REAL DRIVING EMISSIONS TESTS OF A LIGHT TRUCK OPERATING USING A EURO-IV COMPLIANT CI ENGINE

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ABSTRACT

After the outbreak of ‘Volkswagen Dieselgate’ scandal, the intention to measure real-world driving emission has increased. Research worldwide have outlined that laboratory testing does not reflect the actual vehicle emissions under on-road operating conditions. The aim of this study is to conduct real-driving emission (RDE) testing using a Euro 4-compliant diesel truck on pre-designed test routes under the Malaysian context. CO, CO_2, HC, and particulate matter ($PM_{2.5}$) are the targeted emission pollutants in current study. For trip execution and trip design, the In-Service Conformity (ISC) procedure is applied as a guideline to ensure the significance of data obtained. Vehicle specific power (VSP) approach is applied for emission analysis and the overall results obtained are compared to the regulated emission limit to identify the gaps. The overall brake-based emission factors obtained were 0.178 g/kWh CO, 3.126 g/kWh HC and 0.0002 g/kWh $PM_{2.5}$. CO and $PM_{2.5}$ obtained in this study were lower than the regulated emission limit. However, HC emission results obtained were found to be 6 times higher than the regulated EURO IV limit. Findings suggested that emissions results obtained depend strongly on the functional relations and types of emission. CO_2 and $PM_{2.5}$ are more affected by the engine load while CO and HC are affected by the on-road operating conditions. The findings of this study are expected to enhance the knowledge of local automotive industries and assist them in producing better diesel trucks. It is concluded that RDE tests are necessary to ensure the emission are within the regulated limits.

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ABSTRAK

Selepas pencetusan skandal 'Volkswagen Dieselgate', keperluan untuk ujian pelepasan asap pemanduan atas jalan telah meningkat. Dapatan Kajian telah menggariskan bahawa ujian makmal tidak menggambarkan pelepasan sebenar kenderaan di atas jalan raya. Oleh itu, matlamat kajian ini adalah untuk menjalankan ujian pelepasan asap pemanduan atas jalan (RDE) dengan menggunakan lori diesel Euro IV pada laluan ujian pra-rekaan dalam konteks Malaysia. CO, CO_2, HC, dan $PM_{2.5}$ adalah bahan pencemar sasaran dalam kajian ini. Untuk rekaan dan pelaksanaan perjalanan, prosedur Pematuhan Dalam Perkhidmatan (ISC) digunakan sebagai garis panduan untuk memastikan kualiti data. Pendekatan kuasa khusus kenderaan (VSP) digunakan untuk analisa pelepasan dan keputusan keseluruhannya telah dibandingkan dengan had pelepasan terkawal untuk mengenal pasti jurang antara satu sama lain. Faktor pelepasan berasaskan brek keseluruhan yang diperolehi ialah 0.178 g/kWj CO, 3.126 g/kWj HC dan 0.0002 g/kWj $PM_{2.5}$. Faktor pelepasan CO dan $PM_{2.5}$ yang diperolehi dalam kajian ini adalah lebih rendah daripada had pelepasan terkawal. Walaubagaimanapun, faktor pelepasan HC yang diperolehi didapati 6 kali lebih tinggi daripada had EURO IV. Dapat kajian menunjukkan bahawa hasil pelepasan yang diperoleh sangat bergantung pada hubungan fungsi dan jenis pelepasan. Faktor pelepasan CO_2 dan $PM_{2.5}$ lebih dipengaruhi oleh beban enjin manakala CO dan HC lebih dipengaruhi oleh operasi kenderaan di jalan raya. Dapatan kajian ini dapat meningkatkan pengetahuan industri automotif tempatan dan juga membantu mereka dalam menghasilkan lori diesel yang lebih baik. Kesimpulannya, ujian RDE adalah perlu untuk memastikan pelepasan asap kenderaan berada dalam had yang ditetapkan.

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LIST OF SYMBOLS AND ABBREVIATIONS

F_a	-	Aerodynamic Resistance
F_r	-	Rolling Resistance
F_g	-	Acceleration Due to Gravity
F_{acc}	-	Vehicle Inertia
C_d	-	Aerodynamic Drag Coefficient
C_r	-	Rolling Resistance Coefficient of Truck Tire
θ	-	Road Grade
q_{gas}	-	Mass Flow of Component Exhaust Gas
u_{gas}	-	Molar Mass Ratio of Component Exhaust Gas
c_{gas}	-	Concentration of Exhaust Gas Component
Q_{gas}	-	Exhaust Gas Flow Rate
EF	-	Emission Factor
TSEF	-	Time-Specific Emission Factor
BBEF	-	Brake-Based Emission Factor
DBEF	-	Distance-Based Emission Factor
VSP	-	Vehicle Specific Power
IS	-	Instantaneous Vehicle Speed
RG	-	Road Grade
DOC	-	Diesel Oxidation Catalyst
DPF	-	Diesel Particulate Filter

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

‘Volkswagen Dieselgate’, which is an emission scandal that has affected more than a half-million diesel cars in the US and roughly 10.5 million more worldwide, was discovered by the US Environmental Protection Agency (EPA) in 2015 (Atiyeh, 2019). Volkswagen, the largest car company in Germany that owns 70 per cent of the U.S. passenger car diesel market, had admitted to installing an emission software known as “defeat device” that was designed to “cheat” in federal emission tests. After this shocking emission scandal was exposed, various experimental campaigns aimed to assess the real-world driving emission of the in-use vehicles were conducted (Prati et al., 2019). It was also discovered through the on-road emissions testing that these vehicles were equipped with a “defeat device” that had in-use NOx emissions of a factor of 10 to 40 above the EPA standard (Barrett et al., 2015).

Consequently, questions such as “do discrepancies exist between real-world driving emission and regulated laboratory emission?” have always been the concern of policymakers and researchers globally. It is well known that conventional vehicle approval testing is conducted on an engine or chassis dynamometer in laboratories under controlled conditions and this regulation is still being implemented in most countries, especially the developing nations. Previous studies in Asian countries have reported that these laboratory testing does not reflect vehicle emission under real-driving condtions, especially from the on-road diesel truck fleet (Mahesh et al., 2019; Q. Zhang et al., 2016). Ro et al. (2021) also reported that on-road NOx emissions were 2.1 to 6.9 times higher on average than those measured through Korean Driving Cycle

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as this driving cycle applied for regulation purpose does not cover wide variability of actual on-road operating conditions such as vehicle speed and acceleration. In the year 2014, the United Nations Economic Commission for Europe (UNECE) made the transition from the New European Driving Cycle (NEDC) to the Worldwide Harmonized Light-Duty Test Cycle (WLTC) as an effort to close the gap of real-world driving emission (Tsokolis et al., 2016). As observed in Figure 1.1, the main difference to WLTC is NETC tested under shorter duration and distance, constant speed and acceleration which is not representative of real-world driving (Tsokolis et al., 2016). Although laboratory testing still being the regulated testing for type-approval process in most countries (e.g. Malaysia), the European (EU) government have mandated real-driving emission test, specifically with the used of Portable Emission Measurement System for their in-service conformity (ISC) testing of heavy-duty vehicle and non-road machineries starting since September 2017 (Rahman et al., 2021).

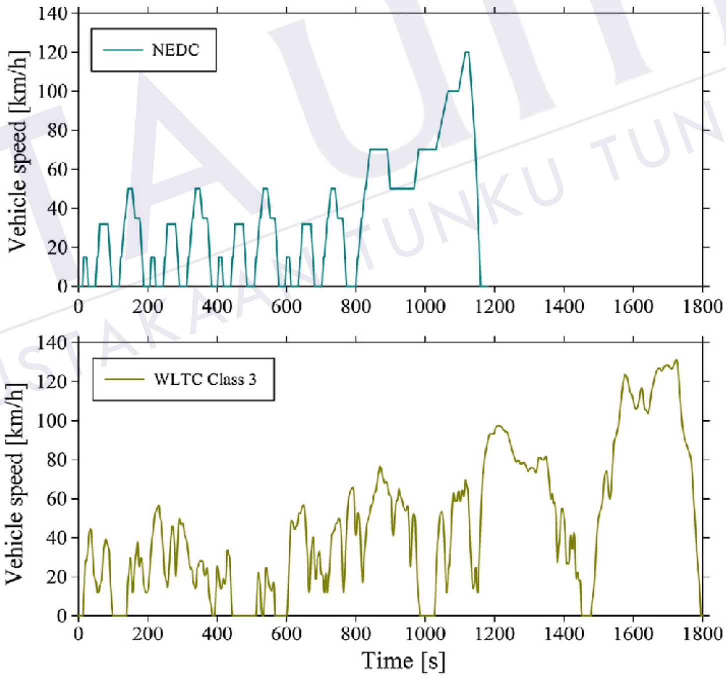

Figure 1.1: The difference between NEDC and WLTP (Tsokolis et al., 2016)

On-road diesel truck fleets are known to be significant contributors to emissions of gas and particulate such as nitrogen oxide (NO_x) and particulate matter (PM) in the ambient air (Huo et al., 2012; Sandhu et al., 2015). Even though these truck fleets only comprise a relatively small portion of the total vehicle fleet, they are still considered as one of the dominant contributors to air pollution and the associated

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health problems (Grigoratos et al., 2019). Due to the rising demand for goods transportation and the rapid urbanisation across the globe, the need for diesel vehicles is projected to escalate in the coming years (Huy et al., 2020; Keramydas et al., 2019). As reported in Satisca (Müller, 2020), there are about 54 thousand commercial vehicles registered in Malaysia in the year 2019. Thus, more attention should be given to emission quantification and measurement so that good air quality can be assured and maintained. For this reason, the current study intends to assess the real-world driving emission of selected Euro 4-compliant heavy-duty compression-ignition (CI) engine of a light commercial truck on a pre-designed route under the ambient and traffic conditions in Johor, Malaysia.

1.2 Issue and Problem Statements

Previous studies have outlined that laboratory measurement, especially on diesel truck fleet, do not reflect the actual vehicle emission under real-world driving conditions (Mahesh et al., 2019; Q. Zhang et al., 2016). These discrepancies of emission results found between laboratory and real-world driving measurement had been explained previously. Sandhu et al. (2014) reported that real-world driving emissions, as well as the fuel consumption of on-road trucks, are highly sensitive to daily activity cycles, which in turn are sensitive to other operating conditions such as driving speed, acceleration, road grade and truck weight. Even so, the regulated driving cycles that are mostly used in laboratory measurement are constructed in developed countries, in which road types, operating conditions, ambient temperature and even geographical aspects differ from those in countries that adopt the proposed driving cycles for legislative purposes (Osorio-Tejada et al., 2018).

According to the emission standards from Department of Environment Malaysia (2017) only the minimum EURO II emission standard is required for all new or existing models of motor vehicles by the year 2017. The implementation of these standards is considered outdated as compared to other developed European countries that are implementing the latest EURO VI standards. Moreover, the emission studies conducted using diesel truck fleet, especially on real-world emission in Malaysia, are still scarce despite the growing awareness about the negative effect of diesel emission. Therefore, the main objective of the current study is to conduct measurement of real-

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driving emission from a selected diesel light commercial truck (DLCT) on a pre-designed route under local conditions in Johor, Malaysia to better understand the real-world driving emission as well as provide better insight for local authorities and policymakers in Malaysia towards enforcement of stricter emissions regulation.

1.3 Objectives

The main aim of this research is to address the gap between the certification limit and real-world driving emission from a selected diesel light commercial truck (DLCT) on a pre-designed route under local conditions in Johor, Malaysia.A series of research objectives have been defined as follows:

(a) To construct real-driving emission measurement on a selected DLCT on a pre-designed route under the local conditions in Johor, Malaysia.

(b) To evaluate the on-road operating conditions of the pre-designed route that affect the real-world emission factors of on-road DLCT

(c) To compare real-world emission factors of the selected DLCT with the regulated certification levels and emission standard

1.4 Scopes of Study / Delimitation of Study

The analysis presented in this study only concerns real-world driving emissions from selected DLCT, specifically the Euro 4-compliant heavy-duty compression-ignition (CI) engine light truck. Only gases and particulate pollutants such as hydrocarbon (HC), carbon dioxide (CO_2), carbon monoxide (CO) and particulate matter less than 2.5 micrometres ($PM_{2.5}$) were included. Emission factor analysis of the complete cycle was done to investigate the discrepancy between lab-based and real-world measurement methods, specifically portable emission measurement system (PEMS) or on-board measurement. The need for a stricter legislative standard in Malaysia was elaborated in this study as well. The focused areas in this research include Batu Pahat, Ayer Hitam and Yong Peng in Johor, though many of the findings are transferable to other states in Malaysia and even other developing countries that share the same climate conditions.

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1.5 Significance of study

The current study applied the real-world driving emission measurement method to investigate the discrepancy between laboratory testing (type approval) and real-world driving emissions of the selected light-duty diesel truck. The findings of this study are expected to enhance the knowledge of local automotive industries and assist them in producing better and greener diesel commercial trucks that best fulfil the legislative limit in actual driving. On the other hand, this study also aims to provide real-world driving data for constructing local emission factors and also driving cycles that can best predict the pollution impact on human health as well as the fuel and energy efficiency of the vehicle used. Last but not least, the data and results obtained from the current investigation can also be used as references and guidelines for future studies in Malaysia.

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CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

A series of literature reviews have been conducted in this chapter in order to provide better insight regarding the topic of real-driving emission. These literature reviews comprise the studies on the mechanism of diesel engines, emission measurement specifically lab-based and real-driving measurement methods, emission standards and factors that affect the real-driving emission during real-world driving. This chapter ends with a summary of each sub-section and a research framework that provides a comprehensive picture of the current research.

2.2 Diesel Emission

Diesel engines are known as one of the most reliable engines in history but they are always accompanied by a serious environmental pollution problem. Exhaust emissions such as carbon monoxide (CO), unburned hydrocarbon (HC), nitrogen oxide (NOx), particulate matter (PM)—also known as soot—and greenhouse gas carbon dioxide (CO_2) have always been the concerns of policymakers as well as researchers worldwide. Therefore, engine after-treatment technologies have been created and introduced in recent years to reduce emission pollutants during operation. In the following sub-sections, all the exhaust pollutants, as well as the after-treatment system, are be briefly discussed.

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2.2.1 Exhaust Emission

In the course of complete combustion, the reactant burns in oxygen, producing a number of products as per Equation (1.1) below. Even though complete combustion fully extracts all the energy from the reactants, a 100% combustion efficiency is not realistically achievable in daily life (Speight, 1932).

$$CH_4 + O_2 + N_2 \rightarrow CO_2 + 2H_2O + N_2 + CO + NO_x + \text{heat} \qquad (1.1)$$

The exhaust end products, namely carbon monoxide, nitrogen oxides, unburned hydrocarbon and particulate matter or soot, are all produced during incomplete combustion in a diesel engine. Diesel engines are characterized as lean combustion, which means the fuel is burnt under excess air conditions. Since it is unrealistic to maintain a stoichiometric ratio (a chemically correct ratio of 14.4:1) during the combustion process, a part of the fuel will not be fully consumed, which will then produce unburned hydrocarbon. For the same reason, insufficient oxygen during the combustion process also results in the production of carbon monoxide (Engine combustion process explained, 2017) whereas HC pollutants are usually produced during instantaneous acceleration and stop-and-go driving under congested traffic conditions.

Nitrogen gas does not involve in the oxidation process but at high temperatures, nitrogen gas will be converted into nitrogen oxides through a chemical reaction. NOx emission, especially from diesel engines, has become a major concern in major cities worldwide as it contributes to acidification and the formation of ozone. Particulate matter or soot is also an emission pollutant of diesel engines. This emission originates from burnt fuel and its formation depends on many factors, one of which is the fuel quality. Previous literature stated that diesel engines produce more NOx and PM emissions than gasoline engines (Reşitoılu et al., 2015). Therefore, emissions of these two pollutants especially from diesel engines have become a hot topic among researchers. As all these exhaust end-products will bring negative effects to human health, exhaust after-treatment technologies have been introduced to assist in reducing pollutant emissions from road transport.

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2.2.2 Advanced after-treatment system

In order to reduce exhaust emission effectively, several exhaust after-treatment technologies have been introduced and are currently available in the market. These exhaust after-treatment technologies are installed for various purposes and may installed together and used simultaneously to reduce the overall exhaust tailpipe emission. The common technologies are diesel oxidation catalytic (DOC), and diesel particulate filter (DPF) as shown in Figure 2.1

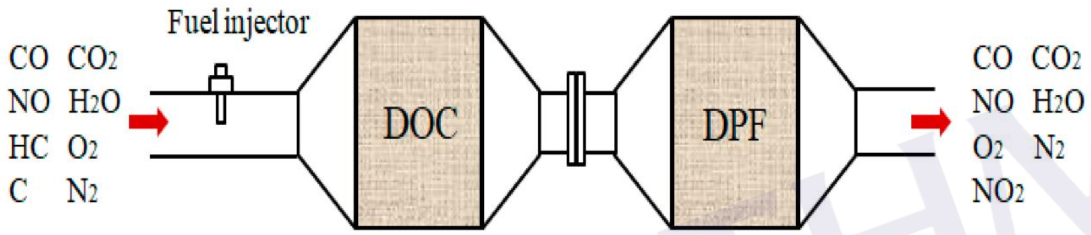

Figure 2.1: Mechanism of DOC and DPF (Liu et al., 2021)

DOC plays an important role in enhancing the oxidation of HC and CO into CO_2 and water vapour (H_2O). However, the effectiveness of DOC often depends on the "light-off" temperature, which is known as the temperature at which reactions start in the catalyst. In most cases, DOC is often used together with the DPF and the DPF is installed downstream of the exhaust system. This combination is preferred mainly because DOC also functions as a catalytic heater, in which heat energy is released during the oxidation process. This heat energy is absorbed by the DPF to support the regeneration event. On the other hand, DPF is used to remove particulate matter (PM) through physical filtration. A honeycomb monolith structure is used to filter the PM from the exhaust gas and this structure is commonly made from materials such as silicon carbide or cordierite (Reşitoılu et al., 2015). These accumulated ashes or particulate matter can be removed through active and passive regeneration events. During the passive regeneration event, heat generated from the oxidation process in the DOC is consumed to burn the accumulated soot or ashes. The main difference between passive and active regenerations is that active regeneration depends on the post-injection process to produce heat in the DOC. It can be seen that DPF and DOC are two important exhaust after-treatment technologies used to mitigate CO, HC, and PM, especially in vehicles that abide by Euro IV standards and higher.

2.3 Emission Measurement

Emission measurement can be conducted either under real-world or controlled lab conditions. There are mainly two types of lab-based measurement, namely chassis dynamometer and engine dynamometer testing. According to Franco et al. (2013), there are several types of real-world emission measurement including remote sensing, tunnel study, plume chasing and on-board measurement, which is also known as the portable emission measurement system (PEMS). All of these measurement methods are discussed in the following sub-sections.

2.3.1 Lab-based Measurement

Chassis dynamometer and Engine dynamometer are two methods that are performed under controlled lab-based conditions. The main difference between these two methods is that the chassis dynamometer simulates the resistive power imposed by the wheel of the vehicle (the whole vehicle is placed on a test bench) while the engine dynamometer simulates the resistive power imposed by the engine of the vehicle (only the engine is placed on the test bench). Due to the high accuracy and consistency of the utilized equipment, lab-based testing has been designed for regulated type approval testing. Engine dynamometer testing is the most common method used for regulated heavy-duty vehicle type approval testing. As heavy-duty vehicles are used in various applications and are often equipped with various chassis and body types, it is more practical to test the engine alone rather than the vehicle as a whole. Furthermore, there are only a few heavy duty chassis dynamometer laboratories in the world due to the costly equipment used to accommodate larger vehicles (Franco et al., 2013). Despite all these facts, previous literature highlighted that the driving cycle used in lab-based testing does not fully represent the real-world emission from vehicles (Mahesh et al., 2019).

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2.3.2 Real-Driving Emission

As regulations across the globe continuously updated and improved, more pollutants are being subject to control with new regulations and especially the measurement method are being changed to be done under real-world driving conditions (Barouch Giechaskiel et al., 2022). There are several real-driving emission methods available, which are designed for different purposes and each has its advantages as tabulated in Table 2.1 (Huang et al., 2018). The portable emission measurement system (PEMS) and plume chasing are suitable for collecting individual emission data on a journey. The main difference between these two methods is in their measurement instrument. PEMS comes with on-board measuring equipment for emission testing whereas plume chasing collects emission data via a "laboratory vehicle" that chases the target vehicle. Because of this, limited vehicle speed and minimum distance between the target and chasing vehicles become the main limitations of the plume chasing method. On the other hand, remote sensing, tunnel studies and ambient measurement have made the collection of massive real-world emission data possible. These three methods only collect emission data at a specific point because a huge amount of sensing equipment are required to collect data for an entire journey, deeming these methods impractical.For example, tunnel measurement collects emission data at the tunnel entrance and exit, while remote sensing and ambient measurement method collect emission data at certain points along the journey. The operating mechanism of remote sensing and tunnel measurement complicates the emission assessment for certain vehicle classes or individual vehicles travelling on the road. Therefore, it is important to understand the types of emission data that are required, so that the most appropriate measurement method can be selected.

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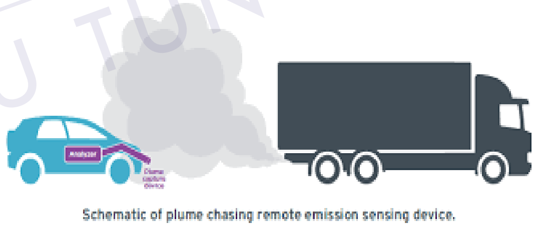
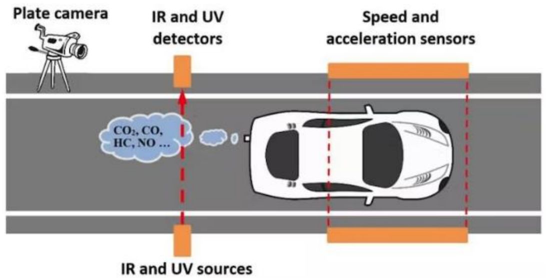
Table 2.1: Comparison between different technique of real-driving emisison measurement method

Technique	Method	Advantages	Disadvantages	Picture
Portable Emission Measuremnet System (PEMS)	Measures vehicle emission using portable instrumentations	• High Accuracy • Emisison data of a full trip	• Small sample size • Focus on one vehicle at a time • PEMS eqipmments are expensive	
Plume Chasing	Measures target vehicle emisison by moving laboratory through vehicle chasing	• Emisison data of a full trip	• Small sample size • Focus on one vehicle at a time • Limited speed and minimum distance for safety purpose	
Tunnel Measurement Ambient Measurement Remote Sensing	Measures ambient pollutant concentrations at tunnel entrane & exit (Tunnel), roadside (Ambient) and when passing through IR and UV beams on-road (Remote Sensing)	• Large Sample Size	• Difficult to determine emissions of specific vehicle classes or individual vehicles • Limited driving conditions • Limitations in site selection (road grade) • Only measures emisison at specific point or distance	

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2.4 International and Local Emission Standards

2.4.1 International Emission Standards

The heavy-duty vehicles (HDV) are important sources of emission that brings negative impact to the environment and human health. Therefore, stringent emission limit has been introduced by policymakers to ensure emission reduction. There are several emission standards currently being implemented globally, which was initially launched in the United States and then followed by European Union and other countries such as Japan, China and India. With these emission limits, huge emission reductions have been made possible.

The evolution of emission standards started with Euro I and the latest emission standard available to date is the so-called Euro VI emission standard by the European Union, which stringency is comparable to that of U.S. EPA 2010 in the United States or to those of other foreign variants that have equivalent emission limit but with different names. Table 2.2 below lists down the adoption date of the latest EU Euro VI standard and its equivalent foreign variants as the regulatory emission limit for diesel vehicles or compression-ignition engines (DieselNet, 2017). China and India are among the earliest Asian countries that adopted emission standards that are equivalent to the Euro VI standard. China introduced the national China VI program in 2019 and India have proposed a standard transition from Bharat Stage IV to Bharat Stage VI since 2020. Moreover, Singapore adopted Euro VI or Japan 2009 since 2018. **APPENDIX A** presents all the EU Emissions limits starting from Euro I to Euro VI for both Steady-State Testing and Transient Testing. In the next sub-section, both Steady-State Testing and Transient Testing together with their testing cycles are discussed briefly.

Table 2.2: Adoption date of the EU Euro VI emissions standards and their equivalent foreign variants for the heavy-duty engines (DieselNet, 2017).

Country/ Region	Adoption date
Europe	became effective since 2013/2014 followed by several ‘comitology’ packages*
China	phase-in schedule from July 2019 until July 2023
Singapore	Since January 2018
India	Proposed schedule since 2020; 2025 for a new model; 2026 for all existing model

*comitology packages starting from Euro VI-A to Euro VI-E

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