Efficiency and Emission Simulations of Hydrogen-Fuel City Buses

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Abstract
In this study, the AVL Cruise is implemented to simulate driving parameters including the driving path, the power loss on engine accessories, the gear-shifting scheme and the engine’s fuel cut-off strategy influencing the bus fuel efficiency and emission. The Mercedes Conecto LF city bus using a diesel engine with Standardised On-Road Test Cycles was firstly simulated and compared with available literature. The application of hydrogen fuel was then examined and its result was compared with the diesel fuel on the specific fuel consumption. In addition, the driving cycles in Bangkok were simulated. The results show the pattern on both driving cycles with different fuel are similar, however, the fuel consumption of H2 is significantly less than in the case of Diesel. Moreover, it is also evident that the SORT driving cycle cannot represent the heavy traffic of Bangkok.

Keywords: City Bus, Modelling and Simulation, Performance Simulation, Hydrogen, Efficiency and Emission

1. Introduction
Regarding the pollution emission especially in big cities caused by the transport sector, governments worldwide generate a lot of policies targeting to enhance the efficiency of energy use, support independency from fossil fuels, and also boost alternative fuels [1]. Road transport in Europe has a significant share of total carbon dioxide emissions [2]. The transport segment is the second largest source of pollutant emissions in the EU and despite the measures taken, the volume of emissions is still growing [3]. An expansion of energy application including impact on the greenhouse gas and pollutant emissions are also related to this sector. Based on these statements the reduction of CO2 has become an important task. In addition, since the fuel consumption and CO2 emission are proportional, together with other emissions also sensitive to fuel consumption rate, it is clear to mention that the lowering of the fuel consumption induces to emissions decreasing effect as well.

The experimental methods are costly and time-consuming. Therefore, it is not proper to conduct many investigations with changing vehicle specifications and driving cycles. The simulation methodology, on the other hand, has advantages to get results in a short time along with many...
applications which are also available. Thus, extensive studies can be enabled with varying vehicle factors and driving conditions [4]. In the present works, a commercial program, i.e. AVL CRUISE, has been implemented to simulate the engine’s and vehicle’s characteristics based on the vehicle dynamics. Engine diagrams, gear shifting scheme, the gear ratio and other input parameters were applied to model the fuel consumption and other significant outputs in the simulation. The fuel consumption of city buses counts on many factors that characterize the technical parameters of the bus and the behavior of the driver, as well as traffic conditions [5, 6].

The alteration of the driving procedures is also an important factor, which influences fuel consumption [7]. Each of the base cycles composes of three sections. In each section, three phases were distinguished: acceleration, constant speed and braking. In this study, the basis cycle called SORT2 has been applied in the early steps/stages. Later the represented Bangkok driving cycle, named BKK2, was implemented.

The uneconomical driving style of the driver can cause an increase in fuel consumption by 5 - 10% compared to economic driving [1]. Secondly, the electric energy on board demands constantly increasing, resulting in a reduction in the overall efficiency of the bus and increased fuel consumption. Even though the drivers were on a similar road, the behavior of them influences the high deviation of fuel consumption quantity [8]. However, in this investigation, the driver was set as a constant factor, whereas the standard driver has been applied.

Based on the properties of the hydrogen-fuelled in the internal combustion engine, the advantage is including wide flammability range, high flame speed and propagation, however, its drawbacks are low ignition energy and small quenching length causing the premature ignition, which is the main problem especially in these kinds of engines [9].

2. Simulation Modelling

2.1. AVL CRUISE

AVL CRUISE is a system for modeling vehicles at the level of drive systems. It supports ongoing tasks during the analysis of vehicle and drive systems in all development phases, from conceptual planning, commissioning and actual testing. Its application covers the demand in the field of conventional car engines, through advanced hybrid systems and electric vehicles. The vehicle model in the AVL CRUISE consists of assemblies and subassemblies. This allows the user to model various vehicles, such as motorcycles, passenger cars, trucks and buses. In addition, it is possible to model all configurations of drive systems, such as hybrid systems, two-motor concepts or advanced transmission systems [10].

2.2. Bus Modelling

The 12-meter-long urban bus MAXI Mercedes Conecto 12LF has been chosen for investigation. The basic technical data of the bus including the drive units are shown in Table 1. These basic variables have been implemented into the simulation program. The power train unit is a supercharged self-ignition Diesel engine powered by a Common Rail system and meeting the Euro V purity standard.

Table 1. Mercedes Conecto 12 LF parameters [11].

| Parameter      | Valve                        |
|----------------|------------------------------|
| Dimensions     | 11950 x 2550 x 3076 mm      |
| Wheelbase      | 5845 mm                      |
| Own weight     | 10860 kg                     |
| Engine         | OM 926 LA                    |
| Type                        | 4-stroke, in-line, 6 cyl. |
|-----------------------------|---------------------------|
| Displacement                | 6370 cm³                  |
| Power                       | 205 kW                    |
| Torque                      | 1120 Nm @ 1300 rpm        |
| Fuel consumption            | 39 dm³ / 100 km           |
| Transmission                | Voith 854.3 - 4 speed     |
| Gear ratio                  | 1:5; 2:1.43; 3:1.0; 4:0.7 |
| Rear axle system            | ZF AV-132 Gear ratio: 7.38|

The model has been divided into three parts. The first one concerns the vehicle. It includes object properties such as mass, dimensions, location of the center of gravity. The second part involves the powertrain including engine, clutch and gearbox, whereas the third one relates to the driveline, for example, rear differential, brake system and tires. The schematic diagram of the bus model is illustrated in figure 1.

![Figure 1. Schematic presentation of the bus model in AVL Cruise](image-url)

2.3. Driving Cycles

As already mentioned the driving cycle is one important input parameter for the vehicle system simulation. It can be apprehended that the vehicle would undergo this driving path repeatedly thoroughly.
its route. By statistical it stands for an essential driving path for the vehicle fleet of a city. Moreover, this driving path is also supposed to be repeated uninterruptedly [12].

In this study, two driving cycles have been involved, i.e. SORT2 and BKK2. The explanation of them is introduced in the next section.

2.3.1. Standardised On-Road Test Cycles - SORT
SORT is a driving cycle for measuring the buses’ fuel consumption under the aim of consumer protection and information [13]. It is created by the UITP - International Association of Public Transport in cooperation with the bus producers and public transportation providers mainly in Europe. SORT is employed to correlate between buses regarding their fuel consumption in true working conditions. There are three different driving cycles available, including SORT1, SORT2 and SORT3. They represent also the different traffic conditions, which are “Heavy Urban”, “Easy Urban” and “Suburban”, respectively.

In this study, the SORT driving cycle has been used in the early step to validate the simulation program with the selected publication [2]. Based on this reason, SORT2 has been applied. The characteristic of this driving cycle on a velocity versus distance and time is shown in figure 2.

2.3.2. Bangkok Driving Cycle
In order to assess exhaust emissions and fuel consumption of newly registered automobiles in Thailand, the standard driving cycle of the European Community is ground on [14]. However, regarding the traffic condition especially in Bangkok, the European driving cycle cannot represent the exact situation.

Figure 2. The driving cycle SORT2: Easy urban [13].

Figure 3. Example of driving cycle in Bangkok [12].
Tamsanya et al. [12] have proposed the driving cycle for Bangkok generated by means of numerical simulation based on the traffic flow data input. In their study, the traffic stream information at each selected junction in the city center of Bangkok observed. The highest traffic quantity takes place in the morning period from 7 to 9 O’clock. The physical speed and time outlines are contained small parts of driving information, named micro-trips, separated by idling time. It can be summarized that the main driving paths in Bangkok are short driving trips with low speeds and often stops. The usual stops and high-velocity fluctuation are the causes of extended emissions and fuel consumption, as pointed by Ericsson [15], Haan and Keller [16]. The generated driving cycles from the experimental input data are illustrated as an example in figure 3.

In order to select the most substitute for the true driving circumstances, the driving variables of the created driving cycles must be nearest to the pointed statistics. Their research work concluded that the most representative of Bangkok traffic is the BKK2 driving cycle.

3. Validation
The validation on AVL Cruise has been done earlier step of this study. The vehicle and engine characteristics following the selected publication [2] have been set up. The conducted simulation tests to confirm the possibility of using the AVL Cruise software to investigate the vehicle system. The 12-meter-long MAXI Mercedes Conecto 12LF equipped with the Mercedes engine OM926LA has been examined. The SORT2 has been applied for the driving cycle as well.

The comparing results are shown in this section. In figure 4 the comparing on engine power and acceleration along the driving cycle SORT2 is illustrated. The compatibility between the investigation in this work and the publication is significantly acceptable.

![Figure 4.](image)

**Figure 4.** Comparison of engine power and vehicle acceleration with the reference data.

Further on emission CO₂ and fuel consumption are also presented in figure 5. The results are agreed in the right manner.

![Figure 5.](image)

**Figure 5.** Comparison of CO₂ and fuel consumption with the reference data.
4. Simulation Results and Discussion

As the aims to implement the complicated driving condition such as inside the city of Bangkok and also to propose the alternative way for public transportation using H\textsubscript{2} fueled engine. The simulation on the BKK2 driving cycle, which represent more closely to the real condition of traffic in Bangkok, has been accomplished. In addition, the investigation on changing Diesel to H\textsubscript{2} has also been achieved.

4.1. Variation of Driving Cycles

The results of acceleration on SORT2 comparison with the BKK2 driving cycle are illustrated in figure 6. On SORT2, the maximum acceleration of the vehicle is not more than 2.39 m/s\textsuperscript{2}, while the deceleration during the braking time does not exceed 2.48 m/s\textsuperscript{2}. Conversely, on BKK2 both maximum acceleration and deceleration are higher than the SORT2, their values are 3.47 m/s\textsuperscript{2} and 4.36 m/s\textsuperscript{2} as shown in the graph, respectively.

![Figure 6. Diesel bus acceleration on SORT2 (left) and BKK2 (right).](image)

Further comparison of engine power is exhibited in figure 7. It is evident that on BKK2 driving cycle the bus engine needs c.a. 33.3% more maximum power than on the SORT2. Its maximum value is reached 194.77 kW in 727 s of the test.

![Figure 7. Diesel bus engine power on SORT2 (left) and BKK2 (right).](image)

The emission of carbon dioxide depends on the fuel consumed by the drive unit. In the case of Diesel, the fuel consumption in SORT2 is approximately 69.50% of fuel consumption in BKK2. The results are presented in figure 8.
4.2. Applying Hydrogen
In this phase of work, the hydrogen fuel has been applied based on the Diesel engine model configuration. The fuel properties including engine maps have been implemented. In addition, the weight-increase due to the larger hydrogen tank has been ignored.

The diagram on dimensionless specific fuel consumption between Diesel bus and hydrogen bus running on the BKK2 driving cycle is shown in figure 9. It is evident that the specific fuel consumption in different fuel on the same bus configuration has also the similar characteristic, however, the value between these two types of fuel are significantly different.

Conclusion
In order to design, evaluate or develop the new vehicle and drive systems, the simulation method would be a bright solution because the consumption of costs and time can be economized. The vehicle specification and driving mode can be varied during the simulation. In addition, the components, i.e. gross weight, engine configuration, gear-shifting strategy, gear ratio, tire radius, etc., can be also modeled, tested and optimized in a short period of time.

The results for different driving cycles clearly confirm that the SORT – Standardized On-Road Test Cycles could not well represent the complicated traffic condition in Bangkok. Regarding the acceleration together with the CO₂ results, it can be concluded that the steady or cruising speed-driving pattern are cleaner than acceleration and deceleration pattern. It also corresponds to the former study that the Bangkok driving cycle causes a bigger quantity on both exhaust emissions and fuel consumption.

The combustion between hydrogen and air can also produce oxides of nitrogen (NOx) as a product. However, with its lower final combustion temperature, its amount emitted in the exhaust is significantly
reduced. Moreover, the produced oxides of carbon, i.e. CO, CO$_2$, are not available, since carbon is not a component as in conventional fossil fuel. Based on the emission aspect, hydrogen is considered as the forthcoming fuel especially for the public transportation in cities, however, the pre-mature ignition and its storage are the big issues, which have to be solved in the near future as well.

**Acknowledgments**

Authors would like to thank Mr. Jedchan Velasquez for the simulation support. This research is accomplished under collaboration of the DAAD "Praxispartnerschaften zwischen Hochschulen und Unternehmen in Deutschland und in Entwicklungsländern" program between the BTU C-S and KMUTNB. The AVL-CRUISE software is also supported by the AVL List GmbH under the "AVL AST UNIVERSITY PARTNERSHIP PROGRAM". Several results are financially supported in the frame of the project by AiF Projekt GmbH.

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