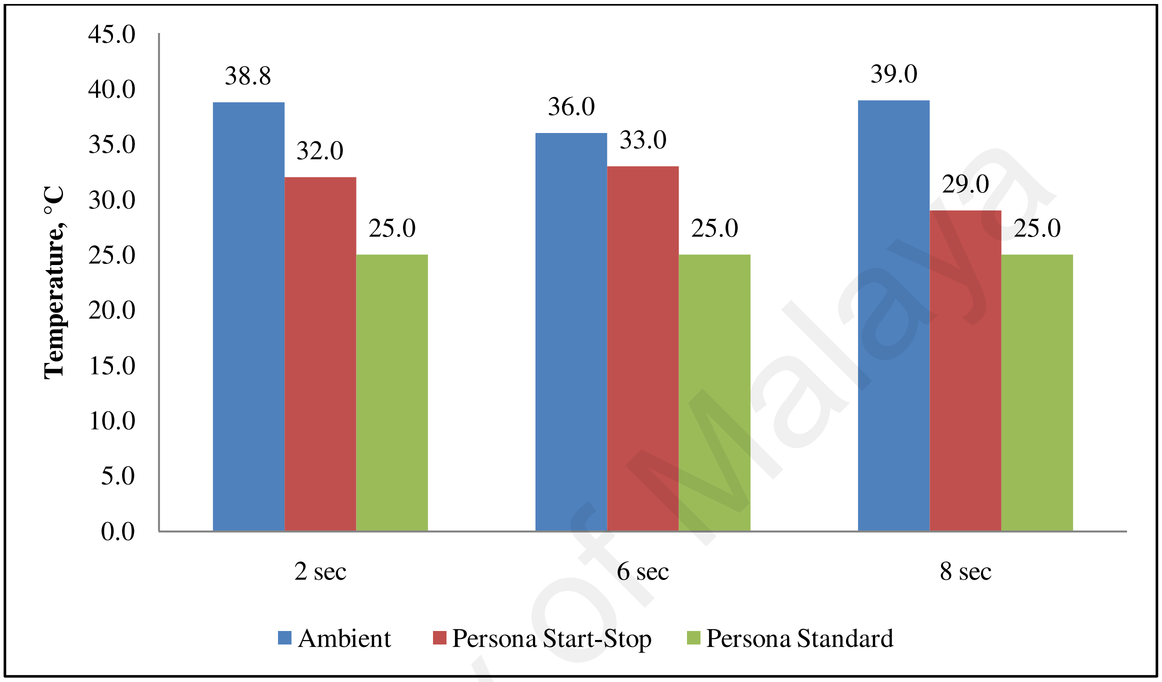

Figure 4.1: PersonaSS cabin temperatures vs. PersonaStd and ambient temperature

In order to overcome the issue especially for Malaysian climate which often to be hot, the manufacturer is ought to install storage evaporator so that the temperature inside the cabin is within the comfort range. A proper calibration also needs to be done by considering this criterion as one a parameter for engine stop inhibitors.

CHAPTER 5.0 - CONCLUSIONS

The description on start-stop technology related to its main components and operation strategies are presented in this thesis. The advantages of this technology are also listed. The challenges are identified to improvise the system.

Fuel consumption tests were conducted to evaluate and compare start-stop performance with standard vehicle. The tests were conducted on Proton Persona. Three time settings were included in the calibration to evaluate on the passenger comfort level during engine stop. The time settings were 2 seconds, 6 seconds and 8 seconds. Based on the tests results, fuel consumption reduction percentages are 16.75%, 8.84%, and 8.34% for 2 seconds, 6 seconds and 8 seconds respectively. The annual fuel saving computed is 296 liter/100 km and the annual cost saving is RM 562.40. The fuel price used was RM1.90/liter. However, Persona equipped with start-stop system experienced difficulty to crank once during the actual on-road test. Thus, a worst scenario business case was established with the assumption that the battery needs to be change twice month to maintain the battery performance. The study showed that the cost to change the battery has surpassed the fuel saving achieved annually. Therefore, it was recommended that manufacturer to use higher performance of battery to ensure customer satisfaction.

According to test result for thermal comfort, the passengers were not happy with the thermal condition inside the cabin during engine stop due to temperature increase. Thus, start-stop system must be accompanied with devices that will make the thermal comfort level as per standard conventional vehicle. One of the proposed solutions is to use a storage evaporator where the principle of the system has been applied by Valeo for their STOPStayCOOL system.

Besides start-stop technology, there are few other technologies that are capable to reduce the fuel consumption with comparable additional premium cost. The technologies are fuel cut while coasting, engine downsizing with turbocharger and the combination of these technologies plus start-stop.

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