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MODELS AND SIMULATIONS OF TRANSMISSION OF HYBRID AND ELECTRIC VEHICLES

Milan Bukvić[1], Živojin Petrović, Blaža Stojanović, Saša Milojević

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ABSTRACT: All systems in the construction of vehicles can be grouped logically, either as a structural system or control system. Structural systems consist of one or more sub-systems, as well as the optional files that define the system. Structural systems do not contain models, but only describe the structure, connecting systems and subsystems. The control systems consist of a model which defines the behaviour of the system and all the files needed to support or calculation of the output value of the system. Models and control systems include mathematical equations that describe the functions of the system or subsystem. Both of these types of systems are arranged in a hierarchical manner in order to define a vehicle that will be simulated. To avoid confusion, the best solution is to replicate the composition of the actual system, as far as possible. For example, small controllers should be grouped with the components they control, at various hierarchical levels wherever possible. Also, only systems that really are in the vehicle should be represented, in other words, there is no need for the unused components or space controllers. In addition to simplifying the construction, this concept will allow easy transfer between users and the system will be fully supported hardware and software, while ensuring effective control of the prototype, according to the needs.

KEY WORDS: hybrid and electric vehicles (HEV), transmissions, model simulation, simulation, software

MODELI I SIMULACIJE TRANSMISIJA HIBRIDNIH I ELEKTRIČNIH VOZILA

REZIME: Svi sistemi u konstrukciji vozila mogu se grupisati logično, bilo kao konstruktivni sistem ili sistem kontrole. Strukturni sistemi se sastoje od jednog ili više podsistema, kao i odgovarajuće datoteke koje definišu sistem. Konstrukcijski sistemi ne sadrže modele, ali opisuju samo strukturu, povezivanje sistema i podsistema. Sistemi kontrole se sastoje od modela koji definiše ponašanje sistema i sve datoteke potrebne za podršku ili proračun izlaznih vrednosti sistema. Modeli i kontrolni sistemi uključuju matematičke jednačine koje opisuju funkcije sistema ili podsistema. Obe ove vrste sistema su raspoređene u hijerarhijskom smislu u cilju definisanja vozila koje će se simulirati. Da bi se izbegla konfuzija, najbolje rešenje je da se oponaša kompozicija stvarnih sistema, koliko je to moguće. Na primer, male kontrolore treba grupisati sa komponentama koje kontrolišu, na različitim hijerarhijskim nivoima gde god je to moguće. Takođe, samo sistemi koji su zaista u vozilu treba da budu modelirani, drugim rečima, nema potrebe za komponentama koje se ne koriste ili za prostorom za kontrolere. Pored pojednostavljenja izrade, ovaj koncept će omogućiti jednostavan prenos između korisnika i sistem će biti u potpunosti podržan hardverom i softverom, istovremeno osiguravajući efektivnu kontrolu nad prototipom, u skladu sa potrebama.

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KLJUČNE REČI: hibridna i električna vozila (HEV), transmisije, model simulacije, simulacija, softver

MODELS AND SIMULATIONS OF TRANSMISSION OF HYBRID AND ELECTRIC VEHICLES

Milan Bukvić [1], Živojin Petrović [2], Blaža Stojanović [3], Saša Milojević [4]

1. INTRODUCTION

In addition to the variety of HEV topologies, HEV powertrains make use of more components than conventional vehicles [1]; particularly electric components such as energy storage devices, controllers, power electronics and electric machines. These additional components dynamically interact with the conventional mechanical components. Therefore there are a much larger number of parameters and combinations which need to be analysed in order to optimise a particular powertrain design. Analysis of such a system is difficult due to its multidisciplinary nature and testing through prototyping can be both costly and time consuming [2]. The availability and use of computer modelling and simulation tools is a key component in studying the complexities of HEV powertrain design [3].

Traditionally, many computer simulation models are built during the design life-cycle of a new vehicle. Different models are built for different purposes such as models to study fuel economy, models for controller evaluation, models for optimization or models for design exploration [2]. This leads to the creation of many models of the same system which all need to be maintained and managed.

For conventional vehicle design, even though the complexity of modern vehicles is increasing, many of the systems being modelled are based on well-known and understood previous designs and architectures [4, 5].

The availability of existing validated models and expert knowledge of the systems involved is an essential part of the initial development of new designs. With HEVs, however, there is a much smaller and limited amount of prior knowledge and many designs are still at a conceptual phase, meaning that many changes may still occur to the system.

The primary reasons for looking at new ways of developing HEV powertrains are [6]:

- reducing development time
- exploring new designs
- increased complexity
- higher expectations for reliability and
- reducing the amount of prototype testing needed.

In the software development domain, it has been shown that the time and effort required to build a system increases exponentially with the size and complexity of the

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design [7]. It can be argued that the same applies to modelling. The use of traditional modelling methods for exploring different HEV design options, risks reaching its limitations as far as managing the complexity of the design space is concerned [8]. Further, it will be necessary to provide sufficient flexibility to the designer to explore many possibilities in as short a time as possible. This leads to a model maintenance and management problem when considering the number of models that such a process will generate and the potential number of different users that would be involved.

2. BASIC CONCEPTS AND CLASSIFICATION OF HYBRID AND ELECTRIC VEHICLES

Hybrid vehicles have been based on two sources of energy - aggregate energy conversion (combustion engine or fuel cell) and the aggregate accumulation of energy produced (batteries or ultracapacitors). Complete drive system comprising: IC (internal combustion) engine, electric generator, electric motor, power converter and the battery pack. The point of the existence of hybrid vehicles is the fact that these vehicles have no problems with the radius of movement, because they use chemical fuel to power combustion engines at the same time are environmentally cleaner and more efficient compared to conventional vehicles, because they use the benefits of electric drive systems. Power installed thermal and electrical machines is greater than the required traction power, and the system itself is much more complex than electric vehicles and conventional vehicles with internal combustion engines [9].

There are two basic configurations of hybrid vehicles: serial and parallel. In addition there is a serial - parallel configuration of a hybrid vehicle, resulting from efforts to consolidate good characteristics and serial and parallel configurations of hybrid vehicles [9].

In serial hybrid vehicle internal combustion engine runs a special generator that supplies the electric traction motor with energy and supplement batteries. Internal combustion engine has been used in the optimal mode, a speed control has been achieved by an electric motor. The existence of the battery and the electric motor provides a reversible (engine) braking, thus increasing vehicle efficiency.

The main features of the serial hybrid vehicles are [9]:

- use a larger battery
- use charging batteries while driving
- batteries can be upgraded and when the vehicle is not in use (external)
- optimize the operation of separating the work of both the speed of the motor vehicle
- electric motor does not idle, which reduces emissions
- does not require a complex transmission vehicles
- use high power IC engine.

Parallel hybrid vehicles are designed so that the wheels driven by the IC engine and an electric motor/generator. IC engine with the vehicle runs in optimal mode, where the electric machine operates as a generator and supplements the battery, when the movement of the lower power output of IC engines, and when you need more power, then electric machine operates as a motor using energy from battery. The point of introducing this concept of hybrid vehicles can be found in the fact that the installed capacity of electric machines smaller, reducing the weight of the vehicle. Instead of separate motors and generators, as used herein is only one machine, whose power is less than the power of the traction motor with the serial vehicle size.

The main features of parallel hybrid vehicles are [9]:

• electric motor and IC engine are directly connected to the wheels

• use less battery

• has the ability to charge the battery when the engine is not working IC engine

• faster speeds

• electric motor has a neutral

• installation of components in the vehicle is less flexible

• use medium power IC engine.

There are electric motor and generator to the serial - parallel hybrid vehicle, but with lower power than the pure serial hybrid concept vehicle. According to the needs it is possible to drive only IC engine runs generator or with an electric motor drives the wheels and the generator idle.

The main features of serial - parallel hybrid vehicles are [9]:

• use battery of medium size

• has the rechargeable battery when IC engine works, and when it not works

• faster speeds

• electric motor does not idle

• installation of components in the vehicle is less flexible

• use high power IC engine.

Fully electric vehicles are vehicles for their movements using electrical energy stored in batteries or the battery is obtained from a fuel cell. The drive of the vehicle consists of the following subsystems:

• batteries

• inverter power electronics

• electric motor and

• most often, the mechanical force transmission system.

The electric motor is the only electric machine that has been installed in the towing vehicle subsystem and its strength is equal to the force required to tow.

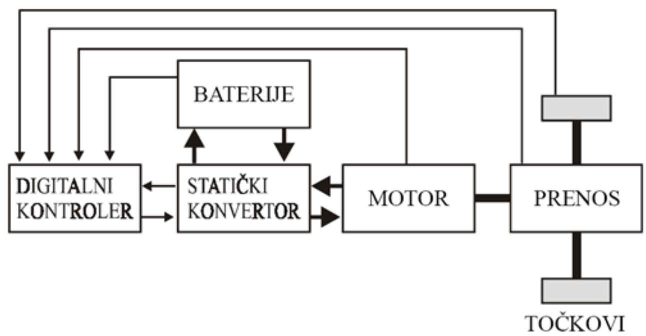

Figure 1 Schematic representation of an electric vehicle [9]

In the above figure are thin lines displayed information and control connections, while thick lines indicate the energy links in the system. The arrows indicate the direction of movement of information, or electricity. Such vehicles do not emit any exhaust gases and are classified as vehicles with zero emissions. This means that they are environmentally friendly assuming that the careful handling batteries, since certain types of batteries contain highly toxic substances. Lacks of electric vehicles are their relatively poor performance. This primarily applies to a small radius of movement, the relatively poor acceleration and low final speed due to the high weight of the battery. In the case of a large number of vehicles, the vast mass of the battery weight distribution and a bad condition and bad behaviour of the vehicle when cornering.

3. FUNDAMENTALS OF VEHICLE SYSTEMS MODELLING

It is important to define the common terms used in modelling. The following definitions have been related to HEV modelling [11]:

1. System: The object or objects we wish to study. In the context of this paper, the system will be an electric or HEV.
2. Experiment: The act of obtaining information from a controllable and observable system by intelligently varying system inputs and observing system outputs.
3. Model: A surrogate for a real system upon which experiments can be conducted to gain insight about the real system. The types of experiments that can be validly applied to a given model are typically limited. Thus, different models are typically required for the same target system to conduct all of the experiments one wishes to conduct. Although there are various types of models (e.g., scale models used in wind tunnels), in this paper, we will mainly discuss about physics-based mathematical models.
4. Simulation: An experiment performed on a model.
5. Modelling: The act of creating a model that sufficiently represents a target system for the purpose of simulating that model with specific predetermined experiments.
6. Simulator: A computer program capable of performing a simulation. These programs often include functionality for the construction of models and can often be used in conjunction with advanced statistical engines to run trade studies, design of experiments, Monte Carlo routines, and other routines for robust design.

4. MODELLING CONCEPTS

Powertrain models are traditionally classified as one of the following causal types [2], [12], [13], [14]:

1. Forward facing - Models of this type follow a "cause-effect" calculation process in the direction of the driving vehicles physical power flow. Starting with a demand set point, usually in the form of an accelerator signal, torque demands for each subsystem can be calculated in a forward direction until the resultant force at the wheel is found and from this the vehicle speed. Additionally driver models can incorporate logic for steering commands, gear changes and clutch actuation. These

models are more representative of the real world system, making use of measurable variables such as torque inputs, brake and accelerator demands. This makes them well suited to controller development and testing, in particular real-time control strategies [2]. Also it is possible to include transient subsystem models for studying the system dynamics [15].

2. Backward facing - These models calculate in the opposite direction to the power flow. In other words, calculations are performed backwards from the wheels to the power sources in an "effect-cause" manner. By imposing a drivecycle, tractive effort at the wheels can be calculated and continuing to move backward through each powertrain subsystem until the energy required from the input sources can be determined. These models are generally computationally faster than forward facing models and are therefore useful for architectural studies and optimization routines that require many iterations of relatively longer cycle times [2, 17]. Steady-state efficiency and lookup tables are generally used to account for subsystem losses and hence these models tend not to take dynamic effects into account [16].
3. Combined backward/forward – It is possible to combine both approaches by iterating backward simulations to achieve a target setpoint [14]. This approach requires a forward and backward model for each component. First a back-wards simulation determines component efficiencies and operating limits, and then the forward facing models are used for a forwards simulation using the previously calculated efficiency and limit values [18]. The ADVISOR simulation software uses this "hybrid" approach, more details on the way this is implemented are given in [16]. Using this type of model allows for faster simulation than the standard forward facing approach since it is possible to make use of larger time-steps and lower orders of integration [16, 19]. Further, designing control algorithms suitable for usage on the real-world system is made difficult by this modelling method [20].

5. HEV MODELLING USING ADVISOR

ADvanced VehIcle SimulatOR (ADVISOR) is a modelling and simulation tool developed by U.S. National Renew-able Energy Laboratory (NREL) [21], [22]. It can be used for the analysis of performance, fuel economy, and emissions of conventional, electric, hybrid electric, and fuel cell vehicles. The backbone of the ADVISOR model is the Simulink block diagram shown in Fig. 2, for a parallel HEV as an example.

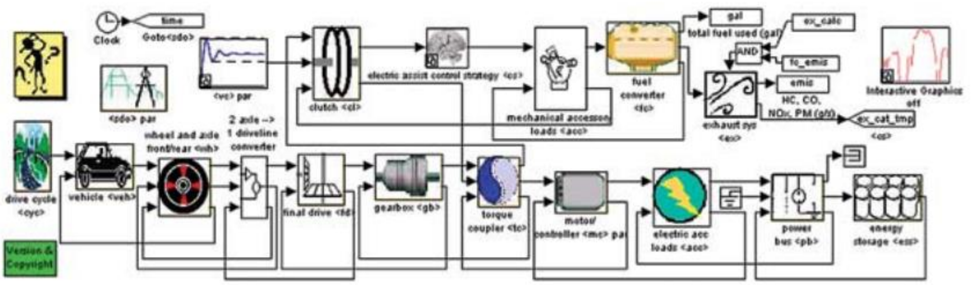

Figure 2 Block diagram of parallel HEV in ADVISOR [21]

Each subsystem (block) of the block diagram has a Matlab file (m-file) associated with it, which defines the parameters of that particular subsystem. The user can alter both the model inside the block as well as the m-files associated with the block to suit the modelling needs. For example, the user may need a more precise model for the electric motor subsystem. A different model can replace the existing model as long as the inputs and the outputs are the same. On the other hand, the user may leave the model intact and only change the m-file associated with the block diagram. ADVISOR provides modelling flexibility for a user.

The program also allows for the linear scaling of components. For an IC engine, this means linear scaling of the torque to provide the required maximum power. This type of scaling is valid only in the neighbourhood near the actual parameter where the efficiency map for a slightly larger or smaller component would not change drastically.

In the latest version of ADVISOR, the functionality of the software was improved by allowing links to other software packages such as Ansoft Simplorer [23] and Synopsys Sabre [24]. These powerful software package sallow for a more detailed look at the electric systems of the vehicle.

6. HEV MODELLING USING PSAT

The Powertrain System Analysis Toolkit (PSAT) is a state-of-the-art flexible simulation software developed by Argonne National Laboratory and sponsored by the U.S. Department of Energy (DOE) [25]. PSAT is modelled in a MATLAB/Simulink environment and is set up with a graphical user interface (GUI) written in C++, which make sit user friendly and easy to use. Being a forward-looking model, PSAT allows users to simulate more than 200 pre-defined configurations, including conventional, pure electric, fuel cell, and hybrids (parallel, series, power split, series-parallel). The large library of component data enables users to simulate light, medium, and heavy-duty vehicles.

The level of details in component models can be flexible, e.g., a lookup table model or high-fidelity dynamic model can be used for a component, depending on the user's simulation requirements. To maintain modularity, every model must have the same number of input and output parameters. The use of quasi-steady models and control strategies including the propelling, braking, and hifting strategies in PSAT sets it apart from other steady-state simulation tools like ADVISOR. This feature makes PSAT predict fuel economy and performance of a vehicle more accurately. Its modelling accuracy has been validated against the Ford P2000 and Toyota Prius. PSAT is designed to co simulate with other environments and is capable of running optimization routines. Hardware-in-the-loop (HIL) testing is made possible in PSAT with the help of PSAT-PRO, a control code to support the component and vehicle control [25].

As an application example, PSAT is used to optimize a parallel HEV for maximum fuel economy on a composite driving cycle. Four global algorithms, Divided RECTangle (DIRECT), Simulated Annealing (SA), Genetic Algorithm (GA), and Particle swarm optimization (PSO) are used in the model-based design optimization [26]. The vehicle model ISG (available in the PSAT model library) has been chosen for this optimization study. This vehicle is a two-wheel-drive starter-alternator parallel configuration with manual transmission. The basic configuration of the parallel HEV used for simulation is illustrated in Fig. 3.

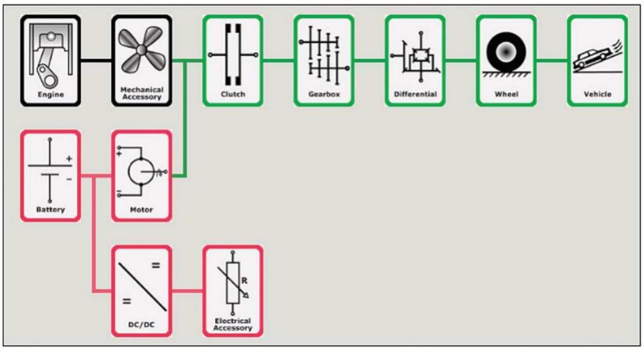

Figure 3 Configuration of selected HEV in PSAT [26]

The driving cycle is composed of city driving represented by FTP-75 (Federal Test Procedure) and the highway driving represented by HWFET (Highway Fuel Economy Test).

7. PHYSICS-BASED MODELLING

PSAT and ADVISOR are based on experiential models in the form of look-up tables and efficiency maps. The accuracy of these tools may not be good enough for vehicles operating under extreme conditions. For detailed dynamic modelling and simulation of HEV system, physics-based modelling is needed. VTB, PSIM, Simplorer, V-Elph are good examples of physics-based modelling tools, where the state variables of a component or subsystem are modelled according to the physical laws representing the underlying principles. The resulting model is a function of device parameters, physical constants, and variables. Such physics-based models can facilitate high fidelity simulations for dynamics at different time scales and also controller development.

The most useable technique of the physics-based modelling is Resistive Companion Form (RCF) [27, 28]. The RCF method originates from electrical engineering but is suitable for multi-disciplinary modelling applications such as hybrid powertrain.

Using the Resistive Companion Form modelling technique, we can obtain high-fidelity physics-based models of each component in modular format. These models can be seamlessly integrated to build a system simulation model suitable for design. Just as a physical device is connected to other devices to form a system, the device can be modelled as a block with a number of terminals through which it can be interconnected to other component models, as shown in Fig. 4. Each terminal has an associated across and a through variable. If the terminal is electrical, these variables are the terminal voltage with respect to a common reference and the electrical current flowing into the terminal, respectively. Notice that the concept of across and through variables in RCF is similar to the effort/flow concepts used in ADVISOR and PSAT.

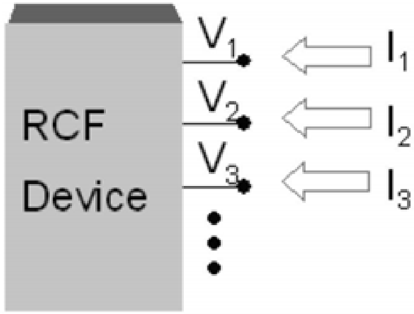

Figure 4 Physics-based RCF modelling technique [29]

After all the powertrain components are modelled in RCF, they can be integrated into one set of algebraic equations by applying the connectivity constraints between neighbouring modular components, which can then be solved to get system state variables.

4. CONCLUSIONS

With the advent of powerful computing, development of computational methods, and advances in software-in-the-loop (SIL) and hardware-in-the-loop (HIL) modelling and simulations, it is now possible to study numerous iterations of different designs with the combinations of different components and different topology configurations. HIL is becoming increasingly important for rapid prototyping and development of control system for new vehicles.

With the ever more stringent constraints on energy resources and environmental concerns, HEV will attract more interest from the automotive industry and the consumer. Although the market share is still insignificant today, it can be predicted that HEV will gradually gain popularity in the market due to the superior fuel economy and vehicle performance. Modelling and simulation will play important roles in the success of HEV design and development.

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A MONITORING DEVICE OF FORKLIFT'S STABILITY TRIANGLE

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ABSTRACT: In most branches of industry forklifts are used for lifting and handling various shaped loads. These machines classified as lifting trucks vary in size and might be equipped with various attachments to enable work as universal lifting cranes. However, the main issue related to their usage is their critical stability that causes a lot of accidents resulting in human and material losses. These machines have been gone through years under development so as to render them more and more stable; the present research is a trial and a step forward towards better passive stability of forklifts. This research aims at enhancing the forklift longitudinal stability by monitoring the status of the so called forklift "stability triangle", and at keeping the forklift operators working within stable range of load and speed. A new monitoring device which locates the forklifts center of gravity (C.G.) during its forward movement (uphill and downhill) instantaneously displays the C.G. point together with the stability triangle. In addition, a warning red light will be lightened in case the C.G. point tends to get out of the stability triangle or, in other words, in case of dangerous situations that might lead to forklift tipping-over.

KEY WORDS: forklifts stability, stability triangle, monitor, safety

UREĐAJ ZA PRAĆENJE STABILNOSTI TROUGLA VILJUŠKARA

REZIME: U većini grana industrije viljuškari se koriste za podizanje i rukovanje teretima različitih oblika. Ove mašine se klasifikuju kao vozila za dizanje tereta različitih veličina i mogu biti opremljena uređajima kako bi mogli da se koriste kao univerzalni kranovi. Međutim, glavni problem sa njihovim korišćenjem je njihova kritična stabilnost koja izaziva mnogo nesreća dovodeći do ljudskih i materijalnih gubitaka. Ove mašine su prošle godine razvoja, kako bi se učinile što stabilnije. Prikazano istraživanje je pokušaj da se poboljša pasivna stabilnost viljuškara. Ovo istraživanje ima za cilj poboljšanje podužne stabilnosti viljuškara i praćenjem položaja takozvanog trougla stabilnosti viljuškara, a u cilju zadržavanja položaja operatora viljuškara u stabilnom opsegu opterećenja i brzine. Novi uređaj za praćenje locira centar masa (CG) viljuškara tokom njegovog kretanja napred (uzbrdo i nizbrdo) i trenutno prikazuje tačku CG zajedno sa trouglom stabilnosti. Pored toga kao upozorenje crvena lampica svetleće u slučaju da tačka CG teži da izađe iz trougla stabilnosti, ili drugim rečima u slučaju opasnih situacija koje bi mogle dovesti do prevrtanja viljuškara.

KLJUČNE REČI: stabilnost viljuškara, trougao stabilnosti, kontrolni uređaj, bezbednost

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A MONITORING DEVICE OF FORKLIFT'S STABILITY TRIANGLE

Mohamed Ali Emam[1], Mostafa Marzouk[2], Say Shaaban[3]

1. INTRODUCTION

Forklifts are actually classified into eleven (11) categories, from hand pallet trucks to counterbalanced trucks and including more than 50 different types. Each one of them can be ordered with different capacity and loading range to meet different needs. The loading capacity is from 0.75 t - 8.5 t. The maximum lifting height can be up to 14.8 m [1]. As a result of various uses of hundreds of thousands of forklifts worldwide and due to forklift instability, a large number of accidents occur that lead to the loss of loads, damage of forklifts and injury to operators each year. The need for solving this problem of forklift stability occurs mainly in a number of different circumstances, such as: when the forklift is moving on uneven surfaces, while turning on a tight radius, accelerating and braking, at the beginning and the end of lifting or lowering, maneuvering the forklift, when lifting a tall stack loaded on the forks, when unloading, when the angle of the chassis of the forklift to the load is a maximum, when the forklift is angled on an adverse camber and when the forklift is braking suddenly from high speed [2].“OHSA estimates forklifts cause about 85 fatal accidents per year, 34,000 accidents result in serious injury and 61,800 are classified as non-serious” [3-4]. One of the most important causes of such accidents refer to the forklift design which due to nature of work should have a narrow track and a variable CG [4].

2. STABILITY TRIANGLE

A stability triangle is determined by three points (A, B, C) as shown in Figure 1 (a). The point “A” is the midpoint of the rear axle and the two other points “B” and “C” is the two front tires mid points located at the front axle. This brings us to the imaginary stability triangle. In order to maintain a stable forklift, its center of gravity must be kept within the stability triangle area. The most stable area while handling a load is close to the base of the forklift. If the load you are carrying moves too far forward from the forklift's base, it will more than likely tip forward, Figure 1 (b) [5].

Forklift dimensions such as: wheel base, overall width at front axle, weight distribution between axles and height of load lifting are factors that affect its stability. The forklift stability should be investigated in both longitudinal and lateral directions as the operating conditions such as: the speed of cornering, the speeding up and braking rates, and the lifting rates and heights affect the forklift stability in these directions.

Investigation of forklift stability can be done on a tilt table test rig that allows the determination of the critical level of forklift instability, as Figure 2 shows. From the figure, it

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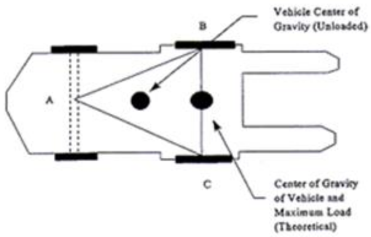
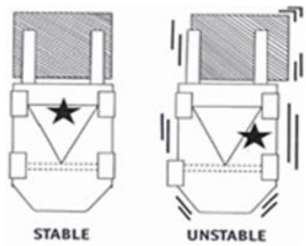
can be concluded that the forklift will be stable in case the vertical line passes through the point of combined C.G. of the forklift and the load falls within the triangle of stability [6].



(a) [5]



(b) [6]

Figure 1 Triangle of stability of the forklift

The longitudinal stability of the forklift is achieved by its rear counterbalance weight but in many situations (dynamic and static) the stabilizing moment it creates is less than the destabilizing moment created by the load lifted and in such cases it will tip over [6]. The forklift's stability system consists of 3 points of contact with ground for a three wheeled forklift or 4 points for a four wheeled forklift as seen from Figure 3. When loading the forklift to its maximum capacity, the combined C.G. shifts to the front axle and the stability will be endangered if it falls outside the stability triangle. Most of the counterbalanced forklifts are three-point suspended. This is true even if it has four wheels. This three-point support makes the so-called stability triangle, Figure 4 [6].

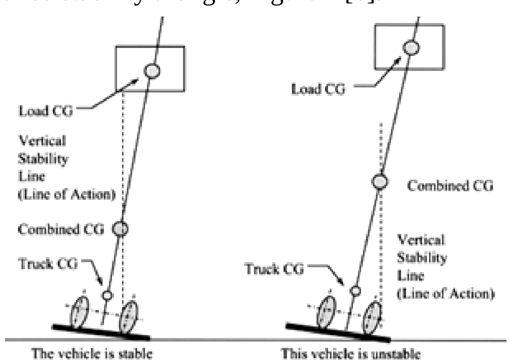


Figure 2 The vehicle in the different situations (stable and unstable) [6]

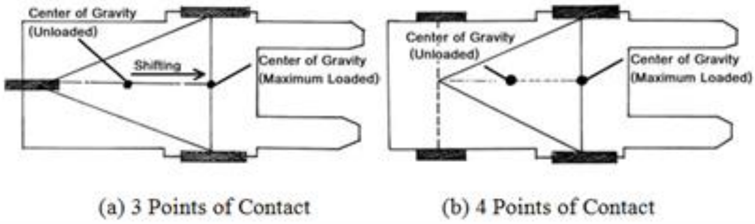


Figure 3 Center of gravity horizontal shifting illustrations [1]

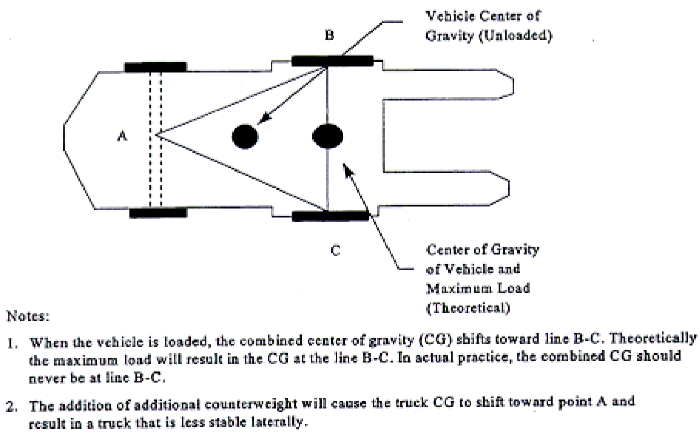


Figure 4 Three-point support forms the stability triangle [6]

To enhance the forklift stability, Toyota Co. introduced an active safety system named SAS - System of Active Stability in 1999, which aimed at protection of operators and goods as well as the truck itself [7].

The SAS is an active safety system that reduces the risk of accidents. The SAS is a computer-controlled system having 10 sensors, 3 actuators and one controller. The system sensors monitor the forklift operations and sends electric signals to the controller which outputs electric signals to the actuators so as to take corrective actions for ensuring forklift stability, as Figure 5 shows [8-10].

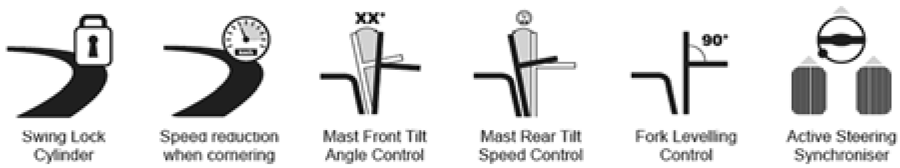


Figure 5 SAS features [8-10]

3. EXPERIMENTAL WORK (STABILITY TRIANGLE MONITOR)

A new proposal of a monitor which determines the load weight, the road inclination angle and the position of forklift centre of gravity in the stability triangle is shown in Figure 6. Figure 7 shows a layout of the stability monitoring device.

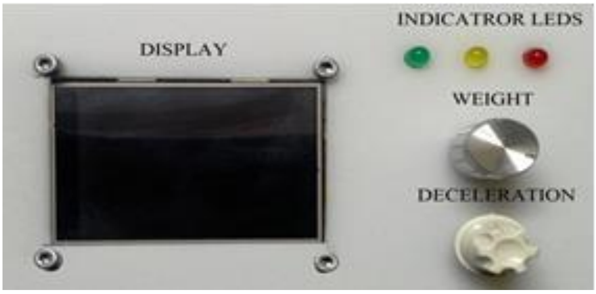


Figure 6 Stability monitoring device

The stability monitoring device consists of the following main parts:

- Arduino Mega 2560
- Gyroscope
- Light emitting diodes
- Two Potentiometers
- Weight button
- Deceleration button
- Display
- Computer.

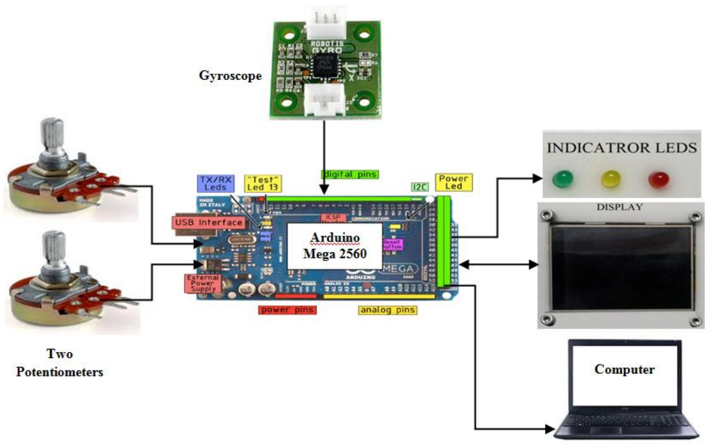


Figure 6 Stability monitoring device layout

Table 1 describes some technical specifications of the forklift.

Table 1 Forklift data

Truck mass, kg	4840
Load capacity, kg	3500
Overall width, m	1.29
Truck wheelbase, m	1.7
C.G. position from front axle, m	1.12

The Arduino processes the input data determined by the weight button, deceleration button and gyroscope to locate the forklift center of gravity position (C.G.) relative to the stability triangle on the display screen and indicates it by using a diode illumination. The output data are also saved in the processor memory. Figure 8 shows this process flow chart.

The Arduino Mega 2560 (Figure 9) is a microcontroller board that uses a ATmega2560 and has 14 pins used for Pulse Width Modulation output, 16 pins for analog inputs, 4 hardware serial ports, a 16 MHz oscillator, a USB connection, a power jack, an ICSP header and a reset button. The Mega is compatible with most shields designed for the Arduino Duemilanove or Diecimila [11-13].

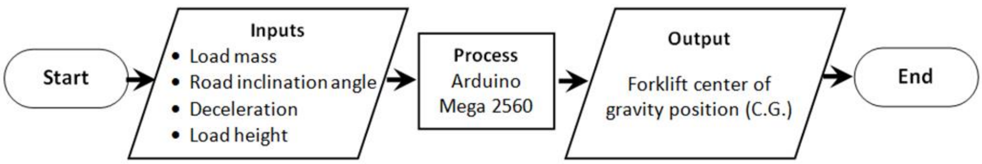


Figure 8 Flowchart for forklift C.G. determination

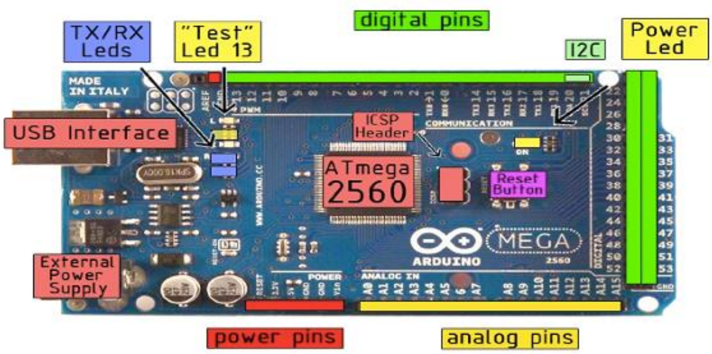


Figure 9 Arduino Mega 2560 board [13]

The gyroscope is used for sensing an inclination of the road. The sensor is installed inside the device. When the device rotates around the x-axle, the angle will be changed which refers to road inclination angle [14].

The potentiometer is variable electric resistance that controls the rate at which an LED blinks. It is connected with Arduino board and by turning the potentiometer knob it changes the electric resistance on wiper's either sides and accordingly changes giving a different analog input. When knob is turned all its way in one direction, zero volts go to the pin, and reads zero. As shaft is turned all its way in the reverse direction, 5 volts go to the pin and reads 1023. For in between turns of the pin, a number between 0 and 1023, proportional to the amount of voltage is being applied to the pin [15].

The Light Emitting Diode Indicators (LEDs) are the indicators of a stability triangle zone. When the green LED is on, that means that the situation is still in the stability triangle zone. When the yellow LED is on that means that the situation starts to be close to the danger zone of the triangle and the driver must attend. When the red LED is on that means that the situation starts to be outside the stability triangle zone and becomes dangerous, so the driver must stop the forklift operation.

The weight button is a simulator of a load sensor, which is connected with a potentiometer. Turning the button to right or left will increase the input weight or decrease it according to the product weight and the input weight it will change automatically and appear on the display. The range of the weights in this case is from 0 to 6000 kg. The range can be adjusted by Arduino 1.0 programs.

The deceleration button is a simulator of a deceleration sensor that is conneced with a potentiometer. Turning the button to right or left will increase the input deceleration or decrease it according to a specified range of brake force and the input deceleration will change automatically and appear on the display. The range of it is from 0 to 8 m/s2. The range can be adjusted by Arduino 1.0 programs.

The screen shows the stability triangle and the position of the forklift center of gravity. The position changes according to the parameters (input weight, road inclination angle, input deceleration and load center). This display is a touch screen and when putting the finger on it a keypad will appear. The keypad is used to enter the load center (see Figure 10).

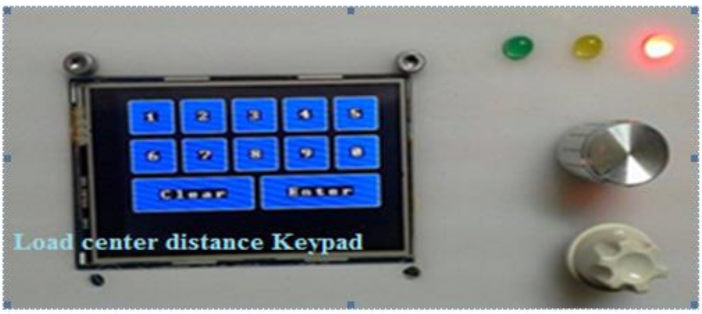


Figure 10 Keypad

4. RESULTS AND DISCUSSIONS

4.1 Effect of load mass on forklift center of gravity position (C.G.)

As shown in Figure 11, the center of gravity moves forward to the front axle with increasing the load mass. Analyzed data on effect of load mass on forklift center of gravity position are recorded in Table 2.

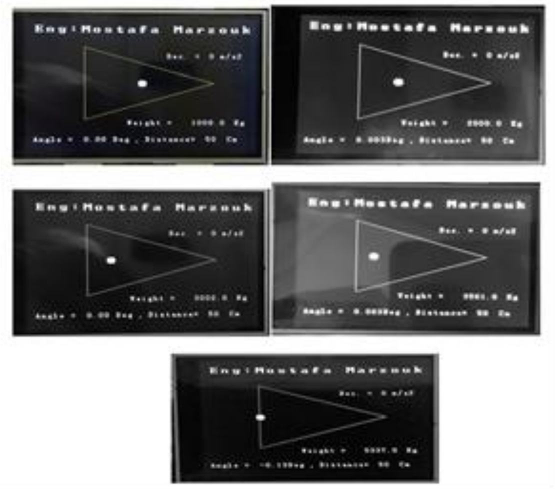


Figure 11 Forklift C.G. position at different load mass

Table 2 Analyzed data on effect of load mass on forklift center of gravity position

Load Mass (kg)	Rear reaction (N)	C.G. position from front axle (m)
1000	25916	0.754
2000	19945	0.495
3000	13975	0.300
3500	11200	0.228
5340	Zero	Zero

Where: Load centre = 0.5 m, Angle = 0^o, and Deceleration = 0 m/s^2.

4.2 Effect of load center on forklift center of gravity position

Figure 12 shows the position of forklift centre of gravity according to the load centre such that the C.G is directly proportional with the product load centre. Analysis of data for effect of load centre on forklift centre of gravity position recorded in Table 3. The load centre can be changed by touching the display, the keypad will appear, and then the distance is entered in cm.

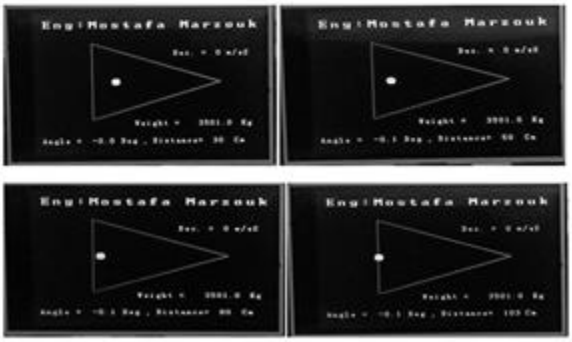


Figure 12 Forklift C.G. position at different load center

Table 3 Analysis of data for effect of load center on forklift center of gravity position

Load centre (m)	Rear reaction (N)	C.G. position from front axle (m)
0.3	15107	0.3
0.5	11200	0.228
0.8	4813	0.09
1.034	Zero	Zero

Where: Load Mass = 3500 kg, Angle = 0^o, and Deceleration = 0 m/s^2.

4.3 Effect of deceleration on forklift center of gravity position

Figure 13 shows the effect of deceleration on the position of forklift center of gravity with constant product load mass. Analysis of data for effect of deceleration on forklift center of gravity position is presented in Table 4. By turning the deceleration button right or left, the deceleration increases or decreases and the variation will be automatically displayed.

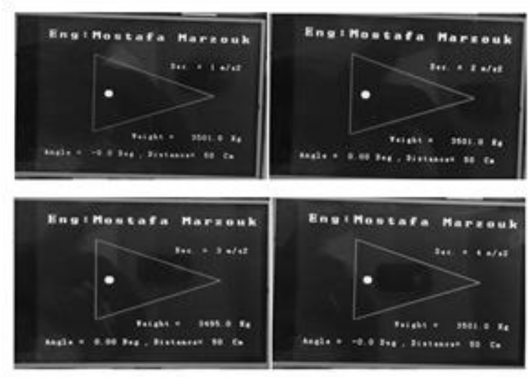


Figure 13 Forklift C.G. position at different deceleration

Table 4 Analysis of data for effect of deceleration on forklift center of gravity position

Deceleration (m/s^2)	Rear reaction (N)	C.G. position from front axle (m)
0.5	9865	0.213
1	8742	0.208
1.5	7617	0.203
2	6494	0.198

Where: Load Mass = 3500 kg, Angle = 0^o, and Load centre = 0.5m.

4.4 Effect of road inclination angle on forklift center of gravity position

Figure 14 shows the variation in the forklift center of gravity position depending on road inclination. Analysis of data for effect of road inclination angle on forklift center of gravity position is presented in Table 5. By turning the device, the angle will be changed, and it will automatically appear on the display.

Figure 14 Forklift C.G. position at different road inclination angles

Table 5 Analysis of data for effect of road inclination angle on forklift center of gravity

Angle of inclination (°)	Front reaction (N)	C.G. position from front axle (m)
5	15730	0.22
7	15383	0.228
9	15018	0.231
11	14634	0.236

Where: Load Mass = 3500 kg, Deceleration= 0m/s^2, and Load centre = 0.5m.

4.5 Effect of different load mass at inclined road on the forklift center of gravity position

The effect of the load mass at the inclined road is shown in the Figure 15. Analysis of data for effect of different load mass at inclined road on the forklift center of gravity position is presented in Table 6.

Figure 15 Forklift C.G. position at different load mass on inclination road

Table 6 Analysis of data for effect of different load mass at inclined road on the forklift center of gravity position

Load Mass (kg)	Rear reaction (N)	C.G. position from front axle (m)
1000	28871	0.77
2000	24467	0.52
3500	17862	0.26

Where: Angle = 0^o, Deceleration= $0 m/s^2$, and Load centre = 0.5m.

4.6 Effect of deceleration at inclined road on forklift center of gravity position

Effect of deceleration at the inclined road on position of center of gravity is shown in Figure 16. Analysis of data for effect of deceleration at inclined road on forklift center of gravity position is presented in Table 7.

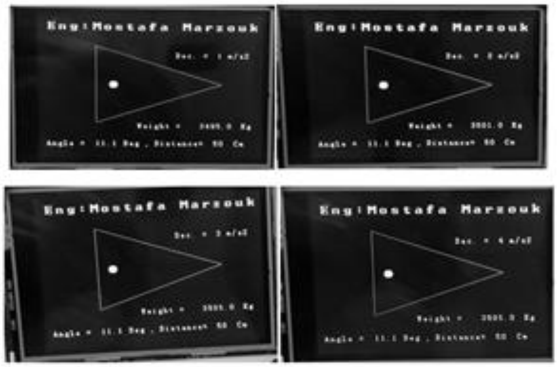


Figure 16 Forklift C.G. position at different decelerations in inclination road

Table 7 Analysis of data for effect of deceleration at inclined road on forklift center of gravity position

Deceleration (m/s^2)	Rear reaction (N)	C.G. position from front axle (m)
0.5	13813	0.28
1	12709	0.26
1.5	11605	0.24
2	10501	0.21

Where: Angle = 11^o, Load Mass= 3500kg, and Load centre = 0m.

5. CONCLUSIONS

The present research investigates how to support and enhance the field of forklift stability throughout the study of forklift longitudinal stability movement and determination of what is known as the Triangle of Equilibrium (Stability triangle). A stability safety device that is capable of monitoring the forklift stability has been designed, fabricated and tested. This monitor enables locating the center position of gravity of forklifts when carrying different loads and longitudinally moving uphill and downhill.

The safety device flashes a warning light to enable the forklift operator to get out of situations with probable instability dangers. This research can be extended to include total or partial integration of this software with hardware so analysis of loads on forklift axles are carried out and automated limits on acceleration and speed can be energized. This would ensure the safety of the operator without much dexterity on his part, which comes with experience.

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ECONOMIC ANALYSIS OF APPLICATION OF DIFFERENT DRIVE TRAINS IN VEHICLES

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UDC: 629.331.1;629.3.026.12;330.123.72

DOI: 10.24874/mvm.2017.43.02.03

ABSTRACT: Vehicles are considered to be the biggest polluters of the environment. An alternative to conventional vehicles are hybrid and electric vehicles. Despite the good qualities of these vehicles, they can rarely be seen on the roads. In this paper, economic analysis is performed in order to determine cost effectiveness of the application of these types of vehicles. A comparison between the costs of owning a hybrid, conventional and electric vehicle is considered, in order to determine whether the costs have the greatest impact on the purchase of these vehicles. The costs included: price of a new vehicle, fuel price per km and maintenance price per km. The performed analysis shows that hybrid and electric vehicles do not have better economic indicators than vehicles with IC engines.

KEY WORDS: hybrid, conventional, electric, vehicles, costs, analysis

EKONOMSKA ANALIZA PRIMENE RAZLIČITIH POGONA U VOZILIMA

REZIME: Vozila se smatraju najvećim zagađivačima okoline. Alternativa konvencionalnim vozilima su hibridna i električna vozila. Uprkos dobrim osobinama ovih vozila, retko se mogu videti na putevima. U ovom radu, izvršena je ekonomska analiza kako bi se utvrdila isplativost primene ovih tipova vozila. Urađeno je poređenje između troškova posedovanja hibridnog, konvencionalnog i električnog vozila, u cilju utvrđivanja da li troškovi imaju najveći uticaj na kupovinu ovakvih vozila. U troškove su uključeni cena novog vozila, cena goriva po km i cena održavanja po km. Izvršena analiza pokazala je da hibridna i električna vozila nemaju bolje ekonomske pokazatelje od vozila sa motorom SUS.

KLJUČNE REČI: hibridno, konvencionalno, električno, vozila, troškovi, analiza

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ECONOMIC ANALYSIS OF APPLICATION OF DIFFERENT DRIVE TRAINS IN VEHICLES

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1. INTRODUCTION

The development of combustion engines, especially vehicle engines, is one of the greatest achievements in technology. More precisely, a life without a vehicle is impossible today. This is because vehicles have a major role in everyday life of modern society. In addition, vehicle production has a big influence on the world economy. It is best explained by an increasing trend of numbers of light duty vehicles in the world, shown in Figure 1. The everyday increase of number of vehicles, unfortunately, has a negative effect, such as air pollution and higher fuel consumption. This kind of problem created a need to produce vehicles that are less polluting and have a lower fuel consumption. One of the best choices of vehicles is a hybrid electric vehicle. Despite their good qualities, the hybrid vehicles are rarely seen on the road [1]. Why does this happen? One of possible answers is the existence of opinion that these vehicles are expensive to own.

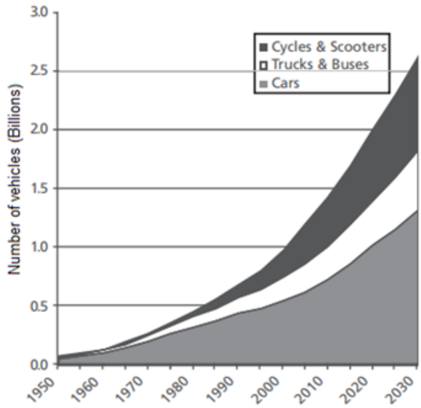

Figure 1 Global growth of vehicles [2]

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The main purpose of this paper is to conduct the cost-effectiveness analysis of buying and owning vehicles with different drive trains. In order to perform the cost-effectiveness analysis, data on costs of buying and owning vehicles with different drive trains are necessary.

2. RESEARCH METHOD AND MATERIALS

The best method for this type of the analysis is a statistical method. Data needed for statistical analysis in this paper are taken from [3]. The basic idea of the research is to compare the costs of ownership of hybrid, conventional and electric vehicles. Six vehicles were used in research, two for each type of drivetrain. The first group of vehicles used in analysis consists of: Toyota Yaris 1.3 (conventional), Toyota Prius 1.5 (hybrid) and Nissan Leaf (electric), Figure 2. The second group contains more luxury vehicles then vehicles from the first group. Vehicles from the second group are: Nissan Qashqai 2.0 (conventional), Toyota Prius 1.8 (hybrid) and Holden Volt (electric), Figure 3.

a) Toyota Yaris 1.3

b) Toyota Prius 1.5

c) Nissan Leaf

Figure 2 Vehicles used for research [4, 5, 6]

a) Nissan Qashqai

b) Toyota Prius 1.8

c) Holden Volt

Figure 3 Vehicles used for research [7, 8, 9]

Table 1 Price values in $ [3]

	Price of a new vehicle (*PNV*)	Fuel price per km (*FP*)	Maintenance price per km (*MP*)
Toyota Yaris 1.3	16,490	0.0819	0.0807
Toyota Prius 1.5	22,990	0.055	0.0945
Nissan Leaf	34,200	0.0483	0.0709
Nissan Qashqai 2.0	28,490	0.0897	0.0634
Toyota Prius 1.8	32,490	0.055	0.0967
Holden Volt	59,990	0.0546	0.0574

Based on prices given in Table 1, the analysis of ownership costs for 75,000 km (P_{75000}) and 150,000 km (P_{150000}) travelled by vehicle is performed and difference between these values (PD) is calculated:

$$P_{75000} = PNV + (FP + MP) \cdot 75000 \quad (1)$$

$$P_{150000} = PNV + (FP + MP) \cdot 150000 \tag{2}$$

$$PD = P_{150000} - P_{75000} \tag{3}$$

In addition, according to data from Table 1, analysis of ownership costs per year (PPY) is conducted, assuming that the vehicle travels 50,000 km per year. For this calculation, the next equation is used.

$$PPY = PNV + (FP + MP) \cdot 50000 \cdot NY \tag{4}$$

3. RESULTS AND DISCUSSION

By using data from Table 1, and equations (1) to (3), the following data are obtained and presented in Table 2.

Table 2 Costs of ownership for 75,000 km and 150,000 km and difference of costs in $

	P_{75000}	P_{150000}	PD
Toyota Yaris 1.3	28,685	40,880	12,195
Toyota Prius 1.5	34,202.5	45,415	11,212.5
Nissan Leaf	43,140	52,080	8,940
Nissan Qashqai 2.0	39,972.5	51,455	11,482.5
Toyota Prius 1.8	43,867.5	55,245	11,377.5
Holden Volt	68,390	76,790	8,400

Data from Table 2 can be better analyses observing the Figure 4 (for the first group of vehicles) and Figure 5 (for the second group of vehicles), where ownership costs after 75,000 km travelled are presented.

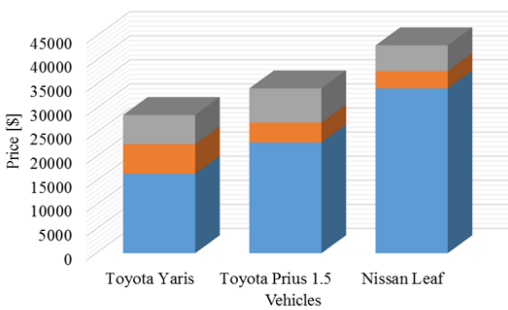

Figure 4 Costs of ownership (the first group of vehicles) for 75,000 km travelled

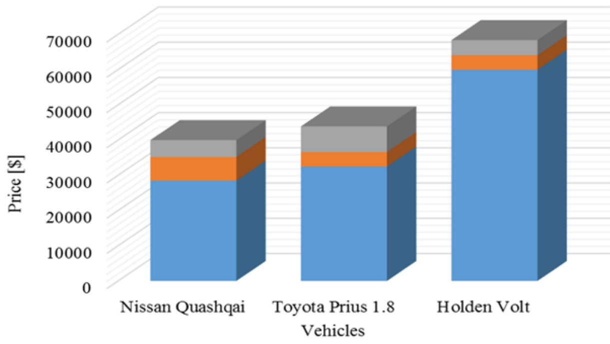

Figure 5 Costs of ownership (the second group of vehicles) for 75,000 km travelled

By analysis of data from Figures 4 and 5, it can be seen that the most expensive vehicle to own is the electric vehicle. The reason is a high price for a new vehicle. Hybrid vehicle is the most expensive to maintain because of the two types of drivetrain. In addition, it can be seen that the hybrid vehicle is still more expensive to own after 75,000 km travelled than conventional vehicle. Also, from Table 2, it can be seen that after 150,000 km travelled, the vehicle with conventional drive train is still cheaper than vehicles with other types of drive trains.

In addition, calculations were performed in order to see how many kilometres the hybrid or electric vehicle needs to travel to be less expensive than vehicle with conventional drive train. Boundaries are set at vehicles traveling 50,000 km per year. Analysis is performed for a period of 10 years. Results are given in Tables 3 and 4 and Figures 6 and 7.

Table 3 Costs of ownership through years in $ (the first group of vehicles)

Distance travelled [km]	Toyota Yaris	Toyota Prius 1.5	Nissan Leaf	Time [years]	Toyota Yaris	Toyota Prius 1.3	Nissan Leaf
Vehicle price	16490	22990	34200				
1	0.1626	0.1495	0.1192				
50,000	8,130	7,475	5,960	1	24,620	30,465	40,160
100,000	16,260	14,950	11,920	2	32,750	37,940	46,120
150,000	24,390	22,425	17,880	3	40,880	45,415	52,080
200,000	32,520	29,900	23,840	4	49,010	52,890	58,040
250,000	40,650	37,375	29,800	5	57,140	60,365	64,000
300,000	48,780	44,850	35,760	6	65,270	67,840	69,960
350,000	56,910	52,325	41,720	7	73,400	75,315	75,920
400,000	65,040	59,800	47,680	8	81,530	82,790	81,880
450,000	73,170	67,275	53,640	9	89,660	90,265	87,840
500,000	81,300	74,750	59,600	10	97,790	97,740	93,800

Table 4 Costs of ownership through years in $ (the second group of vehicles)

Distance travelled [km]	Nissan Qashqai 2.0	Toyota Prius 1.8	Holden Volt	Time [years]	Nissan Qashqai 2.0	Toyota Prius 1.8	Holden Volt
Vehicle price	28490	32490	59990				
1	0.1531	0.1517	0.112				
50,000	7,655	7,585	5,600	1	36,145	40,075	65,590
100,000	15,310	15,170	11,200	2	43,800	47,660	71,190
150,000	22,965	22,755	16,800	3	51,455	55,245	76,790
200,000	30,620	30,340	22,400	4	59,110	62,830	82,390
250,000	38,275	37,925	28,000	5	66,765	70,415	87,990
300,000	45,930	45,510	33,600	6	74,420	78,000	93,590
350,000	53,585	53,095	39,200	7	82,075	85,585	99,190
400,000	61,240	60,680	44,800	8	89,730	93,170	104,790
450,000	68,895	68,265	50,400	9	97,385	100,755	110,390
500,000	76,550	75,850	56,000	10	105,040	108,340	115,990

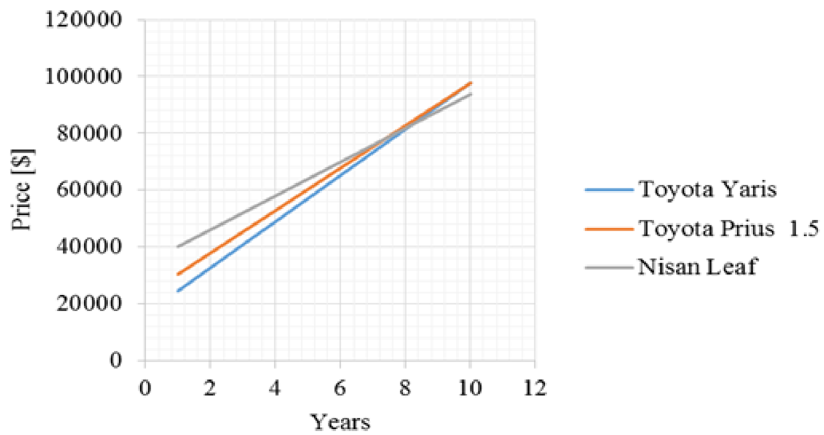

Figure 6 Costs of ownership through years (the first group of vehicles)

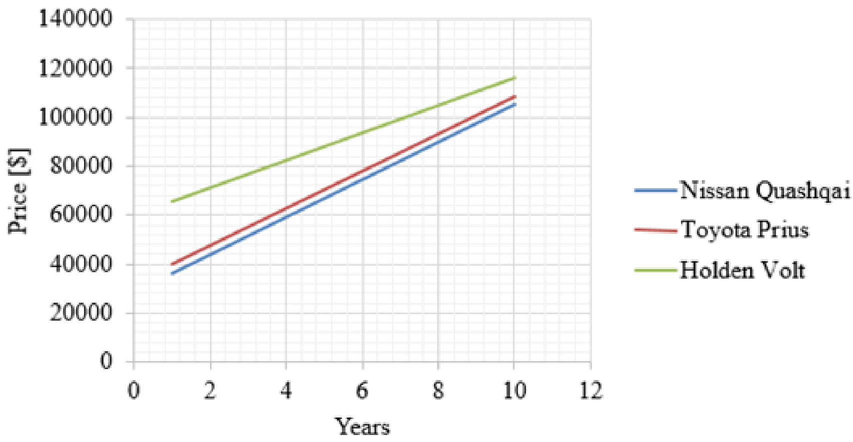

Figure 7 Costs of ownership through years (the second group of vehicles)

By analysis of Figure 6, it can be seen that the hybrid and electric vehicles have more cost effectiveness after 7 years, but if we take into account that vehicle travels over 350,000 km during this time, that is not good. Figure 7 shows that the vehicle with conventional drive train is more cost-effective even after 10 years.

4. CONCLUSIONS

Eclectic and hybrid vehicles are not something new, but strict laws have begun to impose their re-use. Despite the good qualities of these vehicles, they are rarely seen on the road. The main reasons are the costs of ownership. Based on performed analyses, these types of vehicles do not have better economic indicators than conventional vehicles. In one case (the first group of vehicles) these types of vehicles have better economic indicators after 350,000 km travelled, but this is a very big number. On the other hand, the hybrid and electric vehicles are friendlier to environment. There is a need to motivate people in some way to buy vehicles with these types of drive trains. The good way to achieve this is for states to give some benefits for citizens that are driving these types of vehicles, one of which may be the lower taxes for hybrid vehicles.

ACKNOWLEDGMENT

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EUROPEAN REGULATION ON VEHICLE REAL DRIVING EMISSIONS CONTROL

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ABSTRACT: The paper discusses the actual problem of NO_x emission in real driving conditions. In the first part of the paper the existing situation in regard to the NO_x emission of light vehicles in real use is presented using the tests performed all around Europe. Since the obtained emission is several times higher than existing limits according EU standards, the main causes for such differences have been analysed. Special attention is paid at the use of defeat devices applied by many car manufacturers using certain emission control strategy at approval test to obtain low emissions and another control strategy in real driving to obtain good fuel economy. To prevent excessive emission in real use, EU Commission has undertaken regulatory measures to accept new regulation which defines new limits for NO_x emission in real use as well as control testing the light vehicles in real driving conditions.

KEY WORDS: passenger cars, exhaust emissions, regulation, real driving, NO_x

EVROPSKI PROPISI O KONTROLI EMISIJE VOZILA U STVARNOJ VOŽNJI

REZIME: U radu se razmatra aktuelni problem emisije NOx u stvarnim uslovima vožnje. U prvom delu se prikazuje postojeća situacija u pogledu emisije NOx lakih vozila u stvarnoj eksploataciji koristeći rezultate ispitivanja obavljenih širom Evrope. Pošto je izmerena emisija nekoliko puta veća od granica propisanih standardom, analiziraju se glavni uzroci tih razlika. Posebna pažnja se poklanja primeni uređaja za promenu kontrolne strategije kod mnogih proizvođača vozila kada se koristi jedna strategija za kontrolu emisije pri homologacionom ispitivanju u cilju dobijanja niske emisije, a druga kontrolna strategija u stvarnoj eksploataciji u cilju postizanja povoljne ekonomičnosti goriva. Kako bi se spečila preterana emisija u stvarnoj eksploataciji, Evropska Komisija je preduzela korake ka stvaranju propisa koji bi definisali nove granice dozvoljene emisije NO_x u stvarnoj eksploataciji kao i kontrolno ispitivanje lakih vozila u stvarnim uslovima vožnje.

KLJUČNE REČI: putnička vozila, izduvna emisija, propisi, stvarna vožnja, NO_x

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EUROPEAN REGULATION ON VEHICLE REAL DRIVING EMISSIONS

Velimir Petrović [1], Stojan Petrović [2]

1. INTRODUCTION

Euro 6 standards entered into force at the end of 2014. The main novelty in them in relation to the Euro 5 was significant reduction of NO_x emission limits for light vehicles (passenger cars – PC and light duty vehicles – LDV) with diesel engines: from 180 mg/km to 80 mg/km. This reduction is practically equalized nitric oxides (NO_x) emissions of light vehicles with gasoline and diesel engines (Figure 1) [1].

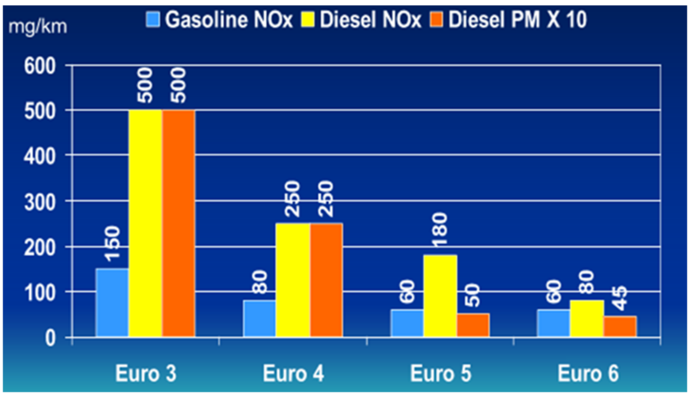

Figure 1 EU standards on NO_x and Particulate Maters (PM) for light vehicles

Gasoline NO_x limits were significantly lower than diesel NO_x limits until Euro 6 standard [2]. Actually, to reach NO_x limits it was much easier to gasoline engines than to diesel engines. Application of three way catalyst (TWC) technology for gasoline engines successfully solves the problem of NO_x emission, as well as CO and HC emissions, allowing very small limits. However, it is very difficult for diesel engine to find a solution that successfully reduces at the same time particulate matters PM and NO_x.

Euro 5 standard [2] was generally requested drastically reduction of diesel engine particles emission and therefore introduced almost mandatory application of diesel particulate filter (DPF). The NO_x emission was only slightly reduced by this standard, but to achieve the required limits it was necessary further diesel engine improvement and the application of additional solutions, primarily exhaust gas recirculation (EGR) and eventually lean NO_x trap (LNT).

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Euro 6 standard has significantly reduced NO_x emissions of diesel engines by about 60%. New limits for NO_x required more sophisticated solutions such as electronically regulated cool exhaust gas recirculation (EGR), lean NO_x trap (LNT) or selective catalytic reactor (SCR). Although SCR is the most efficient technology for reduction of NO_x emissions, this solution have not found wide application in passenger vehicles because of its complexity and higher costs. Therefore, in the domain of passenger vehicles mainly dominates the application of EGR with a possible addition of LNT. However, the efficiency of the EGR system is not too big and a higher decrease of NO_x reduction can jeopardize the economy of the engine.

2. REAL DRIVING EMISSIONS OF PASSENGER CARS

Unfortunately it turned out that the exhaust emissions of vehicles in real driving conditions can be significantly higher than the limits defined by standards. Figure 2 shows mean NO_x emission factors (values in g/km converted in g/kg fuel using measured fuel consumption rates) of gasoline (left) and diesel (right) passenger cars (PC) and light commercial vehicles (LCV) as a function of model year [3]. NO_x emission is measured in test cycle that represents real driving conditions. Obtained mean values during the test of different model year vehicles are presented with 95% confidence interval over the mean.

Actually it was concluded that passenger vehicles with gasoline engines do not have a lot of problems with exhaust emission in real use since TWC technology is very effective, especially with normally warmed engine. Therefore, the emissions in normal driving conditions correspond very well to the emissions obtained during approval test.

In the case of passenger cars with diesel engine a situation is much worse. Though the NO_x emission limits were constantly diminished, the emission in real driving conditions stayed almost the same. Therefore the gap between test and real driving results for diesel engines was very big. Figure 3 schematically illustrates the comparison between approval limits and real driving NO_x emissions for different classes of vehicles. Actually diesel engines NO_x emission in real driving conditions can be higher than limits by a factor of 2 for Euro 3 cars, more than 3 times for Euro 4, and more than 4 times for Euro 5 [4]. It was believed that the main reasons for the observed gap were different test and real conditions.

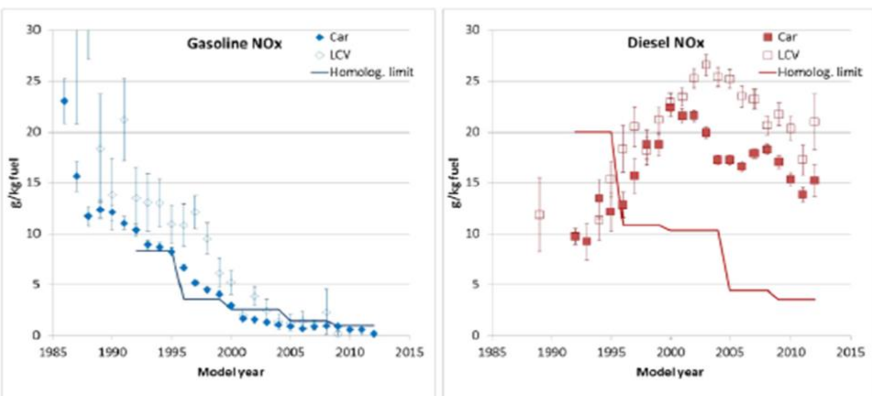

Figure 2 Mean hot NOx emission of gasoline (left) and diesel (right) passenger cars and light commercial vehicles (LCV) as a function of model year [3]

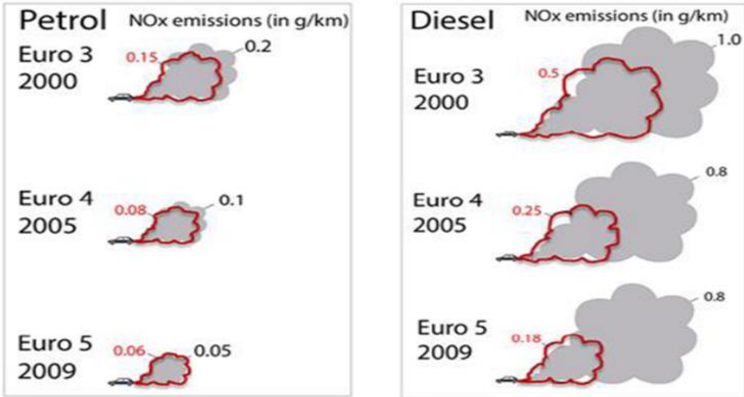

Figure 3 Test and real driving results (red – approval limits, black – real drive) [4]

However, the situation became more serious when in September 2015 the U.S. EPA and the California Air Resources Board announced that a number of VW 2.0L diesel vehicle models sold in the U.S. during model years 2009 to 2015 was equipped with illegal defeat devices. The EPA issued a second notice of violation in November 2015 for VW model year 2009–2016 vehicles equipped with 3.0L diesel engines stating that "VW manufactured and installed software in the electronic control module (ECM) of each vehicle that causes the vehicle to perform differently when the vehicle is being tested for compliance with EPA emission standards than in normal operation and use." While the description of the defeat device was more detailed than in the September notice of violation, in both cases the vehicles were operating under two emissions control regimes: one during emissions testing, and one at other times. The EPA described the defeat device used in the 3.0L vehicles as software that determines when the vehicle has begun the FTP 75 certification test and then employs a low-NO_x temperature conditioning mode, varying a number of engine parameters to yield lower engine-out [5].

Having in mind critical situation and knowing that also a lot of other European vehicles have high emissions in real driving conditions, from the beginning of 2015 started in Europe intensive testing of real driving exhaust emissions of passenger cars (PC) and light commercial vehicles (LCV). Tests have been performed in laboratories simulating real driving conditions, as well as on roads in real traffic.

It was found [6] that over four in five cars that meet the Euro 5 standard for NO_x in the laboratory (180g/1000km), and were sold between 2010-2014.years, actually produce more than three times this level when driven on the road. Also two-thirds of Euro 6 cars (most on sale since 2015) still produce more than three times the 80g/1000km limit when driven on the road.

When Euro 6 vehicles first entered the market in 2014 they typically produced in real use around 600mg/km of NO_x or 7.5 times the 80mg/km limit. More recent models are better, typically 5.5 times the limit (440mg/km). However, some models' exceedances are over 10 times. It is estimated that about 80% of total registered Euro 5 vehicles and about 64% of Euro 6 diesel cars exceed existing NO_x limits [6].

According to the performed tests in last year and recently published results on NO_x exhaust emission in real driving conditions there are a lot of cars manufacturers which sold cars with higher emissions than declared level at approval test. For Euro 5 cars, the five worst performing companies were (in order of the highest emissions): Renault (including Dacia), Land Rover, Hyundai, Opel/Vauxhall (including Chevrolet) and Nissan. The best performing Euro 5 cars were made by (in order of lowest emissions): Seat, Honda, BMW (including Mini), Ford and Peugeot. For current Euro 6 cars a different pattern emerges. The worst performers are: Fiat (including Alfa Romeo + Suzuki to whom Fiat supply engines); Renault (including Nissan, Dacia and Infiniti); Opel/Vauxhall; Hyundai; and Mercedes. The cleanest Euro 6 car is VW Group with VW cars, followed by Seat, Skoda and Audi; BMW (including Mini) and Mazda [6]. Fig. 4 illustrates this situation using the EQUA Air Quality Index results on real-world emissions data.

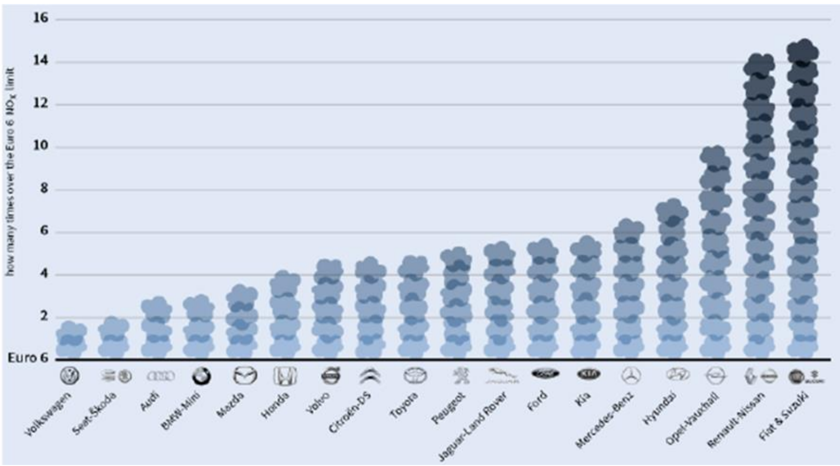

Figure 4 Euro 6 manufacturers (selling cars in Europe) over approval limits rated according their average real driving emissions index [6]

Similar situation is also in United Kingdom. Fig. 5 shows the results of tested used cars taken from rent companies in England. Euro 5 cars have six time greater emission than limits and Euro 6 cars seven times exceedance.

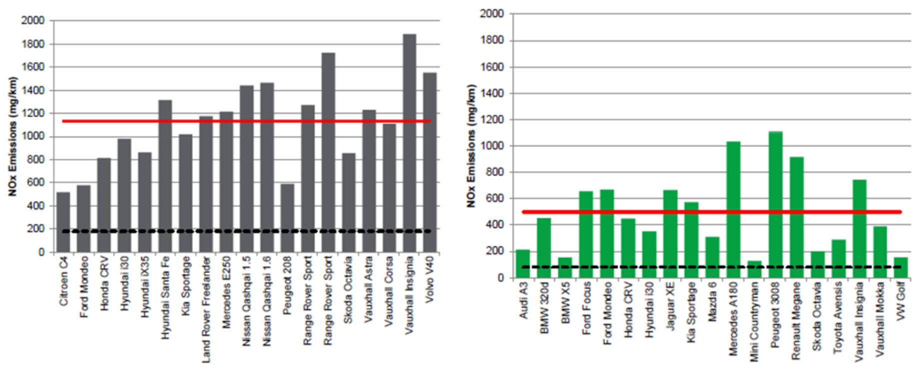

Figure 5 Real driving emissions (RDE) of certain Euro 5 (left) and Euro 6 (right) cars (red line – mean RDE, black dotted line – limits) [7]

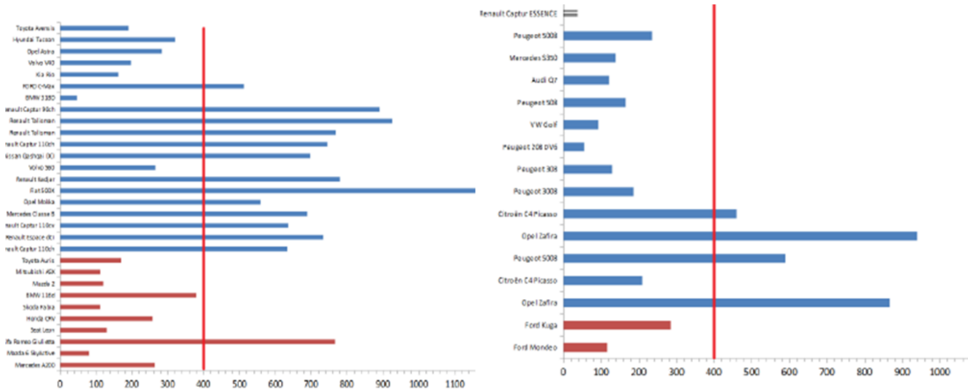

Figure 6 NO_x emissions measured on track of vehicles without SCR (left – red are with EGR only and blue are with EGR + LNT) and with SCR (right – red are with SCR+EGR+LNT and blue with SCR+EGR) [8]

The results of Euro 6 vehicles tested in France are shown in Fig. 6 [8]. The aim of tests was to find the vehicles with NO_x emission five times the limit. The vehicles were driven at open track (not in laboratory) using approval cycle NEDC (New European Driving Cycle) but in real driving conditions. The emissions values were measured using PEMS (Portable Emissions Measurement System) equipment. The worst results in RDE conditions have Euro 6 passenger cars with EGR + NO_x trap (LNT): some of them five up to 15 times over the limits. The better results have Euro 6 passenger cars with SCR, but again some of them are ten times over the limits.

3. THE REASONS FOR HIGHER EMISSIONS IN REAL DRIVING CONDITIONS

There are two principal causes for the failure to meet limits on the road.

First, the laboratory test procedure used to measure the pollutant and CO2 emissions in Europe in the past is unrealistic and does not represent real-world driving conditions. The actual NEDC driving schedule practically has not transient regimes and high loads, testing conditions are almost ideal and the test is performed with specially prepared vehicle for approval. Also, there are too many flexibilities and loopholes in the testing protocols that allow carmakers to game the system.

It is allowed to carmakers to “shop around” for the best offer from the regulators that compete among themselves for type approving business. Some, for example, approval authorities KBA in Germany, CNRV in France and MIT in Italy, protect their national carmakers. Others, like the VCA in the UK, RDW in the Netherlands or SNCH in Luxembourg see type approval as a lucrative business [6].

This feeble system of approvals is exacerbated by technical services that are supposed to undertake tests but routinely only witness these in carmakers’ own labs and are paid for their assistance. Sometimes the testing and approval organizations are even the same. Once the vehicle has been approved there are virtually no independent on-road checks to verify its performance in use due to a lack of will or resources. Figure 7 illustrates where are performed approval tests for first fifty cars with the high emissions in real driving conditions [6]. Although it is normal that carmakers perform approval tests in their own country, the national pride can be significant. It highlights that approvals are often done to support domestic manufacturers or as a business for the approval authority.

Figure 7 The figure shows which authority approved the 50 most polluting Euro 6 cars [6]

Second reason for higher NO_x emissions in real driving conditions is a widespread practice of disabling emission control technologies in many conditions when the car is driven on the road. Manufacturers claim that they are utilising a legitimate loophole in the legislation. National type approval authorities have turned a blind eye to the use of defeat devices leading to such widespread health and environmental impacts.

Diesel cars are failing to operate their exhaust after-treatment systems for most of the time the car is driving, almost certainly illegally misusing a loophole in the rules governing the use of defeat strategy or defeat devices. This is done partially to improve official fuel economy figures but also due to doubts about the durability of the emissions treatment systems carmakers have chosen to use.

According to the EC regulation No. 595/2009 [9] *'defeat strategy' means an emission control strategy that reduces the effectiveness of the emission controls under ambient or engine operating conditions encountered either during normal vehicle operation or outside the type-approval test procedures.* According to the ECE Regulation 83 and EC Regulation No 715/207 [2] *'defeat device' means any element of design which senses temperature, vehicle speed, engine speed (RPM), transmission gear, manifold vacuum or any other parameter for the purpose of activating, modulating, delaying or deactivating the operation of any part of the emission control system, that reduces the effectiveness of the emission control system under conditions which may reasonably be expected to be encountered in normal vehicle operation and use*.

Defeat strategies, i.e. the techniques which raise emissions on the road include the use of:

1. Thermal window defeat device
2. Hot restart defeat device
3. Cycle detection defeat device.

A list of car models sold in Europe using mentioned types of defeat devices is presented in literature [6].

It has been identified that a lot of PC and LDV models show the presence of a "thermal window" defeat devices. These devices switch off or lower the effectiveness of the exhaust treatment systems at temperatures below those typically used during laboratory tests (23 - 29°C). Tests conducted in late autumn, winter and early spring on track or road produced high emissions highlighting that the cars were turning down or switching off the emission control systems during these tests. Manufacturers claim such behaviour is needed to protect the engine and therefore switch off their pollution control systems bellow certain temperature (some models of Opel and Vauxhall bellow 17oC, Renault and Nissan also bellow 17oC, Daimler bellow 10oC, Peugeot bellow 5oC, etc. [6]).

The second type of defeat device relates to "hot restarts". Again a high number of the models on the road show much higher emissions after a hot engine restart than when the engine is cold. Manufacturers' explanation is that high emissions are generated by hotter engine temperatures experienced at warm restarts. However the effectiveness of the after-treatment should be much better when hot conditions. High warm start emissions are highly suspicious and suggest that during the EU test cold start a different and more effective engine and exhaust calibration is being used.

The third defeat device relates to "test recognition" strategy. Such defeat device was described as a "switch" that "senses whether the vehicle is being tested or not based on various inputs including the position of the steering wheel, engine compartment cover, vehicle speed and load, the duration of the engine's operation, etc. It was reported that several tests by the German type approval authority (KBA) have found evidence that the exhaust treatment system in some Fiat models would switch itself off after 22 minutes (test duration is 20 minutes). Also some of Ford and Fiat models switch off their pollution control systems at high vehicle speeds and when a car is full with passengers [6]).

However, it is proved that only Volkswagen Group used the defeat device recognizing control test and switching software for emission control [10]. Fig. 8 show the results of NO_x emissions during unrecognized and recognized test of Škoda passenger car. The recognition was done according to the shape of the first part of driving cycle. At normal start of standard cycle (laboratory NDEC) the engine used base emission control software enabling low emission of NO_x. If reverse cycle was used (first extra urban cycle and then urban cycle) the driving cycle was not recognized and the engine used auxiliary emission control software giving high NO_x emissions.

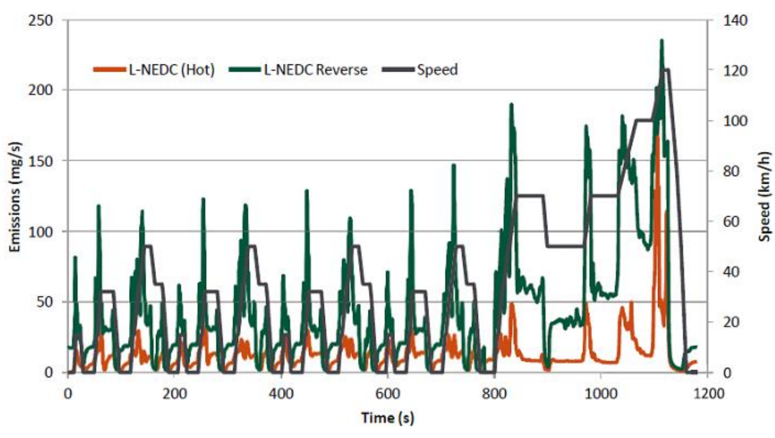

Figure 8 Test recognized (red) and unrecognized (green) NOx emission [10]

4. MEASURES FOR THE IMPROVEMENT OF REAL DRIVING EMISIONS

Keeping in mind current situation, the European Commission, in cooperation with research institutions, not governmental associations and vehicle manufacturers, has undertaken regulatory measures to reduce emissions in real driving conditions. These measures have included the monitoring of current situation, the determination of possible emissions deviations in real exploitation, the improvement in the existing regulations regarding the performance of approval tests conformity checks in exploitation, the definition of emission limits in real driving conditions and the proposal of RDE control test. It is envisaged that the entire process of creating additional regulations to control emissions in real use is carried out in several steps.

The first step was already implemented in 2015 using EU research institutions in order to check the possible variations of approved NO_x emission values of new vehicles comparing them with the measurements in realistic conditions. Actually it was immediately concluded that there is a high probability that the emission during real operation is greater than the value from homologation. The first reason is that during the approval the vehicle is running from cold conditions in contrary to the hot engine of vehicle used in real driving conditions. Second reason is that the environmental conditions (pressure and temperature) differ from standard conditions prescribed for the control in laboratory. Third reason is the use of different emissions control software in laboratory and in real driving. This is illustrated in Figure 9 for the same new car tested in and out the laboratory [10]. If the standard driving control cycle (NDEC) is performed with a hot engine, laboratory NO_x emission already exceeds the limits by more than 50% (left side - red of figure 9). However if the test is performed outside the laboratory in real environmental conditions differences are much greater (right side – green).

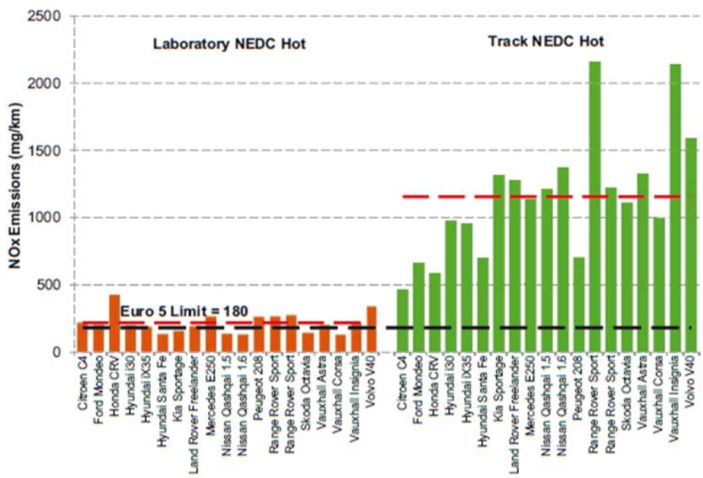

Figure 9 Laboratory versus track NOx emission of new Euro 5 vehicles [10]

Based on these measurements, so-called Conformity Factor, defined as the ratio between real NOx emission and standard limit, should be establish. The Conformity Factor will be then used to define the maximum allowed NOx emission in real driving conditions, so called Not To Exceed (NTE) limit, according to the expression

NTE limit = Conformity factor x Euro 6 limit

On the October 2nd 2015 European Commission sent the proposal [11] on so called First RDE package to the EU Council and on 10 November 2015, the Council gave its green light to the adoption of the first package of rules on real driving emission (RDE) tests to measure pollutants emissions of light vehicles. This first package introduces the concept of RDE procedures with a portable emissions measurement system. It will apply from 1 January 2016. At this initial stage the system will be used only for monitoring purposes. It will therefore not yet have any implications on the approval of new models.

During the discussion about future conformity factors, the European Commission had proposed significantly more stringent limits applying conformity factors of 1.6 in the short term and 1.2 in the longer term, but a lot of Member states suggest much higher values [12]. On the 28 October 2015, the European Commission and Member states reached an agreement on the Second RDE package establishing implementation dates and conformity factors on NOx RDE. On 12 February 2016, the Council gave its green light to the adoption of the second package of rules with real driving emission (RDE) limits. According to this package 2.1 short term and 1.5 long term conformity factors are adopted. This second conformity factor will be annually reviewed to take into consideration technical improvements to the test equipment during RDE control test definition. The implementation dates of RDE limits for new model type approvals and for all new vehicles are shown in Figure 10 [12].

	New Type Approvals	All vehicles
1.1.2016		Testing commences
1.9.17	Not to exceed limit 168mg/km	
1.9.19		Not to exceed limit 168mg/km
1.9.20	Not to exceed limit 120mg/km	
1.9.21		Not to exceed limit 120mg/km

Figure 10 RDE limits and implementation dates [12]

Meanwhile the discussion on RDE control test continued. Proposal of Third RDE package includes three important items [13]:

a) Particle number (PN) PEMS RDE testing. PN PEMS testing seems to be possible, albeit with somewhat higher uncertainties than the NO_x PEMS testing. The results of the testing at the JRC as well as of the interlaboratory exercise were presented at the RDE-LDV meeting of 20th April 2016. [14, 15].

b) Coverage of the vehicle cold start. There are two possibilities: to include the cold start data in the normal RDE data evaluation and to calculate separately the contribution of the cold start and weighing it in the RDE data evaluation [16].

c) Special RDE testing conditions for hybrids. All hybrids should be certifiable with the RDE procedure and appropriate evaluation methods need to be developed [17].

In September 2016 also started consideration of Fourth RDE package which should cover the definition of in-use-conformity RDE testing including the concepts developed by the “RDE surveillance task force” [13].

All agreed items are included in EU Commission Regulation 2016/646 from April 20, 2016 [18]. This Regulation defines two emissions strategies: ‘base emission strategy’ that is active throughout the speed and load operating range of the vehicle, and ‘auxiliary emission strategy’ that becomes active and replaces or modifies a BES for a specific purpose and in response to a specific set of ambient or operating conditions and only remains operational as long as those conditions exist. Appendix 6 to Annex I of this Regulation introduces Euro 6c and 6d standards for different classes of vehicles supplied by gasoline, diesel, E10 and B7 fuels. The implementation dates are defined according to norm levels and vehicle classes with the application from 1.9.2017 to 1.1.2022. RDE testing is also included with NTE limits. Annex II of this regulation defines final and temporary NTE limits as well as proposal of procedure of RDE control test with the verification and calculation of testing results.

New requirements for low real driving emissions need the application of new more expensive technologies. It is concluded that Euro 6 light vehicles with real-world compliance are technically feasible, even with stringent RDE requirements. Therefore, EGR system, frequently used in light vehicles, will be probably change to SCR system which gives smaller deviations in real use. The additional production costs of vehicle equipped with SCR can be up to €500.

Taking in account all undertaken measures it is expecting that in 2021 approval and in use emissions data will be closer. The forecast is shown in Figure 10.

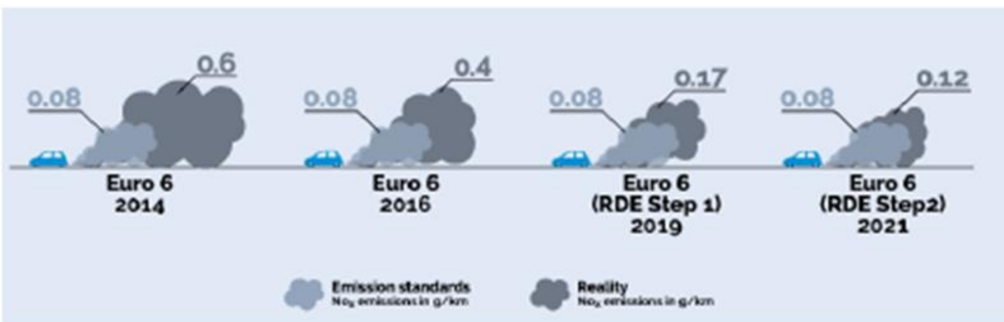

Figure 10 The forecast of future NOx emission according to EU standards and in real driving conditions [6]

5. CONCLUSIONS

NOx emissions of light vehicles is several times higher in real driving conditions than in laboratory during approval test. It is higher by a factor of 2 for Euro 3 vehicles, more than three times for Euro 4, four times for Euro 5 and seven times for Euro 6 vehicles.

The main reasons for higher NO_x emissions in real driving conditions are:

1. The standard test procedure used to measure the pollutant in laboratory is unrealistic and does not represent real-world driving conditions.

2. The manufacturers of diesel cars are failing to operate their exhaust after-treatment systems for most of the time the car is driven with the aim to improve fuel economy as well as to keep the durability of the emissions treatment systems they have chosen to use.

EU Commission has undertaken certain regulatory measures to improve the level of NOx emissions in real driving conditions. These measures involve the adoption of so-called „RDE Packages“. The proposals of First and Second RDE packages are already accepted and Third and Fourth are under consideration. Their conclusions will be included in EU Regulation 2016/646 with adopted conformity factors (defining permitted deviation between standard limits and real driving data), temporary and final NTE (Not To Exceed) limits with the implementation dates, real driving emissions (RDE) test procedure, and validation and calculation of test data.

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PERSPECTIVES OF APPLICATION OF FUEL CELL ELECTRIC BUSES – SOME EXPERIENCES FROM THEIR OPERATION

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ABSTRACT: The on-going requirements for reduction of fossil fuels consumption, harmful emissions, and noise in the cities enforced the development of city buses using alternative propulsion systems as a potential answer to these requirements. Even though some improvements, as regards harmfull effects upon environment, have been accomplished by Euro VI diesel engines, no significant developments in this direction can be expected. For this reason transition to electric propulsion systems of city buses having zero emissions, such as batteries or fuel cells buses (FCBs), is imperative for many cities and city operators.

The paper presents an analysis of the development of FC buses accomplished by several European projects and points at numerous problems and obstacles that have to be overcome in order to make this technology commercially sustainable. Special attention has been paid to the comparative analysis of FC buses and buses using other propulsion technologies as regards both, fuel economy and operational costs.

KEY WORDS: fuel cell buses, FC bus projects, operating cost and fuel economy, environmental benefits

PERSPEKTIVA PRIMENE AUTOBUSA SA GORIVNIM ĆELIJAMA - NEKA ISKUSTVA IZ NJIHOVE EKSPLOATACIJE

REZIME: Stalni zahtevi za smanjenjem potrošnje fosilnih goriva, štetne emisije i buke u gradovima, nametnuli su razvoj autobusa sa alternativnim pogonskim sistemima koji mogu da odgovore na postavljene zahteve. Premda su određena poboljšanja, u pogledu smanjenja štetnih efekata na životnu sredinu, dobijena sa Euro VI dizel motorima, dalji značajniji napredak, u tom pravcu, se ne može očekivati. Zato prelazak na električne pogonske sisteme autobusa sa nultom emisijom, kakvi su autobusi sa baterijama i gorivnim ćelijama je imperativ za mnoge gradove i operatere.

U radu se analizira dosadašnje stanje razvoja FC buses, u okviru nekoliko evropskih projekata i ukazuje na mnogobrojne probleme i prepreke koje još treba savladati da bi ova tehnologija bila komercijalno održiva. Posebna pažnja posvećena je uporednoj analizi autobusa sa gorivnim ćelijama i autobusa sa drugim tehnologijama pogona, kako u pogledu potrošnje energije, tako i ukupnih eksploatacionih troškova.

KLJUČNE REČI: Autobusi, gorivne ćelije, potrošnja energije, eksploatacioni troškovi

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PERSPECTIVES OF APPLICATION OF FUEL CELL ELECTRIC BUSES – SOME EXPERIENCES FROM THEIR OPERATION

Zlatomir Živanović [1]

1. INTRODUCTION

Fuel cell buses use compressed hydrogen as fuel and on board fuel cell(s) to generate electricity which powers the electric motor. This devices use hydrogen and oxygen to generate electricity through an electro-chemical process producing only water and heat as by-products.

Modern fuel cell electric buses in general additionally have a small battery or super capacitors. These devices improve the performance of the fuel cell and overall energy efficiency of the vehicle, for example they boost the acceleration and allow recuperation of braking energy. Apart from that, the bus structure and the other non-electric components of the bus are the same as those of conventional buses.

Fuel cell buses have the potential to provide zero emission and ultra-low carbon public transport. Because of this potential, there has been considerable research and demonstration effort dedicated to developing hydrogen bus technology. The technology is, however, not fully commercially mature and will require further public support in the coming years to stand on its own within the market.

This paper is structured in the following way:

In Section 2 are briefly presented possible FCB drivetrain configurations and descriptions of the basic components of the hybrid bus concept.

Some characteristics of fuel cell technologies are described in Section 3. They related to the operational costs of buses and infrastructure, limitations in terms of the speed of charging and range. Also, the risks arising from the use of hydrogen are pointed at.

In Section 4 are presented the most important European projects that have been realized and those whose realization is in progress, which involve a large number of partners, the bus manufacturer, European regions, and cities.

The latest generation of FCBs, which are involved in the current European CHIC (Clean Hydrogen in European Cities) project, with the main technical data is given in Section 5.

In Section 6, in the absence of European data, the comparative results of operational costs and fuel economy of FCBs and diesel buses, obtained by manufacturer Van Hool, after many years of demonstration in the United States, are shown. Data about NOx and PM emissions (per year) presented by Van Hool in its promotional materials for three different fleets of buses, are also shown.

2. FUEL CELL BUS DRIVETRAIN CONFIGURATIONS

Hydrogen buses have evolved substantially in the last two decades. A number of different design configurations have been used, including hydrogen in internal combustion engines, and various fuel cell technologies.

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Early fuel cell bus designs involved an electric drivetrain, where a fuel cell generates electricity which is directly supplied to an electric motor.

However, this concept has been shown to have many defects related to size fuel cell systems to meet the full peak load and their overall performance and life. This concept there is no mechanism to capture the kinetic energy dissipated during braking.

In the light of these problems, all of the main fuel cell bus developers have now moved to a fully hybridized mode, with the fuel cell operating in a series hybrid configuration. In these fuel cell buses, developers are still experimenting with the energy storage device, which can be batteries, ultra capacitors, or a combination of both [1].

A third hybridized configuration is known as „battery dominant". In battery-dominant designs, the fuel cell system is considered a „range extender", which recharges the battery during the drive cycle. The batteries themselves provide the main motive power for the bus.

The hybridized systems have, however, still to prove the high availability standards achieved by the non-hybridized fuel cell buses. The most recent demonstration of hybridized designs has shown availabilities generally below 80% against an average 92% achieved by the non-hybridized fuel cell buses. These next generation hybrid buses are at the beginning of their demonstration life. Most bus developers report that the availability problems come from problems in power electronics or energy storage systems as opposed to the fuel cell itself [1].

Hybridized designs, however, became the dominant choice only from 2005. The largest fleet demonstration ever programmed started in occasion of the 2010 [1]. Today, every demonstration of fuel cell buses is based on hybrid concept, Figure 1 [2]. Key system components are: fuel cell system, energy storage system, hydrogen storage system, wheel drive, cooling system, and auxiliaries [3].

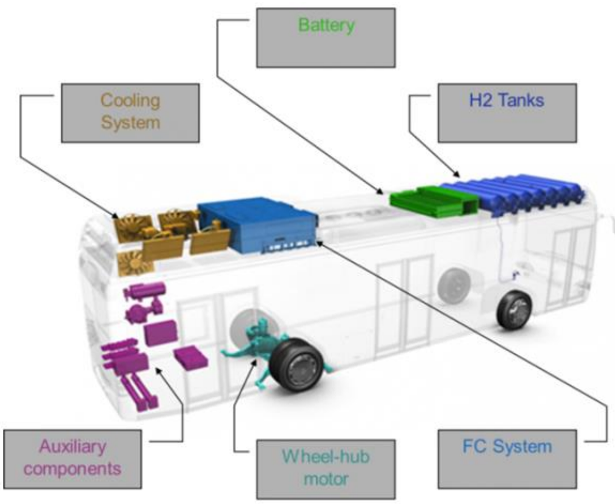

Figure 1 Key components of the fuel cell hybrid bus

Fuel cell system: A fuel cell is an energy conversion technology that allows the energy stored in hydrogen to be converted back into electrical energy for end use. In a fuel cell vehicle, an electric drive system, which consists of a traction inverter, electric motor and transaxle, converts the electricity generated by the fuel cell system to traction power to move a bus. The fuel cell system and additional aggregates are usually located on top of the roof of the bus.

Fuel cells are classified by their electrolyte and operational characteristics. For application in vehicles mostly used are the Polymer Electrolyte Membrane (PEM) fuel cells. They are lightweight and have a low operating temperature. PEM fuel cells operate on hydrogen and oxygen from air. Alkaline fuel cells (AFCs) are made by one of the most mature fuel cell technologies. AFCs have a combined electricity and heat efficiency of 60 percent efficient.

A newer cell technology is the Direct Methanol Fuel Cell (DMFC). The DMFC uses pure methanol mixed with steam. Liquid methanol has a higher energy density than hydrogen, and the existing infrastructure for transport and supply can be utilized.

There are some major fuel cell manufacturers supplying fuel cell power plants for heavy-duty applications: Ballard Power Systems and Hydrogenics (Canada), United Technologies Corporation (UTC) Fuel Cells, Enova Systems (USA), Shanghai Shen-Li High Tech Co. Ltd. (China), Siemens and Proton Motor Fuel Cell GmbH, (Germany), Toyota (Japan), Hyundai Motor Co. (South Korea).

Energy storage system**:** Energy storage systems are generally based on battery packs and/or ultra-capacitors (generally up to 100 kW). Maximum power output and storage capacity vary depending on hybrid architecture. Lithium-ion battery technology is the most appropriate of energy storage technology for use in the buses. The batteries are usually located on top of the roof of the bus. FCBs are equipped with regenerative braking.

Hydrogen storage system**:** Gaseous hydrogen serves as the fuel. It is stored in compressed gas tanks, the number of which is decisive for the maximum range but also confines passenger capacity. The hydrogen storage system has been downsized as a result of the improved efficiency of the drive train. This has led to the reduction in the overall weight of the bus. The cylinders to storage hydrogen on board operate at an increased pressure of 350 bars.

Wheel drive**:** The electric motor can be either a single main motor or hub–mounted (where the motor is designed within the wheel). The bus may be equipped with a central traction system which will be located at the left hand side in the rear of the bus. The rear axle has 2 wheel hub motors and has been specifically developed to match the required speeds, load capabilities and energy efficiency. It also serves as a generator for energy regeneration during braking.

Cooling system**:** While running hydrogen through a fuel cell, water is of course being produced. Some of it becomes steam and leaves the system quite easily, as seen at the steam vent at the back of the bus. Yet, because PEM cells are sensitive to high heat the cell stacks must be cooled down. Therefore the by-product from producing the electricity will always partially turn into liquid water that can accumulate in the stack and slow down the process. This can happen during idle times or at full speed. Therefore all PEM cells need a mechanism that clears the stacks once in a while or else the electricity production will be slowed down. The majority of the stack manufacturers use liquid cooled systems, with radiators to dissipate heat.

Auxiliaries: The auxiliary components in the FCB may be driven electrically. This means that they operate only on demand and are not driven continuously. These solutions are typical for FCB based on hybrid concept. This will result in a higher efficiency and lower maintenance of the components.

3. SOME FUEL CELL TECHNOLOGY CHARACTERISTICS

Fuel cells offer a number of potential benefits that make them appealing for transport use such as greater efficiency, quiet and smooth operation, and, if pure hydrogen is used on board the bus, zero emissions in operation and extended brake life. Infrastructure, buses, fuel, and maintenance costs associated with hydrogen fuel cells are currently prohibitively expensive. The cost of facilities has ranged from several hundred thousand dollars up to $4.4 million for a maintenance facility, fuelling station, and bus wash [4]. Currently, fuel cells for buses are not a commercial product. The existing fuel cell buses are prototypes, manufactured in fairly small numbers. FCB technology continues to show progress toward meeting technical targets for increasing reliability and durability while also reducing costs. Fuel cell buses can cost $2.1 to $2.4 million (or more) since they are hand-built prototypes utilizing a pre-commercial technology.

The purchase cost of FCBs has been cut by 50% since 2011 [5], but their purchase price after 2015 to 2025 will be decreased by account 75% [6].

The hydrogen fuel itself is also currently very expensive. Costs range depending on the method of hydrogen production. One of the major constraints for use of the fuel cell buses is the refuelling time for hydrogen buses. Filling over 30 kg of hydrogen in less than 5 minutes is not currently feasible without pre-cooling the hydrogen (as the temperature increase at these high fill rates would damage the hydrogen tanks) [1].

Hydrogen fuel cell buses have shown very good performance during trials and have high route flexibility, comparable to diesel buses [7].

Cost premiums and lack of infrastructure are proving to be a barrier to most at this stage and there are some reports of problems with the current range of the vehicles, practical difficulties of storing fuels, planning issues with storage facilities and the availability of fuel. Legislation on the use of hydrogen as a fuel is immature, with much of it based on the industrial use of hydrogen.

Due to the risk of explosion, hydrogen buses are not allowed to be used indoors, in garages or underground and even long tunnels in some cases. A possible solution would be to use bio methanol and convert it to hydrogen only when it is used [7].

Hydrogen as a road fuel yields significant potential for carbon neutrality on a well-to-wheel basis along the entire hydrogen value chain, including production and means of delivery. Hydrogen can be produced with electricity from 100% renewable energy sources. Hence, operating FC buses can be achieved with zero CO_2 emissions along the entire hydrogen value chain. By using hydrogen produced from renewable energy sources only, one standard FC bus would save approximately 800 tons of CO_2 in its lifetime of 12 years compared to a conventional diesel bus [8].

4. FUEL CELL BUS PROJECTS

The introduction of new types of buses in urban public transport is sometimes a challenging process that includes testing, demonstration and limited production with a tendency to increase the number of vehicles. Fuel cell-powered buses continue to be demonstrated in public transport service at various locations around the world. Many demonstration projects have been launched in the last 10 years in various stages of implementation. Many have been completed, and some of them are still active. An overview of mainly fuel cell city bus development projects is given below:

CUTE (Clean Urban Transport for Europe) (2001-2006): The Clean urban Transport for Europe [9,10] was a European project which saw the deployment and testing of 27 Citaro fuel cell buses – three buses in each of nine cities in Europe. The aim of the project was to demonstrate the feasibility of an innovative, highly energy-efficient, clean urban public transport system. Different hydrogen production and refuelling infrastructures were established in each of the cities. The project saw practical applications of renewable energy sources to the transport system. The project greatly improved public acceptance of the hydrogen fuel cell transport system, and contributed to the development of a more secure energy supply for the EU.

(ECTOS (Ecological City TranspOrt System) [11] was an initiative to test three Citaro fuel cell buses in Reykjavik, Iceland. The project was financially supported by the European Commission.) The overall objective of ECTOS was to implement a demonstration of state-of-the-art hydrogen technology by running part of the public transport system with fuel cell buses within Reykjavík. The energy chain was close to CO_2 free, because domestic geothermal and hydro-powered energy sources were used to produce hydrogen by electrolysis. The main research objectives concerned the socio-economic factors involved in changing the energy base of a modern urban society.

HyFLEET:CUTE (2006-2009) [10] has involved the operation of 47 hydrogen powered buses in regular public transport service in 10 cities on three continents. Its aim was to diversify and reduce energy consumption in the transport system by developing new, fuel efficient hydrogen powered bus technology, clean, efficient and safe production and distribution of hydrogen as a transport fuel. HyFLEET:CUTE was co-funded by the European Commission and 31 Industry partners through the Commission's 6th Framework Programme. The HyFLEET:CUTE project demonstrated in particular major developments in further development of Hydrogen Powered Bus Technology, and further development of Hydrogen Infrastructure.

"NaBuZ demo" (Sustainable Bus System of the Future – Demonstration) is German-funded project [12] in which the Hamburger Hochbahn AG produced four Mercedes-Benz CitaroFuelCELLHybrid buses. Since 2011, the first CitaroFuelCELL Hybrid bus is involved into service.

In contrast to the fuel cell buses which have been tested in Hamburg since 2003, the new CitaroFuelCELL Hybrid, part of the "NaBuZ project", boasts significant new features. For example, hybridization with energy recuperation and storage in lithium-ion batteries, high-performance electric motors with 120 kW continuous outputs in the wheel hubs, as well as electrified auxiliary aggregates and advanced fuel cells. This should make an extended service life of at least six years or 12,000 operating hours possible.

A new feature is the lithium-ion batteries which store energy recovered from braking. The power from these batteries alone is enough to drive the CitaroFuelCELL Hybrid over several kilometres. The concept for the new FuelCELL buses is actually very similar to that of the Mercedes-Benz BlueTec Hybrid buses which are also operated in Hamburg. The main difference between the two lies with the diesel generator of the BlueTec Hybrid buses, which supplies the latter with electrical energy. With the FuelCELL buses, the fuel cell supplies the drive motors with energy in a 100% emission-free process.

CHIC (Clean Hydrogen In European Cities) [13,14] is a major European project to deploy a fleet of fuel cell electric buses and associated refuelling infrastructure. CHIC builds on the expertise acquired in the framework of previous fuel cell bus projects: The HyFLEET:CUTE and CUTE project.

The European Fuel Cells and Hydrogen Joint Undertaking (FCH JU) public private partnership has co-funded 26 buses and their infrastructure in: Aargau (Switzerland), Bozen

(Italy), London (UK), Milan (Italy) and Oslo (Norway), Figure 1. In Germany, Cologne and Hamburg operate an additional fleet of 10 buses through separately funded programs, and an additional 20 buses were deployed in Whistler (Canada).

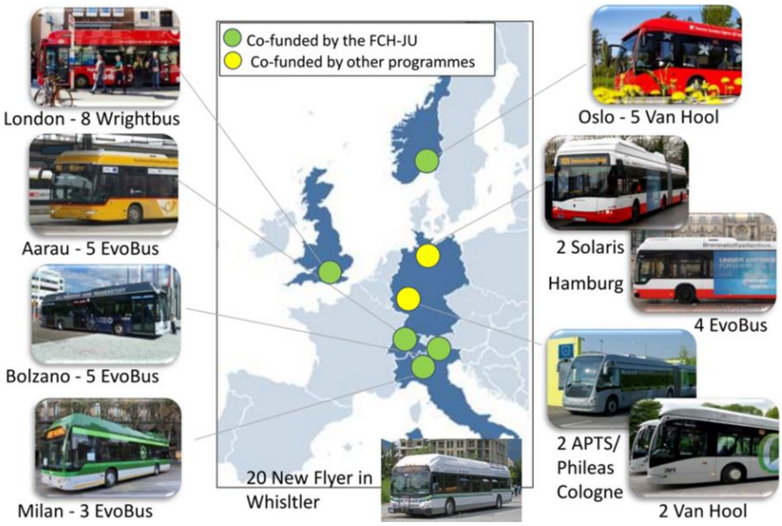

Figure 2 Participating cities and bus manufacturers in the GHIC project

In the time period from 2010 to 2016, the buses are tested for their reliability and sustainability and the participating cities gather both data on bus and infrastructure performance. At the same time dissemination activities should be put in place in order to raise public awareness regarding hydrogen technology and its applications.

Hamburg is a front runner in trialling fuel cell buses: Between 2003 and 2009, up to 9 EvoBus fuel cell buses have been operated, carrying 1.9 million passengers over 700,000 km. Four 12 m EvoBus fuel cell buses are in operation since 2011. Two 18 m Solaris battery electric buses with fuel cells as range extender started their operation in January 2015. The buses have a 400 km range and operate between 8 and 16 hours daily [14].

Most of the fuel cell buses today are running on European and North-American streets, while additional buses are being demonstrated in other parts of the world, for example in Japan and Brazil. Over 90 fuel cell electric buses are in operation today in Europe or about to start operation, Figure 2 [16].

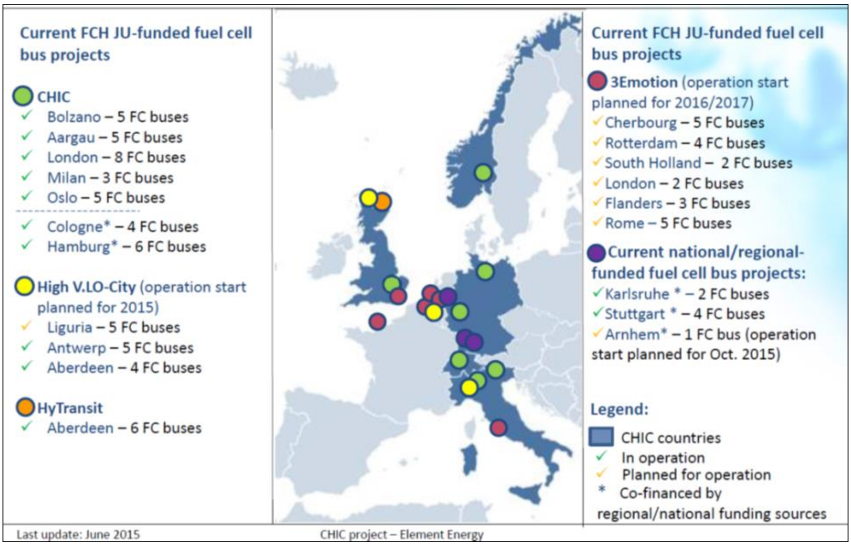

Figure 3 Fuel cell buses in operation or about to start operation

5. NEW GENERATION OF FUEL CELL BUSES

In this section are given basic information about the new generation of FC buses involved in the European CHIC project.

Mercedes-Benz fuel cell hybrid buses: Production of the second generation of Mercedes fuel-cell hybrid buses started in November 2010 under the CHIC project. Compared with the fuel cell buses which were tested in Hamburg in 2003, the new Citaro FuelCELL Hybrid, Figure 4, provides several significant new features [17]: hybridization with energy recovery and storage in lithium-ion batteries, powerful electric motors with 120 kW of continuous output in the wheel hubs, electrified power take-off units and further enhanced fuel cells. These should achieve an extended service life of at least six years or 12.000 operating hours.

Figure 4 The new Citaro FuelCELL hybrid bus

New additions are the lithium-ion batteries which for example store recovered energy. With the power stored there the new Citaro FuelCELL Hybrid can drive several kilometres on battery operation alone. In general, the design of the new FuelCELL buses is largely the same as that of the Mercedes-Benz BlueTec Hybrid buses that run in regular service; these buses also get electrical energy from a diesel generator. Thanks to improved fuel cell components and hybridization with lithium-ion batteries the new Citaro FuelCELL Hybrid saves on almost 50 % in hydrogen usage compared with the preceding generation. Overall fuel cell system efficiency has also been improved. The fuel cell bus has a range of around 250 kilometres.

Van Hool fuel cell hybrid buses: VAN HOOL (Belgium) is the largest independent manufacturer of integral buses and coaches in Western Europe. More than 80% of the company's production is exported: two thirds stay in Europe, the remainder goes to America, Africa and Asia. In a joint effort with UTC Power (United Technologies Corporation), a supplier of fuel cell systems, Van Hool developed fuel cell buses for the European and US markets. Siemens supplied the twin AC induction electric motor, 85 kW each, converters, and adapted traction software.

Within the project ZEBA demonstration includes 12 new generation fuel cell hybrid buses and two new hydrogen fuelling stations [18]. The buses are 12 m, low floor, with a hybrid electric propulsion system that includes a UTC Power fuel cell power system (120 kW) and an advanced lithium-ion battery (rated energy: 17.4 kWh and rated power: 76 to 125 kW). Eight Dynetek, type 3 cylinders, 350 bars, are mounted on the roof. The new buses, Figure 5, feature significant improvements over two previous generations of fuel cell buses that were demonstrated in California, Connecticut, and Belgium. Improvements include a redesigned Van Hool chassis that is lighter in weight, shorter in height, and has a lower centre of gravity for improved weight distribution. The bus has a top speed of 55 mph (88 km/h). The bus purchase cost is about $2.5 million [18].

Figure 5 The new Van Hool fuel cell bus

The two hydrogen buses for London are hybrid (fuel cell and battery powered) Van Hool A330 model 12-metre bus with two axles. They are equipped with the very latest FCvelocity-HD7 Fuel Cell module from Ballard Power Systems in Vancouver, Canada [19]. The hybrid drive system will enable the buses, with a tank content of 30 kg of hydrogen on board, to travel the planned daily distance of 300 km for TfL (Transport for London).

The drive system is based on fuel cells, lithium batteries and electric motors. The bus runs entirely on electricity. This hybrid drives system and the reuse of braking energy limits hydrogen consumption to around 8 kg per 100 km.

Van Hool has already supplied 49 hydrogen buses to the US and to European member states as part of other European projects, including five buses to De Lijn Antwerp (Belgium).

Wrightbus fuel cell hybrid buses: The buses are VDL SB200 single decker with Pulsar bodywork, supplied by ISE Corporation in collaboration with Wrightbus and Ballard, Figure 6. The hybrid drivetrain (ISE's Thunder Volt drive system) is based on super capacitors and is powered by Ballard's FC velocity-HD6 75kW fuel cell system. The buses carry approx. 42 kg of useable gaseous hydrogen at 350 bar [20]. Transport for London's new FC bus project is being supported by the Department of Energy and Climate Change and the European Commission's Joint Technology Initiative as a part of the CHIC project.

Figure 6 The Wrightbus wit fuel cells

The Phileas fuel cell hybrid buses: The Phileas hybrid FC buses, Figure 7, are based on an innovative 18 meters low-floor lightweight triple-axle platform, which can carry 35 seated and up to 120 standing passengers [20]. The composite body was developed by Advanced Public Transport Systems BV (APTS); the hybrid drivetrain has been developed by Vossloh Kiepe GmBH using super capacitors, HOPPECKE's battery and Ballard's FC velocity-HD6 150kW fuel cell system. The buses carry 42 kg of useable gaseous hydrogen at 350 bars.

Figure 7 The Phileas hybrid FC bus

First Solaris Urbino 18.75 electric with hydrogen fuel cells: To provide its latest electric buses with energy, Solaris is applying hydrogen fuel cells for the first time. So far no one in the Polish automotive industry has used this ultra-modern technology. The first of two Urbino 18.75 electric had its world premiere in Hamburg, on 18th December 2014 [21]. These innovative Solaris buses, Figure 8, are equipped with 120 kWh batteries as the main energy provider to the drive system. They will be charged by Ballard 101 kW fuel cells during operation. A novelty is that the fuel cells are used only when 100% of output is required, which significantly increases their durability. The bus will be fuelled with hydrogen at night in the depot. Battery charging cycles will be pre-programmed so it will be ready to cover 300 km per day.

Figure 8 The Solaris electric bus with hydrogen fuel cells

The Solaris Urbino 18.75 electric with fuel cell range extender has great potential to make a difference in urban public transport. The vehicle is eminently suited to play that role. Its innovative technology has already been appreciated in Germany. The new electric bus for Hamburg is the most technologically advanced Solaris product so far. With the Urbino 18.75 electric with fuel cells, Solaris adds a new innovative solution to its range of battery charging options. Plug-in, inductive and pantograph charging now are accompanied by fuel cells as range extenders [21].

6. SOME RESULTS FROM FUEL CELL BUS OPERATIONS

Many transport operators continue to aid the FCB industry in developing and optimizing advanced transportation technologies. These in-service demonstration programs are necessary to validate the performance of the current generation of fuel cell systems and to determine issues that require resolution.

6.1 Operating cost and fuel economy

The results presented in this section are focused on data optained from operating of 12 Van Hool FCBs, Table 1, in United States from November 2013 through December 2014 [22], as a part of the Zero Emission Bay Area (ZEBA) demonstration.

National Renewable Energy Laboratory (NREL) has been evaluating that results includes baseline data from four Van Hool diesel buses that are the same model as the FCBs. During that data period, the FCBs operated 417,757 miles (672,171 km) over 49,421 hours of fuel cell operation. This indicates an overall operational speed of 8.5 mph (13.7 km/h) [22].

Table 1 provides bus system descriptions for the fuel cell and diesel bus that were analysed.

Table 1 System description of the analyzed buses

Bus system	**Fuel cell bus**	**Diesel bus**
Image of bus		
Number of buses	12	4
Bus manufacturer/model	Van Hool A300L FC low floor	Van Hool A300L FC low floor
Model year	2010	2009
Passenger capacity	33 seated or 29 seated plus 2 wheelchairs	31 seated or 28 seated plus 2 wheelchairs
Engine manufacturer/model	US Hybrid fuel cell power system	Cummins ISL, 8.9L
Rated power	Fuel cell power system: 120 kW	280 hp @ 2,200 rpm
Transmission/retarder	Seico brake resistors regenerative braking	Voith integrated retarder
Bus purchase cost	$2.5 million	$323,000

Table 2 presents the comparative test results for the fuel cell and diesel buses during the evaluating period. The FCBs had an overall average fuel economy of 7.23 miles per diesel gallon equivalent (DGE) or 3.07 km/litre, but Van Hool diesel buses had an overall average fuel economy 3.95 mile per DGE (1.68 km/litre). These results indicate that the FCBs have an average fuel economy that is 83% higher than that of the Van Hool diesel buses. Data for the fuel economy in miles per DGE are converted into km/litre (1mile per DGE =0.425 km/litre).

Table 2 Operating costs and fuel economy of different buses

	Fuel Cell	**Diesel**
Fuel Cost ($/km)	0.88	0.47
Total Maintenance Cost ($/km)	0.38	0.46
Total Operating Cost ($/km)	**1.26**	**0.94**
Fuel economy (km/litre)	**3.07**	**1.68**

The cost of hydrogen production as dispensed during this period was $9.10 per kilogram, not including the capital cost of the station. The hydrogen fuel cost per km calculates to $0.88. Diesel fuel cost during the reporting period was $0.76 per litre, which calculates to $0.47 per km for the Van Hool diesel buses.

1.2 Environmental benefits

Emitting water only, FC buses are zero exhaust emission vehicles and can greatly contribute to reducing emissions in cities. Furthermore, they run at significantly lower noise levels. Standing and in motion, FC buses reduce perceived noise levels by almost two thirds compared to conventional diesel buses, Figure 9 [8].

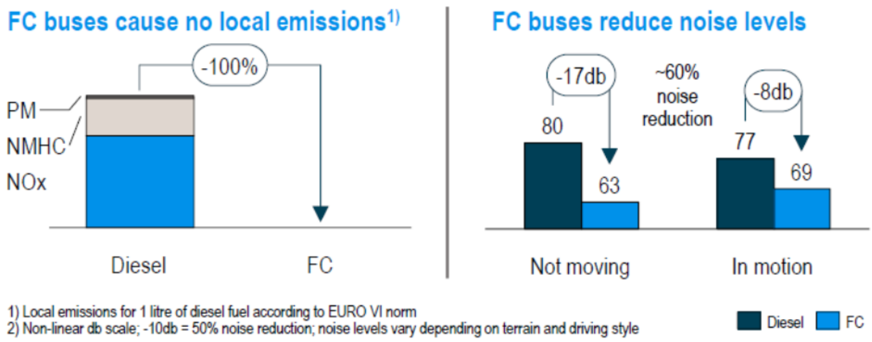

Figure 9 Comparison of local emission and noise levels of diesel and FC buses

Data about NO_x and PM emissions (per year) presented by Van Hool in its promotional materials for three different fleets of buses, are shown in Table 3 [23].The data are calculated for 50.000 km per year, average speed 20 km/h, and power consumption 50 kW/h.

Table 3 Comparative characteristics of NOx and PM emissions for different buses

	NO_x (per year)	**PM (per year)**
100 Diesel Euro III buses	62.5 tons	1.25 tons
100 CNG buses	25 tons	0.25 tons
100 Hybrid fuel cell buses	zero	zero

Equivalent emissions reduction potential of 100 hybrid fuel cell buses gives a CO_2 reduction equal to the uptake of 3.100 acres of forest and a NO_x reduction equal to 10 km of 4 lanes of cars [23]. The presented results show all the environmental advantages of the buses with fuel cell technologies.

Some comparisons with different bus technologies (diesel, diesel-hybrid and fuel cell), in terms of CO_2 emissions per km travelled, have shown potentially significant benefits of FCB. Data below summarises the range of CO_2 emissions per kilometre for hybrid fuel cell buses compared with diesel and diesel hybrid buses [6].

- Fuel cell buses: 0 to 1.8 kg/km. Zero emissions are related to renewable hydrogen and electricity.

- Diesel-hybrid buses: 0.69 to 1.2 kg/km

- Diesel buses: 1.05 to 1.5 kg/km.

There is a very wide range for fuel cell buses, reflecting the wide range in CO_2 emissions for different hydrogen production pathways. At the ultra-low CO_2 end (production from renewable, nuclear or fossils fuels with Carbon Capture and Storage (CCS) technology) the CO_2 emissions are over 90% lower than a conventional diesel bus.

At today's state of the art for hydrogen production from methane (approx. 10 $kgCO_2/kg$ of H_2), there is still a CO_2 advantage over both diesel and diesel hybrid buses at the highest fuel economy for fuel cell buses.

This suggests that any medium term strategy for hydrogen bus rollout should target a CO_2 content below 10 $kgCO_2/kg$ of hydrogen and best in class fuel economy, to ensure that the deployment leads to real CO_2 savings.

7. CONCLUSIONS

Analysis of FC bus drivetrain configuration showed that the initial solution of the buses was based on configurations where a fuel cell generates electricity which is directly supplied to an electric motor.

Hybridized designs with energy storage device where the fuel cell, operating in a series hybrid configuration, became the dominant choice starting from 2005 and especially after 2010. Today, every demonstration of fuel cell buses is based on the hybrid concept.

A large number of current and completed FC bus projects demonstrate a growing interest of stakeholders and bus manufacturer to invest in the development of these technological solutions.

Lessons learned from past demonstration projects show that fuel cell buses have the potential to be operated with the same operational flexibility as a conventional diesel bus, whilst offering zero tailpipe emissions, contribution to decarbonisation of transport, reduced noise and vibration levels.

FCBs that run on hydrogen derived from 100% renewable source, offer a significant reduction in GHG emissions on a well-to-wheels basis.

Some reports indicate that the performances of fuel cell buses in-service are above expectation. One of the many barriers to their wider use is the uncertainty of hydrogen supplies and high production costs of hydrogen. Other barriers are related to the cost of fuel cells, energy storage device, and the security aspects of usage of these vehicles.

Since FC buses have a very favourable energy and environmental potential, which contributes significantly to sustainable public transport, one should expect their intensive development and commercialization in the immediate future.

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