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REGISTRATION AND SURFACE INSPECTION OF AUTOMOTIVE PRESSED PARTS BASED ON POINT CLOUD GENERATED BY OPTICAL MEASURING TECHNIQUES

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ABSTRACT: Modern quality control has become unthinkable without optical measuring systems which are intensively used in automotive industry. This paper shows the analysis of preparation of models in terms of proper positioning in relation to the digitized model and the correct interpretation of the results of quality control. Experimental results verifying the method and the theory are shown. Part of tool for pressing and fabricated physical model of passenger car's suspension control arm is compared to CAD model. Presented results of measurements show that the optical measuring systems are powerful tool for quality control, analysis and discovering of causes of faults.

KEY WORDS: 3D digitizing, Triangulation, Registration, Inspection, CAD/CAM/CAE

REGISTRACIJA I INSPEKCIJA POVRŠINA AUTOMOBILSKIH OTPRESAKA ZASNOVANA NA OBLAKU TAČAKA KOJI GENERIŠU OPTIČKI MERNI SISTEMI

REZIME: Savremena kontrola kvaliteta je postala nezamisliva bez optičkih mernih uređaja koji se intenzivno koriste u automobilskoj industriji. U ovom radu prikazana je analiza pripreme modela u pogledu pravilnog pozicioniranja u odnosu na digitalizovani model i tačna interpretacija rezultata kontrole kvaliteta. Eksperimentalni rezultati koji verifikuju metodu i teoriju su prikazani. Deo alata prese i njime izrađeno ocsilujuće rame su upoređeni sa CAD modelom. Prikazani rezultati merenja pokazuju da su optički merni sistemi moćan alat za kontrolu kvaliteta, analizu i otkrivanje uzroka grešaka.

KLJUČNE REČI: 3D digitalizacija, Triangulacija, Registracija, Kontrola, CAD/CAM/CAE

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REGISTRATION AND SURFACE INSPECTION OF AUTOMOTIVE PRESSED PARTS BASED ON POINT CLOUD GENERATED BY OPTICAL MEASURING TECHNIQUES

Milan Blagojević [1], Miroslav Živković [2], Marko Topalović [3]

1. INTRODUCTION

Classic measuring methods provide insufficient number of points for precise products surface reconstruction, because such free form surface can only be accurately reconstructed based on large number of measuring points. Non-contact digitizing is done through optical measuring systems, which captures hundreds of thousands of points in a single shot of the object. These measuring results provide very accurate computer reconstruction of shape, and so reduce development time and increase product quality. Reconstruction problems of this sort occur in diverse scientific and engineering application domains.

Optical measuring devices offer numerous advantages in comparison to the classic methods of quality control in automotive industry. Greatest advantage is possibility to determine deviation of entire geometry of measured object in reference to CAD geometry, in comparison to the classic coordinate measuring machines (CMM) which can perform control only in specific discrete points.

In the following sections, working principle of 3D scanner is described, and algorithms, on which this modern method is based, are discussed. Methodology presented in this paper is used for determination of deviation field for pressed part and scanned geometry of tool surface.

2. 3D SCANNER

ATOS (Advanced Topometric Sensor) [1] is an industrial, high resolution, white light, optical 3D scanner (Figure 1). Instead of measuring single points, full part geometry is captured in a dense point cloud which can be translated into polygon mesh describing the object's surface and primitives precisely [2]. 3D scanner consists of sensor, control unit, computer hardware and software [3]. Sensor of optical measuring system consists of two high definition cameras and a projector.

The scanning is based on optical triangulation and stereo-viewing [4]. A projector is used to project striped fringe patterns onto the object's surface [5]. Change of shape of

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lines projected on irregular surface of measured object is recorded with two cameras. These images are captured simultaneously by the two measurement cameras from different angles. ATOS digitizing sensor calculates its 3D coordinates based on visible reference objects - uncoded reference points (Fig. 1) [1]. This stereo-setup supports an easy and very accurate 3D capturing of the reference objects. Reference point diameter and strategy of point application to object's surface are function of used measuring volume. With the help of digital image processing, 3D-coordinates are computed fast and with high accuracy for up to 4 million camera pixels using the supplied high end System PCs. Coordinates of a point on measured object are obtained by triangulation using appropriate camera and projector points. The captured scan data is then automatically integrated in the predefined reference marker framework. The additional data captured with two cameras of the ATOS system are used to verify the calibration of the system, detect movements and high ambient light changes during the measurement and verify the matching accuracy of the individual scans into the global coordinate system.

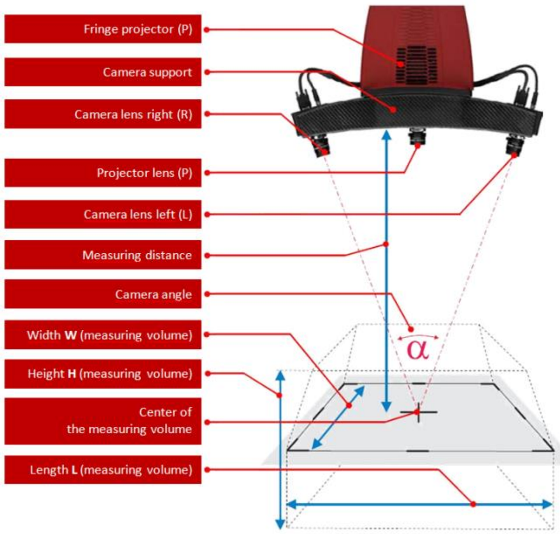


Figure 1. *Measuring Volume of Optical Measuring System*

Depending of complexity of measured object geometry, every 3D measurement consists of number of individual measurements. Each individual measurement means is scanning part of object surface which is visible with both cameras of measuring device [6]. Throughout multiple individual measurements, the entire surface of the measuring object is recorded while scanned surface is represented by the network of triangles (Figure 2). Polygons are oriented so that the normal is always directed towards the sensor.

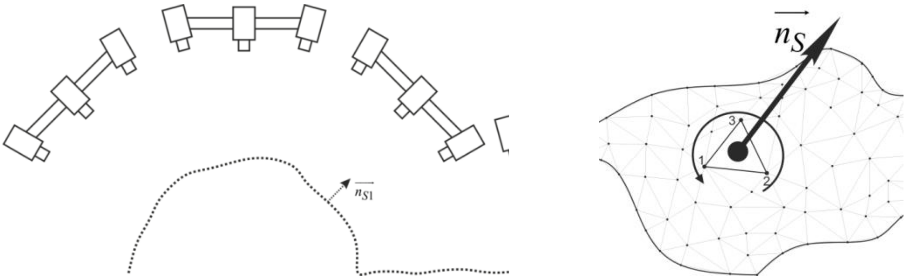


Figure 2. *Normal vectors on digitized surface*

3. POINT CLOUD REGISTRATION

The first of individual measurements is placed in arbitrary coordinate system, while every subsequent measurement overlaps with previous one, and it's placed in common coordinate system (coordinate system of the first measurement). This process is called registration and it is characteristic for all measuring systems, optical in particular, which operate on point clouds. Beside the task of individual measurement transformation into a global coordinate system, there is also a need to transform digitized model into the coordinate system of the CAD model. Most common methods for bringing two point clouds in mutually required position are ICP algorithm and barycentre method.

The majority of commercial optical measuring systems use modified ICP algorithm with matching points used for transformation already known. These points are uniquely determined by random application of adhesive reference objects on measured object surface and/or around it. Measuring devices automatically identify these matching points in every individual measurement. The fact that these reference objects are placed randomly in measured volume means that the reference objects identified in every individual measurement have unique configuration (mutual position). Searching through all relative position of all recorded points makes possible to determine corresponding matching point pairs required for registration. Latest generation optical measuring systems perform registration using all points in observed clouds and find matching points. These matching points are then used for bringing individual measurement into global coordinate system.

3.1 Iterative Closest Point (ICP)

ICP is an iterative algorithm for matching point clouds. Consider 2 point clouds where (point cloud A consists of n points) and (point cloud B consists of m points). We are interested in a one-to-one matching function that minimizes the root mean squared distance (RMSD) between A and B. Mathematically, we want to minimize the following:

$$RMSD\left(A, B, \mu\right) = \sqrt{\frac{1}{n}\sum_{a \in A}\left\| a - \mu\left(a\right)\right\|^{2}} \tag{1}$$

Incorporating rotation and translation into the matching, we want to find:

$$\min_{\mu:A\to B,\ t\in R^d,\ R\in SO(d)} \sum_{a\in A} \left\| Ra - t - \mu(a) \right\|^2 \quad (2)$$

where R is the rotation matrix, t is the translation vector and SO(d) is the set of special orthogonal matrices in d dimensions.

The ICP algorithm seeks to minimize the RMSD, by alternating between a matching step and a transformation step. In the matching step, given a certain rotation and translation, the optimal matching is calculated by minimizing the RMSD. In the transformation step, given a matching, the optimal rotation and translation are computed. This alternating process terminates when the matching remains unchanged in sucessive iterations.

ICP algorithm, matching two point clouds, A and B, consists of the following steps:

1. Initialize (identity matrix), $t = 0$
2. Matching Step: Given and , compute optimal by finding $min_{\mu}\ RMSD\ (A, B, \mu)$
3. Transformation Step: Given μ, compute optimal R and t, by $min_{R,t}\ RMSD\ (RA - t, B, \mu)$
4. Go to step 2 unless μ is unchanged.

The matching steps, find closest in the following manner: (a) construct Voronoi diagram on B and (b), do point-location in V or (B). In practice, a k-d tree is used to find the nearest-neighbour quickly. The matching step is usually the slowest part of the algorithm.

4. SURFACE INSPECTION

Poligonized mesh, obtained as a result of digitalization, with certain accuracy describes surface of measured object. Determination of measurement accuracy is beyond the scope of this paper. Normals on digitalized surface are oriented toward sensor of measuring system (Fig. 2).

During process called polygonization, software creates polygons (triangles) by connecting neighboring points in point cloud obtained by 3D scanning (Figure 2b). Software used for generation and analysis of deviation field imports CAD model and transform it in poligonized mesh, with adjustable polygonization parameters.

Deviation field is generated by software which loops through all points in poligonized mesh obtained by scanning, determines distance between the observed point and triangles in mesh obtained from CAD model (Figure 3). Searching for points is performed on search radius defined by user in direction normal to the current triangle. Since arbitrary point in poligonized mesh can belong to n triangles, this search is performed n times. When all searches are performed for observed point, obtained deviation is summarized as vectors. After search is performed for all points and for all triangles that they belong, entire deviation field is generated. Algorithm for deviation field generation is shown in Table 1.

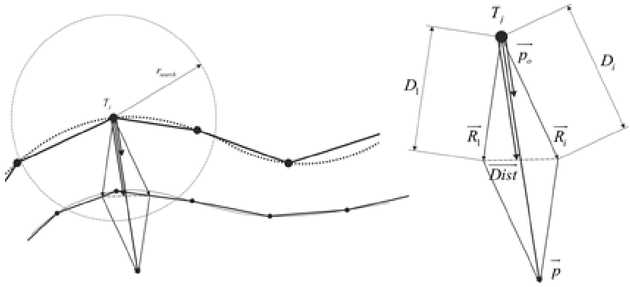


Figure 3. *Determination of distance between observed point in scanned mesh and triangles in CAD mesh*

Table 1. *Algorithm for deviation field generation*

Loop over points in polygonized mesh of scanned model
Loop over triangles that observed points belong
Loop over triangles in polygonized mesh from CAD model
Determination of intersection point defined by normal on triangle in polygonized mesh in current point through current triangle in CAD model polygonized mesh
If intersection exists
Calculate vector (Ri)
Based on coordinates of current point and intersection point calculate lenght (Di)
Based on coordinates of current point and intersection point
End of loop over triangles in polygonized mesh from CAD model
End of loop over triangles that these points belong
Determination of vector (p) using vector summarization of (Ri)
Determination of unit vector (p0)
Determination of average distance (Dis) based on (Di)
End of loop over points in polygonized mesh of scanned model

Relationship between normals on polygonized mesh has influence on results interpretation for deviation field (Figure 4). In case when scalar product of normals for adjacent triangles is positive, (normals facing the same section of space), positive deviation means that on that spot there is more material then needed and vice versa. In case when mentioned scalar product is negative, previous analysis have oposite conclusions. In practice, it means that convex surfaces, for example pressed parts, have normal which exit material for CAD model and normal which face sensor for digitalized model. Scalar product of these normal is positive. On the other hand, scanned models of pressing tools have their normal facing cavity.

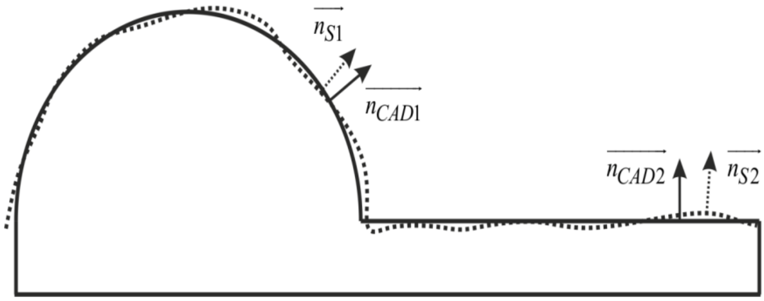


Figure 4. *Normal on scanned surface and CAD model*

5. RESULTS

The methods presented will be confirmed on the example of passenger car's suspension control arm. Based on the 3D digitalization of physical model using optical measuring systems TRITOP and ATOS (Figure 5) the reconstruction of CAD model (Figure 6) is performed [2]. Then, pressing tool design is carried out, fabrication and 3D digitizing of tool surface. Digitized surface of pressing tool and pressed part is shown in Figure 7.

All models are set so that the normal directed out of paper. When determining the deviation field of physical model in reference to CAD, models on Figures 6 and 7b are compared. In this case the dot product of normal vectors is a positive. On other side, when determining the deviation field of pressing tool in reference to CAD, models on Figures 6 and 7a are compared and the dot product of normal vectors is a negative. As a result, deviation fields are generated. Based on these fields engineers can determine necessary steps to improve matching between shape of the real pressed part and the desired shape of the 3D CAD model. These steps could mean changing the shape of the pressing tool, additional treatment of pressed part or any other change in the production process. Deviation field for both cases of dot products of normal vectors are shown in Figures 8 and 9.

(a) *(b)*

Figure 5. *3D digitization of physical model: (a) TRITOP and (b) ATOS*

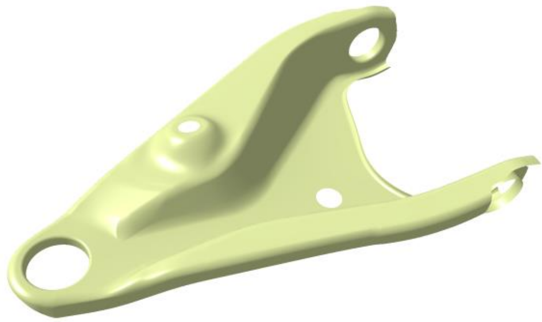
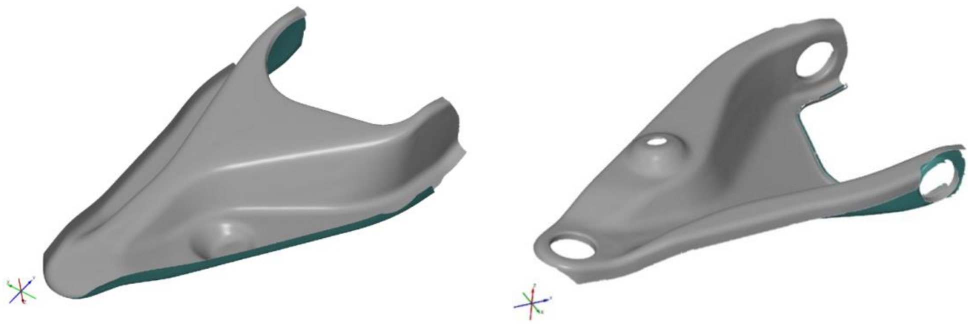


Figure 6. *CAD model of passenger car's suspension control arm*



(a) *(b)*

Figure 7. *Digitized surface of (a) pressing tool and (b) pressed part*

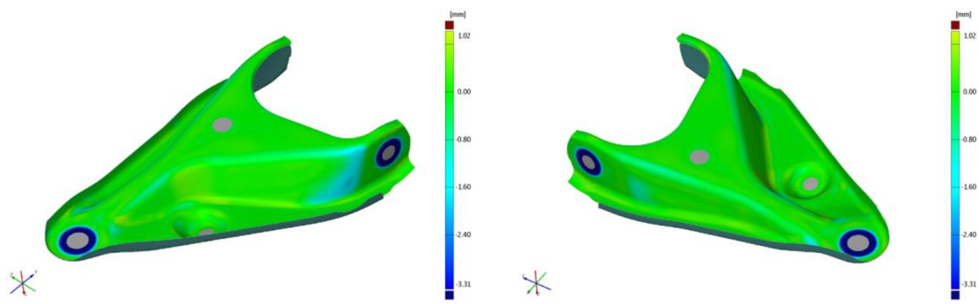


Figure 8. *Deviation field in case when dot products is less than zero*

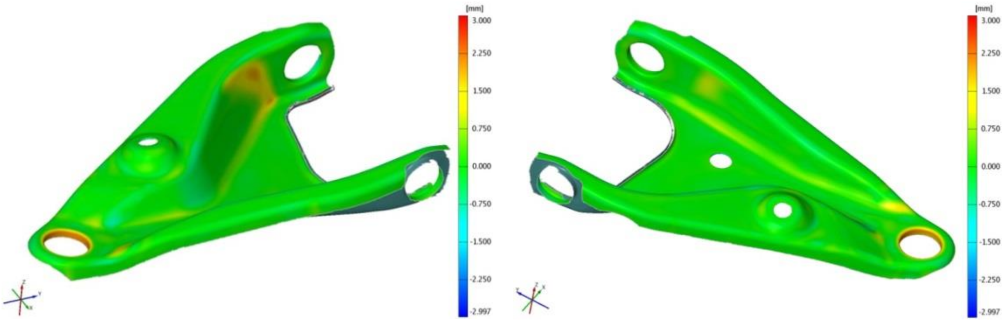


Figure 9. *Deviation field in case when dot products is greater than zero*

CONCLUSION

During recent years, optical measuring systems, 3D scanners in particular, become standard for quality control in automotive industry. Optical digitizing is part of advanced process chains in the development of products and production processes for sheet metals and tools. Presently optical measuring systems are used to optimize time, costs and quality of the product, thus increasing the competitiveness of companies. In the future, this measuring technology will be used increasingly for automated inspection tasks due to its further integration in production processes and the availability of powerful data processing systems.

In this paper theoretical basics on which devices for pressed part quality control operate are presented. Emphasis is placed on registration process and generation of deviation field, as most important components of quality control. Knowing theoretical basics enables proper understanding of obtained model and correct interpretation of measuring results.

The application examples showed the practical use of optical measuring technology in automotive industry. Thanks to the non-contact data acquisition, the influence on the measuring object is very low, so that a large number of measuring points does not negatively affect the tested object. Precise deviation field requires high density point clouds. This allows accurate measurement and capture of the shape and size of the visible surface of almost any 3D object. Their usability for pressed part deviation analysis gives them significant advantage in comparison to the CMM.

ACKNOWLEDGMENT

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SYSTEM FOR SIGNALIZATION OF SPEEDING AND LIMITING THE SPEED OF THE INTERNAL TRANSPORT EQUIPMENT

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ABSTRACT: Modern production requires appropriate logistic approaches to reduce cost and provide better safety conditions during material handling by the forklifts. A forklift can be one of the most dangerous pieces of equipment in the workplace even at lower loads and speeds. The new generation forklifts are equipped with modern control and security systems that make it easier to use. However, older generations of forklifts that do not contain modern control systems are still in use. With lower stability and greater manoeuvrability, combined with uncontrolled traffic areas as well as speed at workplaces, forklifts are involved in many incidents. Even if people are not injured in accidents, there is often damage to buildings, storage systems or stock. This paper describes a safe system that prevents one of the main causes of accidents - speeding. The developed system is related to signalization of speeding as well as to limiting the speed of the electrical forklifts.

KEY WORDS: forklift, logistic, internal transport, safety

SISTEM ZA SIGNALIZACIJU PREKORAČENJA BRZINE KAO I NJENO LIMITIRANJE KOD SREDSTAVA UNUTRAŠNJEG TRANSPORTA

REZIME: Moderna proizvodnja zahteva odgovarajuće logističke pristupe u cilju smanjenja troškova i obezbeđivanje boljih sigurnosnih uslova tokom rukovanja materijalom viljuškarima. Viljuškar može biti jedan od najopasnijih elemenata opreme na radnom mestu čak i pri malim težinama tereta i brzinama. Viljuškari nove generacije su opremljeni savremenim sistemima upravljanja i sigurnosti koji olakšavaju njihovu upotrebu. Međutim, još uvek je jako zastupljena u upotrebi i starija generacija viljuškara koji ne sadrže savremene sisteme upravljanja. Sa smanjenom stabilnošću i većom manevarskom sposobnošću, u kombinaciji sa nekontrolisanim saobraćajnim uslovima, kao i brzinom na radnim mestima, viljuškari su uključeni u veliki broj incidenata. Čak i ako ljudi nisu povređeni u nesrećama, često se oštećuju objekti, sistemi za skladištenje ili materijal. Ovaj rad prikazuje bezbedonosni sistem koji sprečava jedan od glavnih uzroka nesreća, prekoračenje brzine. Razvijeni sistem se odnosi na signalizaciju prekoračenja brzine i ograničavanje brzine električnih viljuškara.

KLJUČNE REČI: viljuškar, logistika, unutrašnji transport, bezbednost

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SYSTEM FOR SIGNALIZATION OF SPEEDING AND LIMITING THE SPEED OF THE INTERNAL TRANSPORT EQUIPMENT

Milan Đorđević [1], Rodoljub Vujanac [2], Nenad Miloradović [3]

1. INTRODUCTION

Internal transport in the strict sense of the word is the transfer of the work items in the production. The transfer of the object is carried out from the warehouse to the production, then within and between production facilities, from the production to the warehouse and within warehouse facilities. Complete internal transport consists of multiple operations such as: loading, transfer, unloading, reloading, where reloading is a combination of loading and unloading of material. Processes of individual, serial or mass production demand the introduction of a suitable method of internal transport, which should be productive, cost-effective, profitable and safe [1]. Efficient and flexible material flow requires appropriate logistic approaches to reduce cost and provide better safety conditions. Growing from individual to serial and from serial to the mass production, increases the degree of mechanization and automatization of transport means. The level of mechanization and automatization of transport means departs from hand trolleys as the least mechanized means used in individual classical production, motorized trolleys, towed trains and forklift trucks (forklifts) to the elevators and conveyors as highly mechanized tools used for modern equipped serial and mass production [2, 3].

A forklift is a powerful tool that allows one person to precisely carry, push, pull, lift, stack or tier large heavy loads with little effort. Using a tool such as a forklift, cart or hand truck instead of lifting and carrying items by hand can reduce the risk of suffering a back injury. There is a wide range of forklifts, including pedestrian operated and ride-on forklifts. Forklifts vary in size, ranging from 1 t capacity for general warehouse type work, up to 50 t capacity for shipping container work. They can be powered by batteries, propane, gasoline or diesel fuel.

Approximately 35000 serious injuries and 62000 non-serious injuries involving forklifts occur in the United States every year. OSHA estimates that 11% of all forklifts are involved in accidents every year [4]. The most common causes of death injuries with a percentage share are shown in Table 1. Even at low speeds, forklifts can cause serious injuries and fatalities. It is not just the forklift operator who can be injured - a forklift or its load can strike pedestrians, too. The human and financial cost of forklift-related incidents for workers, industry and the community is substantial. However, incidents can be prevented, especially when workers and persons conduct a business or work together to improve health and safety outcomes at work through simple and safe practices such as:

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- observing speed limits and warning signs,
- wearing correctly fitted seat belts,
- slowing down and
- sounding the horn at an intersection.

Table 1. *Causes of fatal injuries by forklift truck handling [4]*

Fatal accident type	Percentage (%)
Crushed by vehicle tipping over	42
Crushed between vehicle and a surface	25
Crushed between two vehicles	11
Struck or run over by a forklift	10
Struck by falling material	8
Fall from platform on the forks	4

The main causes of accidents with forklifts are:

- Lack of operator training,
- Poor maintenance of forklifts.

Modern means of internal transport including forklifts have the capability of software speed limitation. Thus, when entering the production plant or warehouse, the worker presses the button with a maximum speed of 20 km/h in the mode of internal operation in which the speed is limited to 5-6 km/h. The most modern forklifts receive a signal from the transmitter through the doors and automatically switch from fast to slow mode and vice versa. However, older models of forklift trucks that do not have the option of changing modes to limit speed are still in use. The paper presents a technical solution for speed limit that can be installed in any electric forklift. The idea was to develop a safe system of work to control risks and help prevent forklift-related incidents.

2. PROBLEM IDENTIFICATION AND PROJECT TASK

2.1 Problem identification

The company's management is required to provide secure operating systems, with part of the responsibility being taken over by the supervisors as well as by the operators themselves. Managers or internal inspectors must control the operation of the operator following a number of rules. The most important rule is the respect for the predicted speed. The procedures stipulate that the speed of the vehicle must be adjusted in accordance with the characteristics of the roads, the type of goods being transported, and the possibility of stopping the vehicle. Speed is particularly limited near intersections, in curves, on slopes, on slippery surfaces, in cases of low visibility, narrow passages, etc.

Maximum speed has been limited as following:

- At the open space, it is limited to 10 km/h in unloaded condition or up to 5 km/h in loaded condition.

- At the enclosed space, regardless of whether the forklift is empty or loaded, it is limited to 5 km/h.

These speeds are maximum allowed, but this does not mean that they can always be achieved. When driving conditions require it, a lower driving speed is appropriate for safe driving. Speed limit signs are placed along the logistics corridors. Although the speed limit signs are placed on all roads within the factory, Figure 1, it was noticed that drivers often did not respect the limits that are prescribed.

Firstly, a retraining of the drivers must be done and a checklist of safe handling of logistic equipment must be printed for all logistic equipment, Figure 1.

Operator's Daily Checklist: Electric Forklift

Check each item before the shift starts. Put a check in the box if the item is OK.
Explain any unchecked items at the bottom and report them to a supervisor.
Do not use an unsafe forklift! Your safety is at risk.

Forklift Serial Number:

Operator:

Hour Meter Reading: Date:

✓	Visual Check
	Tires are inflated and free of excessive wear or damage. Nuts are tight.
	Forks and mast are not bent, worn, or cracked.
	Load back rest extension is in place and not bent, cracked, or loose.
	Overhead guard is in place and not bent, cracked, or loose.
	Attachments (if equipped) operate OK and are not damaged.
	Forklift body is free of excessive lint, grease, or oil.
	Hydraulic oil is full and free of leaks.
	Battery connections are tight.
	Covers over battery and other hazardous parts are in place and secure.
	Load rating plate is present and readable.
	Warning decals and operators' manual are present and readable.
	Seat belt or restraint is accessible and not damaged, oily, or dirty.
	Motor runs smooth without sudden acceleration.
	Horn works.
	Turn signal (if equipped) operates smoothly.
	Lights (head, tail, and warning) work and are aimed correctly.
	Gauges and instruments are working.
	Lift and lower operates smoothly without excess drift.
	Tilt operates smoothly without excessive drift or "chatter".
	Control levers are labeled, not loose or binding and freely return to neutral.
	Battery charge level is OK while holding full forward tilt.
	Steering is smooth and responsive, free of excessive play.
	Brakes work and function smoothly without grabbing. No fluid leaks.
	Parking brake will hold the forklift on an incline.
	Backup alarm (if equipped) works.

Figure 1. *Operator's daily checklist: electric forklift*

The next step is to introduce driver control by placing markings on vehicle wheels, Figure 3, through which excessive speed could be detected. When the driver exceeds the speed of 5 km/h, the observer on the side could observe an overrun, since at 120 rpm there is a "wagon-wheel" effect when the wheel seems to stand in place. Two basic problems with this system are:

- The observer (inspector) must be close to the side of the vehicle, in order to note the effect;
- The effect is achieved at a rotation speed of 120 rpm, which, for the wheel radius of 15 cm, amounts to 6 km/h. For vehicles with wheels radii of 25 cm, the same effect is achieved at a speed of 11 km/h.
- The driver has no insight into his speed.

Figure 2. *Sign of speed limit within production lines*

Figure 3. *Speed observation over the mark on the wheel*

All of these above mentioned problems were sufficient reason to approach the development of a system that will be able to signal when the operator operating the forklift exceeds the allowed speed over 5 km/h and the possibility of automatic limitation to 10 km/h.

2.2 Project task

Since internal logistics has a variety of transport systems, it was necessary to design and implement a system that would cover the entire factory fleet. The set up requests were:

- Precise speed measurement (most available transport systems did not have this).
- The sound signalization should warn the driver that he exceeded the speed of 5 km/h.
- Light signalization - a yellow rotary light that would be noticeable at a distance of 200 m and which would alert pedestrians in the vicinity of a vehicle moving at a speed higher than permitted. In addition, internal inspectors would be able to spot a vehicle moving at a speed higher than permitted from a long distance.
- Physically limit the speed up to 10 km/h. Vehicles could travel at speeds over 20 km/h.

3. DESCRIPTION OF A NEW SYSTEM

The system is designed to set 6 neodymium magnets on the hub of wheel which will rotate together with the hub of wheel [5]. When wheel rotates, the magnets pass at about 5 mm of distance from the fixed magnetic encoder - reed relay, Figure 4. Each time when a magnet passes near the magnetic encoder, an impulse is induced and sent to the electronic module for speed limit and signalling (EMSLS) where the impulses are added. The schematic layout of the system is shown in Figure 5.

Figure 4. *The wheel hub with magnets and magnetic encoder*

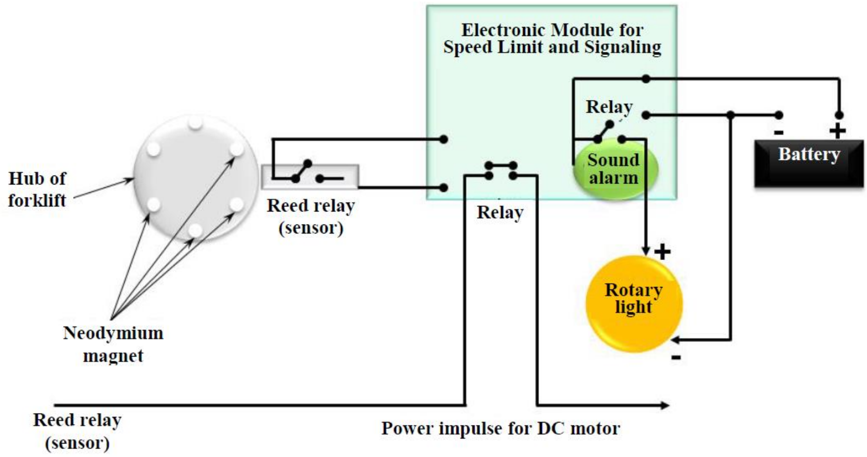

Figure 5. *Schematic layout of the system*

EMSLS (which contains ATMEL microcontroller C8051) is programmed for each type of vehicle, taking into account the dynamic radius of the tire (important for precise measurement of the speed of the vehicle). Through the number of pulses and a time base for a specified range of tires, the speed can be generated, with measurement error below 10% (meets strict requirements). An external programmer programs each microcontroller. The hysteresis loop for „cut off / cut in" DC power impulse (written in assembler) provided fine or "soft" crossings from „cut in" to „cut off" conditions. This means that the driver would not feel sudden vibrations when breaking the motor.

Based on the measured speed, EMSLS decides which action to take. If a speed of 6 km/h is reached, a 72 dB sound alarm (piezo buzzer) is activated, signalling the driver of the vehicle that the programmed limit is exceeded (5 km/h). In addition, the light signalization, yellow rotary light, Figure 6, is included, which warns all persons near the vehicle that there is a potential danger. That is a signal to the competent inspectors that the driver has exceeded the permissible speed.

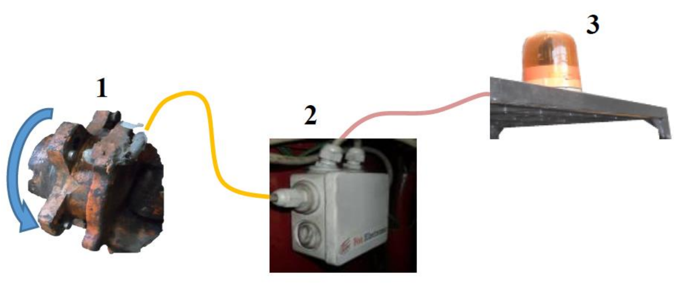

Figure 6. *Basic parts of the system: 1. The wheel hub with magnets and reed relay (sensor), 2. EMSLS (Electronic Module for Speed Limit and Signalling), 3. Rotary light*

The EMSLS will give a signal to switch-off the drive when the operator reaches the second speed limit with the vehicle (in this case - 10 km/h). For electric forklifts, the speed is limited by the break of the current drive to the DC motor using the NC relay in the electronic module, while in the case of gas forklifts, the speed is limited by the interruption of the fuel supply (reprogramming the ECU of the newer generation).

4. CONCLUSIONS

Manually operated forklifts are widely used in the implementation of transhipment - storage and other processes in intralogistics today. However, constant demands for the increase of efficiency, reliability and security of logistics processes in this area imply the research and implementation of new solutions. One of the directions of the research is the application of modern solutions in the field of IT, which significantly provides the preconditions for increasing productivity and security. Clearly, this approach has some disadvantages - it requires additional investments in equipping forklifts as well as additional employee training. The most important advantage of the described system for signalization of speeding and speed limitation is the improvement of safety conditions for operation. After the introduction of this system, no injuries were found in which the causative agent was a logistical means of transport. In addition, savings of 18% in energy consumption are used to start the engine of transport vehicles, which, in addition to economically positive results, also reflects the social responsibility of the company that contributes positively to the environment.

ACKNOWLEDGMENT

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FIRE SAFETY OF CNG BUSES – PROPER EXPERIENCES

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ABSTRACT: Natural gas as engine fuel is a commercially very attractive option for medium and heavy duty vehicles. A combination of low gas price and incentives for environmentally friendly solutions are key arguments for bus fleet operators to convert to natural gas powered vehicles. From the second side, fuel can be dangerous if handled improperly. Gasoline and diesel are potentially dangerous fuels, but over time we are learned to use them safely. The same is true with liquefied petroleum gas and natural gas, as well as hydrogen. For commercial vehicles both, compressed natural gas and liquefied natural gas are equally relevant options. Recent fire accidents involving natural gas buses have shown that cylinders may explode through compliant with current UN ECE R110 regulation. Such a repeated scenario is certainly not acceptable having in mind the tremendous amount of energy released when a compressed cylinder burst. Recent accidents detailed in this paper highlights potential improvements in current natural gas buses fire safety concepts. Fire safety should not solely rely on cylinder behaviour when exposed to fire but also to additional and upstream fire safety barriers. Thermal fuses cannot be seen any more as an ultimate option to control cylinder burst in case of fire.

KEY WORDS: Fire safety, CNG buses, City transport

POŽARNA BEZBEDNOST CNG AUTOBUSA – PRAVA ISKUSTVA

REZIME: Prirodni gas kao pogonsko gorivo je komercijalno, vrlo atraktivna opcija za srednja i teška vozila. Kombinacija niske cene gasa i podsticaja za ekološki prihvatljivo rešenje su ključni argumenti za operatere voznih parkova da se vozila pogone na prirodni gas. Sa druge strane, gorivo može biti opasno ako se nepravilno rukuje. Benzin i dizel su potencijalno opasna goriva, ali vremenom smo naučili da ih bezbedno upotrebljavamo. Isto važi i za tečni naftni gas i prirodni gas, kao i za vodonik. Za komercijalna vozila, komprimovani prirodni gas i tečni prirodni gas su jednako relevantne opcije. Nedavne vatrogasne nezgode koje uključuju autobuse za prirodni gas pokazale su da cilindri mogu eksplodirati u skladu sa važećom regulativom UN ECE R110. Takav ponovljeni scenario sigurno nije prihvatljiv s obzirom na ogromnu količinu energije koja se oslobađa kada se komprimovani cilindar rasprsne. Nedavne nesreće opisane u ovom radu ističu potencijalna poboljšanja postojećih koncepta zaštite od požara u autobusima sa prirodni gasom. Protivpožarna sigurnost ne treba isključivo da se osloni na ponašanje cilindra kada je izložen vatri, već i na dodatne protivpožarne sigurnosne barijere. Termalni osigurači se više ne mogu gledati kao vrhunska opcija kontrole cilindara u slučaju požara.

KLJUČNE REČI: Protivpožarna bezbednost, CNG autobusi, Gradski prevoz

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FIRE SAFETY OF CNG BUSES – PROPER EXPERIENCES

Saša Milojević [1], Radivoje Pešić [2], Dragan Taranović [3]

1. INTRODUCTION

The transport sector has the second biggest greenhouse gas emissions in the EU. More than two thirds of transport-related greenhouse gas emissions are from road transport. Clean transport systems can fully meet the energy demand of the transport sector. Alternative low-carbon fuels should gradually substitute fossil fuels for transport propulsion in the long term. Clean and energy efficient vehicles have an important role to play in achieving EU policy objectives of reducing energy consumption, CO2 emissions, and pollutant emissions [1]. Natural gas as an automotive fuel offers important benefits to consumers, the environment and to the economy as a whole. It provides a quick and cost-effective way to meet key objectives of the EU, including decarbonising road transport and improving air quality in cities. Natural gas as a vehicle fuel is available as compressed natural gas (CNG) and liquefied natural gas (LNG) for cars, vans, buses and trucks, with many different models on the market today from established manufactures. LNG is furthermore becoming the fuel of choice for the shipping industry.

According to previous, natural gas as fuel for motor vehicles has more and more share and like the consequences to this fact are that today world has approximately 22.5 million of natural gas vehicles (NGVs); (in Europe 1.76 million). In the Republic of Serbia, in traffic exist more than 880 NGVs (90 heavy duty vehicles, where is about 60 CNG powered buses and 800 cars and light duty vehicles) [2]. The number of CNG vehicle will be on the rise in Republic of Serbia, especially for public and private vehicles due to the introduction of CNG vehicles refuelling infrastructure.

CNG is stored on board vehicles under 20 MPa in metallic or composite cylinders. Cylinders are manufactured under very strict safety norms and are subject to tests with pressures much higher than the ones existing during a regular refilling. Design and testing pressure is usually 30 MPa, they do not explode at less than 46 MPa, and the working pressure is 20 MPa. Because of reason of space, for buses, cylinders are associated in series (cylinders rack) and located on the roof [3,4]. By application of the CNG cylinders, that made by lightweight materials type III, and reconstruction of the supporting bus roof structure according to UN ECE Regulation No. 110, the aspects of vehicles safety in traffic was kept on high level. In addition, the rest of the CNG fuel line equipment must be also in accordance with UN ECE Regulation No. 110 and 115 [5,6].

Usually when it comes to CNG vehicle safety, all subjects in NGVs service have tended to focus their attention on the fuel cylinders. In reality CNG cylinder failures are

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relatively rare, certainly much less common than CNG vehicle fires. Potential causes of fire or ignition sources are also engine compartment and exhaust system, low voltage battery, heaters, wheel, garages, interior, etc. Mechanical (road accident) and thermal aggressions (on board or nearby fire) are the main causes that may lead to any of hazards. Whichever fuel is used, most vehicle fires have a non-fuel origin; unlike for other fuels, however, the consequences of a fire on the CNG fuel system can be very different due to the potential for high pressure jet flames to occur and in rare cases, cylinder failure and explosion.

Although CNG vehicle fires are no more common than fires on petrol and diesel vehicles, they do have their own special characteristics, so it is necessary to take them into account when implementing ways of preventing and controlling them. Therefore, we will concentrate in this article on CNG bus fire safety issues. After introducing the CNG bus fire safety topic, we will study some CNG bus fires will extract "lessons to be learned" for CNG and other compressed fuels (hydrogen as example).

1.1 Natural Gas as Fuel for Motor Vehicles

Natural gas is a naturally occurring fuel which requires very little processing before use. Chemically it normally consists of over 90% methane with smaller amounts of ethane, propane, butane, CO_2, and other trace gases. The high methane content gives natural gas its high octane rating (120−130) and clean−burning characteristics, allowing high engine efficiency and low emissions [7].

From the other side, it is notable that natural gas in normal conditions has a low density of energy per unit volume. To meet all requirements needed to become engine fuel, it shall be a subject to appropriate treatment. The easiest way is to use CNG stored under high pressure into cylinders on the vehicle (working pressure of 20 MPa). Another possibility for increasing the energy density of natural gas in the fuel tank to the vehicle is its conversion into liquid form through the cooling up to (−162 °C), and storing it into cryogenic cylinders like LNG [7,8].

Before discussing the NGVs design, it is very important to understand some relevant properties of natural gas like vehicle fuel what makes this fuel different from gasoline or diesel. The items below summarize the basic differences between the properties of gaseous and liquid fuels that influence the NGVs design changes [7]:

- it is non-toxic, neither carcinogenic nor corrosive gas, but it is the stuffy
- natural gas is invisible but must been odorized so its presence can be detected
- unlike gasoline vapours, natural gas is lighter than air (methane has density of 0.68 $kg \cdot m^{-3}$ at 15 °C) and it is in the gaseous form at atmospheric conditions. In an event of a leak, this property allows to quickly rise and disperse in the atmosphere, while the propane (1.87 $kg \cdot m^{-3}$) and butane (2.44 $kg \cdot m^{-3}$) are heavy than air, and lower to floor
- Natural gas has an auto ignition temperature of around (480 to 650 °C) whereas gasoline is approximately (260 to 430 °C) and diesel less than (260 °C). This relatively high auto ignition temperature for CNG is an additional safety feature of this fuel; and
- Methane has a very selective and narrow range of flammability. The mixture of gas in air by volume that will support combustion is between (4.4 and 15%). In other words, with less than (4.4%), of the methane in air, the mixture will not burn because it is too lean, and with greater than (15%), the mixture is too rich and will not burn. Ignitable range for gasoline is between (1.4 and 7.6%) and around (0.6 to 7.5%) for diesel.

2. PROTOTYPE CNG BUS DESIGN PROPOSITION

2.1 Existing technical solutions for NGVs

Substitution of existing fuels by natural gas in road transport can be realized by introducing of new vehicles equipped with original CNG engines, or as a first step, by converting engines of existing vehicles to CNG drive. To introduce natural gas as a fuel for road transport, the following options are possible [9]:

- modification of a gasoline engine to CNG combustion (so called conversion to a dedicated fuel)
- modification of a gasoline engine to either CNG or gasoline (two way/bi-fuel) combustion
- conversion of a diesel engine to dedicated CNG (spark ignition) combustion; and
- conversion of a diesel engine to dual fuel (gas and diesel combined) combustion.

For existing buses, driven by diesel engine, there are two options for conversion on CNG drive: conversion for dedicated or dual fuel combustion. The option can be selected, depending on the engine characteristics and the working conditions (routes, working time, available refuelling network etc.).

2.2 Option of CNG storage and propulsion system demonstrated on city bus

According to author's experiences, the best option for reconstruction of existing city buses is the using of completely new propulsion system with dedicated CNG combustion, Figure 1. In the bus, need to be integrated modern automatic fire protection system.

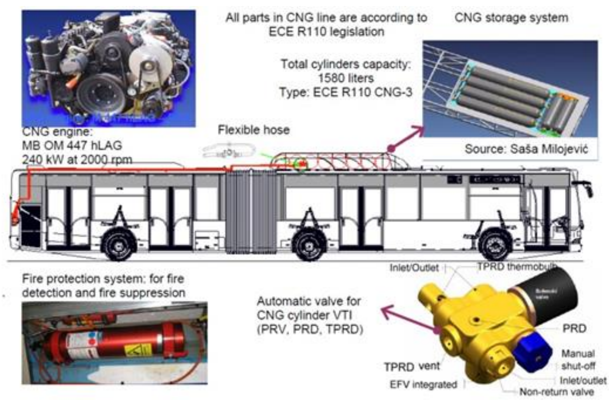

Figure 1. *Proposed design of CNG fuel line equipment installed on the articulated bus CNG-AS®*

On the Figure 1 are shown parts of the installation for CNG supply from bus roof mounted gas cylinders to the engine that is proposed to prototype version of articulated bus CNG-AS®.

The retrofit of diesel bus into dedicated NGV was realized with the joining of the CNG cylinders with the original rack, to the bus roof. It was selected CNG storage system that includes type III cylinders composed of an aluminium 6061 liner reinforced by carbon fiber in epoxy resin (Dyne-cell®), with a favorable ratio between weight and volume (0.3–0.4 kg·L^{-1}) [3,4,10].

3. FURTHER IMPROVING THE FIRE SAFETY OF CNG BUSES

Although CNG vehicle fires are no more common than fires on petrol and diesel vehicles, they do have their own special characteristics, so it is necessary to take them into account when implementing ways of preventing and controlling them.

Vehicle fires can have a number of causes, the vast majority of which are nonfuel related. For example, fire can be caused by electrical faults, or start in the engine compartment due to the failure or leakage of operating fluid hoses causing the spilling of lubricants, hydraulic fluids or even coolant on hot engine surfaces. Vehicle fires can also originate in seized brakes and overheated tires. Vehicles have been set on fire by occupant smoking, or even as a result of arson. Engine compartment fire is the most frequent type of vehicle fire (71%), Figure 2 [11].

Fire on some CNG vehicles has been caused by gas leaked from damaged CNG components (e.g. pipe connections), which is then ignited by the numerous live ignition sources on an operating vehicle. Such fires can be started in traffic collisions when the CNG components are damaged resulting in gas release.

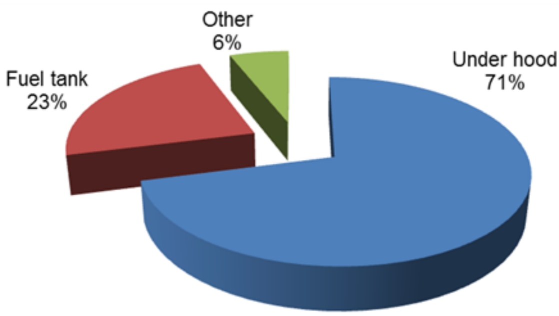

Figure 2. *Causes of vehicle fire*

3.1 Consequences of a CNG vehicle fire

On a CNG vehicle, a fire not involving the gas system has similar characteristics and outcomes as vehicles using the conventional fuels. However, if the gas system develops a leak or releases gas, or the CNG cylinder pressure relief devices (PRDs) are activated, a gas fire will be added to the general fire. If the gas is released at high pressure, e.g. through the PRDs, it can be in the form of a large, powerful jet flame which can reach several meters beyond the vehicle perimeter, Figure 3 [3].

Figure 3. *Long and intense jet flame in a CNG bus fire (Jet flame direction is good, but still perilously close to inhabited building)*

Jet flame may take place suddenly and present an unexpected hazard which could be very injurious to persons involved who are not prepared for this event. Vehicle drivers and the emergency service personnel should be aware of this possibility and take appropriate precautions to avoid injury or damage to both themselves and bystanders or other vehicles.

If the fire finally reaches the on-board fuel storage area but fortunately very rarely, the PRDs fail to deploy, a cylinder failure might result, in some cases as soon as within a few minutes of the fire starting, with explosive pressure and shrapnel reaching people and vehicles several meters away. In most explosions the vehicle is completely destroyed, but it is the projectiles that cause the most damage and casualties, at a longer distance, rather than the pressure wave itself.

The most unwanted event in case of CNG bus fire is the burst of one or more of the compressed storage cylinders located on the roof of the vehicle. Cylinder burst is definitely not a tolerable option having in mind the tremendous amount of mechanical and chemical energy released in the course of this event.

The current safety strategy to prevent tank burst consists in fitting pressurized cylinders with devices that release stored compressed natural gas as they fuse under the effect of temperature rise (fire). The melting temperature of these fuses is about (110±1°C). This is so called temperature pressure relief devices (TPRDs), which are integrated inside automatic cylinder valve, Figure 1. In practical terms, to prevent cylinder burst, internal cylinder pressure has to decay before the fire degrades the mechanical strength of the CNG cylinder. Experience shows that unprotected cylinder (inhibited PRDs) cannot survive a standard bonfire test for more than few minutes. The main cause for a tank to burst is the decay of its mechanical strength and rise in internal pressure [5,12]. According to experience, bus cylinder can be exposed to fire for about (20□30) min, which is an average time frame for a bus to be burnt out. Therefore, PRD should be capable of depressurizing cylinder within a couple of minutes, when CNG fuel cylinders were prevented from failing, Figure 4 [13].

Figure 4. *CNG bus under fire (left) and PRD which were successfully activated in a fire (right)*

Any compressed cylinder or cylinder rack must be certified and submitted to standardized bonfire test according to UN ECE Regulation No. 110 [5]. As example, proposed cylinders (Dyne-cell®) was demonstrated superior performance results in the fire test compared to other lightweight cylinders. Cylinders were exposed to extreme temperatures from fire for up to 20 min without rupturing, Figure 5 [13].

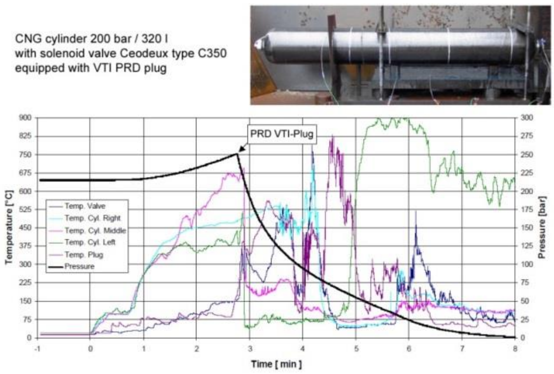

Figure 5. *Bonfire test results of CNG cylinder type (Dyne-cell®)*

Related to previous, though cylinder burst is not supposed to be happen, recent CNG buses cylinder bursts have highlighted potential deficiencies in the existing fire safety concept [12].

3.2 CNG cylinder burst

Large quantity of mechanical and chemical energy is stored in compressed combustible gas storage. Sudden release of this energy in case of cylinder burst may cause some severe damage to the bus environment

When a cylinder bursts, observation shows two consecutive pressure waves propagating in the surrounding environment. The first one which is also the more severe is associated with the pneumatic rupture (gas expansion) whereas the second is caused by the combustion of the released combustible gas into the air (fire ball). It is therefore to be noticed that although the chemical energy stored is usually an order of magnitude larger than the mechanical energy, the sudden release of the mechanical energy induces greater overpressure effects.

Theoretically, the pneumatic burst of a 130 liter cylinder at a pressure of 20 MPa releases an energy equivalent to the detonation of about 1.85 kg of TNT (8.7 MJ). Windows can be broken within a 30 meters radius and pressure wave induced lethality is to be foreseen within a radius of 12 meters. These calculations can worsen due to pressure wave reflection and pressure build up as well as to directional energy release (axial direction) due to the rupture mode of the cylindrical tank. Moreover, projectiles can also cause severe damages within a radius much larger than the one estimated above for overpressure effects. Researches shows that fragments of up to 14 kg (type IV tank filled with hydrogen at 35 MPa, test conducted in open atmosphere, projectiles not hindered by bus equipment) have travelled a distance of 82 m cylinder fire location. The mechanical energy released as the cylinder ruptured was equivalent to about 1.35 kg of TNT (6.3 MJ) [12]. Therefore, an unacceptable event such as the cylinder burst induces a significant damage radius (missiles and overpressure) that goes far beyond the bus geometry.

This makes a major difference with conventional liquid fuel buses with damage radius in case of fire limited to the bus itself (unless the fire propagates).

3.3 CNG vehicle fire protection provisions and firefighting techniques

Fire safety requires a comprehensive approach including CNG vehicle and gas component design, layout and installation, good maintenance, and appropriate firefighting techniques.

On CNG cylinders PRDs are fitted to enable their contents to be safely vented in the event of fire, thus preventing destructive cylinder failure, see Figure 6. To respond safely in a fire, CNG cylinders must be fitted with PRDs which are recommended by the cylinder manufacturer, and which have been used successfully in the design qualification testing of the cylinder (the standard bonfire test).

Figure 6. *These CNG cylinders were prevented from failing by PRDs which were successfully activated in a fire*

CNG cylinders must be installed in such a way that their PRDs are not thermally shielded in feasible fire scenarios. The PRD ports should be so directed their jet flames will not hit other vehicles and persons on the street when activated. CNG vehicle installation/conversion and CNG vehicle design should take these into account.

Many CNG buses are equipped with portable fire extinguishers. However, their size in many cases may not put out even a small vehicle fire, if they are not, or cannot, be directed at the appropriate place or their contents run out before the fire can be put out.

Consideration should be given to adequate extinguisher sizing and the drivers should be trained to use them correctly.

On many CNG buses the drivers can, from their seat, operate an isolation shut off valve on the CNG fuel storage system. This action should be emphasized, as it would minimize any jet flames resulting from the release of gas from damaged downstream components. In recent years, as a result of CNG bus fires, some CNG buses have been equipped with fire warning and automatic engine fire suppression systems. There are other simple, less costly engine firefighting methods which less well-resourced bus operators might need to resort to if automatic suppression is unaffordable. Even with automatic suppression in use, however, good firefighting techniques and procedures should still be in place for fires on the CNG system outside the engine compartment, or brakes and tires. The automatic engine fire suppression system must not be seen as obviating the need for other fire safety measures, e.g. the fire safety features of the on-board CNG cylinder installation.

As the majority of CNG vehicle fires have non-gas origins, regular CNG vehicle maintenance should be no less than that normal maintenance of vehicles using other fuels, in addition recognizing system defects with fire potential. For example, close attention to the condition of brakes, tires, turbochargers, operating fluid piping and the general tidiness and cleanliness of the engine could play an active role in preventing a large proportion of vehicle fires.

The serious potential consequences of a CNG vehicle fire that has spread to the on-board gas storage system mean that it is vital that, while it is still safe to do so, efforts should be made to put out an initially small vehicle fire. However, a CNG vehicle fire may take only a few minutes to complete vehicle destruction, and the emergency response agencies will likely arrive on the scene well past the initial, manageable stage, Figure 4 (left). As the first respondent is likely to be the vehicle operator, the task of fighting this initial fire will therefore likely falls on the driver. For this reason, drivers should be adequately equipped and given good CNG vehicle fire knowledge and effective training for fighting the initial fire.

3.4 Fire protection system of CNG buses

Fire protection system includes a fire detection system which may or may not include a fire suppression system. The purpose is to define the minimum performance requirements for detection of and suppression of thermal events on transit vehicles. The fire protection system shall be capable of detecting and minimizing potential damage of fire events in critical zones of the vehicle identified in this document.

Fire on board buses may be caused by internal or external factors. As explained above, experience shows that fires usually start in the engine compartment, Figure 2. As far as external causes are concerned we can mention human error during maintenance (use of open flame), vandalism and propagating fires from nearby vehicles or infrastructure. Generally, most fires start in engine compartment. A well-developed fire in engine compartment often has a very intensive course of event and is impossible to fight with a hand extinguisher. The solution is a permanently installed and fully automatic fire suppression system.

Related to the previous, CNG-AS® bus is equipped with a fully automatic fire suppression system for the engine compartment and possible separate heating areas, Figure 7. This system is also applicable for Hydrogen powered buses [14]. Scheme of installation the component system for detecting and fire extinguishing on the bus is shown in Figure 8 [15].

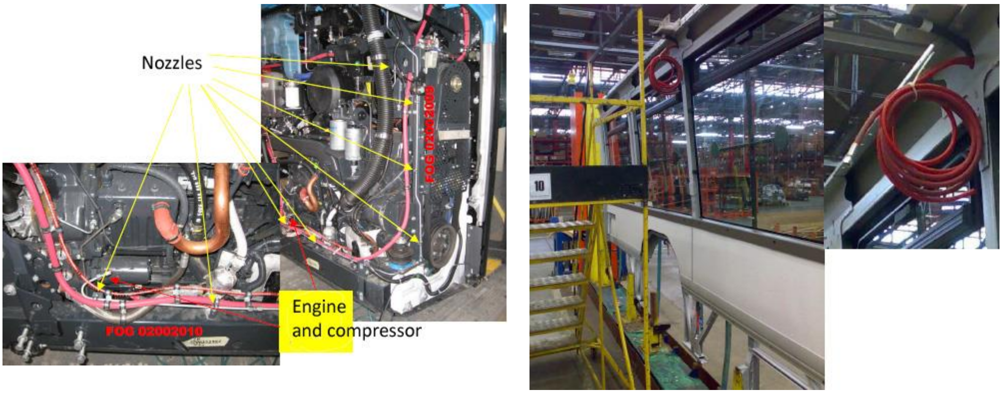

Figure 7. *Nozzles of the fire-extinguishing system, positioned in the engine compartment*

The system is activated hydro-pneumatically and works without any power supply, Figure 8. When releasing, the suppressant is sprayed through nozzles that break down the fluid into pillar-shaped mist clouds that cool the temperature and force the air out. The suppressant is mainly based on anti-freeze water. The releasing time is normally between (3□5) seconds and the effective suppression time is normally (50□75) seconds.

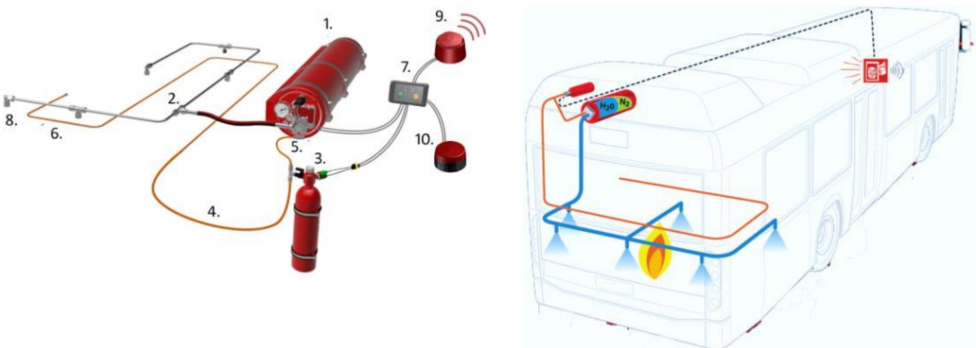

Figure 8. *Overview of fire suppression system components*

The piston accumulator with extinguishing fluid, pressurized to (10-10.5) MPa (1) is connected to a distribution system with a distribution hose and pipe as well as patented nozzles (2). The detector bottle (3) pressurized to between (2.4 and 3.1) MPa (depending on model) is connected to a detection system made of polymer tube (4). The piston accumulator and detector bottle is inter-linked via a patented valve (5) that keeps the piston accumulator closed when the pressure in the detector bottle is normal, Figure 8.

If there is a fire the detection tube bursts (6), the pressure falls in the detection system and the valve in the piston accumulator opens. The pressure switch warns the driver via the alarm panel (7) sounds (9) and light signals (10). The extinguishing fluid is pressed through the distribution system's nozzles and a water mist is spread in the protected compartment (8).

High pressure water is a far superior fire suppression technique in engine compartments. The high pressure in combination with special nozzles creates micro droplets with an average size of 50 µm. As a comparison, 8000 of these micro droplets are needed to fill a regular water drop of 1 mm in diameter, Figure 9 (left). In case of fire, one liter of extinguishing fluid absorbs 540,000 kilocalories and produces 1,700 liters of water mist at the same time, Figure 9 (right).

Figure 9. *Normal sized water drop vs. water mist and extinguishing fluid water mist effects*

During fire suppression, all components in the fire triangle chain reaction must be combated, Figure 10 (left). First, heat: In the evaporation process the water mist cools the burnt gases and hot parts in the engine compartment. One calorie is needed to warm one gram of water (+1 °C), but 540 times more to evaporate the same quantity of water from (+0 °C) to vapor. The effective cooling contributes to a rapid extinguishing and reduces the risk of re-ignition. Second, Oxygen: The micro droplets evaporate immediately upon contact with heat. In the evaporation, 1 liter of water forms 1700 liters of water vapor, Figure 9 (right). The vapor increases the water content of the air and prevents a new supply of Oxygen to the fire. Third, fuel: The extinguish-ant also includes a low concentration of aqueous film forming foam coating the fuel, preventing its contact with Oxygen, resulting in suppression of the combustion.

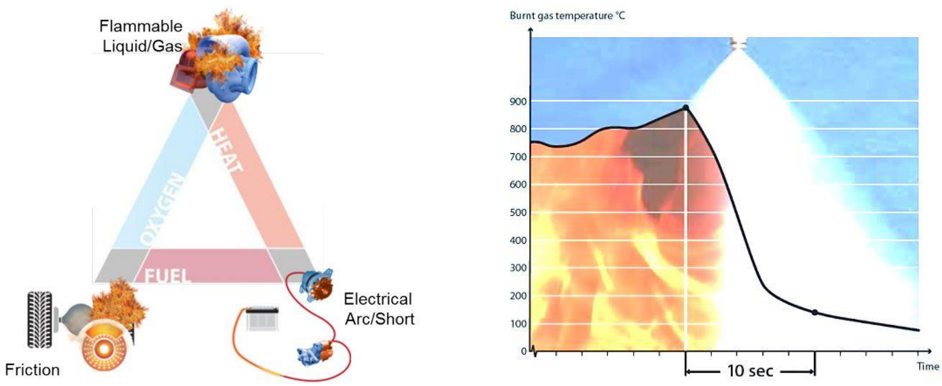

Figure 10. *Fire triangle and fire suppression test results*

According to fire suppression test in a simulated engine compartment, the fire develops during 20 s. The burnt gas temperature increases first to (870 °C), after that fire suppression system is activated manually. In next 10 s the burnt gas temperature decreases to approximately (136 °C) which is normal temperature, Figure 10 (right) [15]. In addition to the rapid extinguishing the risk of reigniting and melting damage to plastics, rubber and cables is minimized. This means reduced repairs and down time of vehicles.

4. CAUSES OF FIRE WITHIN CNG BUSES – RECOMMENDED PRACTICE

According to recommended practice, the potential causes of fire or ignition sources are usually divided into 10 critical zones within the bus, Table 1. This recommended practice provides guidelines for CNG bus fire suppression systems in conjunction with a vehicle fire. For fire detection system there are two basic sensor devices that are used to provide early warning of fires. Thermal sensors detect heat and optical sensors detect flame. For engine compartment need to be installed mix of thermal sensors and optical infrared sensor (usually minimum 4 thermal sensors is used). A control panel should be provided for all detection and/or suppression systems. The control panel should provide, at a minimum, electrical supervision of system power and detection; and system actuation wiring circuits if so equipped. The control panel should be visible an At a minimum the system control panel should include an alarm and signal system. Both a fire and a fault should activate a visual and audible alarm.

All lines, wiring, hoses, cables, and lines must be properly bracketed, insulated, and isolated to avoid chaffing and to protect against heat sources, using heat shields. Power for the fire protection system shall be provided by the bus electrical system directly from the vehicle battery terminals or through dedicated power and ground buss barsd accessible to the seated driver/operator.

Table 1. *Potential causes of fire or ignition sources – zones*

Zones	Location within the bus	Ignition sources
Zone 1	Engine compartment	electrical, combustible or flammable liquids/solids/gases, hot surfaces, belts, clutches, turbo fire, ignition of exhaust blankets, catalytic converter
Zone 2	Exhaust system (external to engine compartment)	high temperatures, exhaust leak, tail pipe fire, ignition of exhaust blankets, catalytic converter and monitoring systems
Zone 3	Low voltage battery	electrical, flammable liquids/solids/gases, cables, equalizers, circuit breakers, fusible link malfunction, corrosion, overcharge, battery box
Zone 4	Wheel well	under inflated tire, overheated bearings, leaky wheel seal, flammable liquids/solids, high heat in brake area, road debris
Zone 5	Heating ventilation air conditioning system - HVAC	electrical, flammable liquids/solids/gases, high heat
Zone 6	Operator’s work station	electrical, flammable liquids/solids/gases, high heat, tobacco smoking, debris build up

Zone 7	Articulated turn table	friction, debris build up, electrical cabling, vandalism, tobacco smoking
Zone 8	Fuel storage (inclusive of roof mounted cylinders)	Fuel leaks, arcing, debris, flammable liquids/solids/gases, cables, equalizers, circuit breakers, fusible link malfunction, corrosion, overcharge
Zone 9	Electrical junction boxes	shorts, electrical, flammable liquids/solids, cables, equalizers, circuit breakers, fusible link malfunction, corrosion, chaffing
Zone 10	Interior	tobacco smoking, debris, HVAC duct, fluorescent light ballast, corrosion, cabling, chaffing, signage, wire harnesses, vandalism, advertisements

7. CONCLUSIONS

(1) The numbers of fires in buses and coaches is up to 5–10 times higher than the number of fires in vans and Lorries. Fire onboard buses may be caused by internal or external factors. Most of these fires occur in the vehicle's engine compartment which is often located at the rear of the bus or coach. This makes it difficult for the driver to discover a fire.

(2) Most unwanted event in case of CNG bus fire is the burst of one or more of the compressed storage cylinders located on the roof of the vehicle. Cylinder burst is definitely not a tolerable option having in mind the tremendous amount of mechanical and chemical energy released in the course of this event.

(3) CNG cylinders must be equipped with PRD that should be capable of depressurizing cylinder within a couple of minutes, when CNG fuel cylinders were prevented from failing. Any compressed cylinder or cylinder rack must be certified and submitted to standardized bonfire test according to UN ECE Regulation No. 110.

(4) Fire protection system includes a fire detection system which may or may not include a fire suppression system. The fire suppression system applies primarily to fire protection of passengers and personnel. Another important aspect is the protection of property where the effectiveness of the system means that damage to machines and material will be small and result in low repair costs.

(5) Research has shown that extinguishing with water mist is 2–3 times more effective than traditional methods. High pressure water is a far superior fire suppression technique in engine compartments.

(6) According to recommended practice, the potential causes of fire or ignition sources are usually classified into 10 critical zones. The recommended practice provides guidelines for CNG bus fire suppression systems in conjunction with a vehicle fire.

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FREE VIBRATIONS ANALYSIS OF COMPOSITE LAMINATE PLATES USED IN AUTOMOTIVE INDUSTRY

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ABSTRACT: The paper describes the process of applying mathematical methods for obtaining analytic solutions in dynamic problems of free vibrations of composite laminate materials which are used in automotive industry. For selected high-order deformation theories the paper presents mathematical method for analytic solving of partial differential equations of motion. The procedure of obtaining results by combining symbolic and numerical values of relevant variables was implemented. Through a kind of comparative analysis, the emphasis was put on the use of HSDTs based on shape functions. Comparative values of results obtained using different shape functions are presented in tabular form. The paper considers simply supported thin, moderately thick and thick laminate plates. Moreover, it shows the influence of the laminate class of symmetry on the method of obtaining results. Simply supported laminate plates were primarily considered, specifically symmetric and anti-symmetric cross-ply laminate plates.

KEY WORDS: free vibrations, high-order deformation theories, shape functions, composite materials, analytical solutions

ANALIZA SLOBODNIH VIBRACIJA KOMPOZITNIH LAMINANTNIH PLOČA KORIŠĆENIH U AUTOMOBILSKOJ INDUSTRIJI

REZIME: Rad opisuje proces primene matematičkih metoda za dobijanje analitičkih rešenja u dinamičkim problemima slobodnih vibracija kompozitnih laminantnih materijala koji se koriste u automobilskoj industriji. Za izabrane teorije deformacije visokog reda u radu je predstavljen matematički metod za analitičko rešavanje parcijalnih diferencijalnih jednačina kretanja. Sproveden je postupak dobijanja rezultata kombinovanjem simboličkih i numeričkih vrednosti relevantnih promenljivih. Kroz vrstu komparativnih analiza, naglasak je stavljen na upotrebu HSDT-a baziranih na funkcijama oblika. Komparativne vrednosti rezultata dobijene korišćenjem različitih funkcija oblika prikazane su u tabelarnom obliku. Rad razmatra jednostavno podržane tanke, umereno debele i debele laminantne ploče. Štaviše, pokazuje uticaj laminantne klase simetrije na način dobijanja rezultata. Pre svega se uzimaju u obzir jednostavno podržane laminantne ploče, posebno simetrične i nesimetrične unakrsne laminatne ploče.

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KLJUČNE REČI: slobodne vibracije, teorija deformacija visokog reda, funkcije oblika, kompozitni materijali, analitička rešenja

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1. INTRODUCTION

Continuous development of automotive industry has imposed the need to change conventional materials with new modern ones whenever possible. The basic reason for that lies in the fact that it is necessary to decrease production costs and improve automobile performances on account of decreasing vehicle weight. Decreasing vehicle weight can significantly affect fuel consumption, increase vehicle speed etc. Passengers' safety should also not be forgotten; therefore attention should be paid to the strengths of newly introduced materials. Therefore, it is necessary to do a detailed macro-mechanical and micromechanical analysis of materials which are to be used for.

Alignment angles can also be altered beyond the maker's specifications to obtain a specific handling characteristic. Motorsport and off-road applications may call for angles to be adjusted well beyond "normal" for a variety of reasons.

production. Both in automotive and aircraft industry there is a growing use of composite materials in various forms. The subject of analysis in this paper are multi-layered composite materials, laminates. The key advantage of these materials is their strength in relation to their weight. It is possible to do macro-mechanical analysis of these materials for various types of static and dynamic loadings. Also a big number of theories have been developed for analysis of these problems.

Aiming to eliminate the shortcomings of the Classical Plate Theory (CPT), Mindlin [1] has developed the First-order Shear Deformation Theory (FSDT) taking into consideration shear deformation effects by linear distribution of plane displacements along the thickness of the laminate plate. Since in this case there was also no geometrical non-linearity for obtaining real solutions, it was necessary to introduce shear correction factors. Shear correction factors are not easy to determine because they depend not only on geometric factors, but also on loadings and boundary conditions. Another theory which takes into consideration shear deformation effects was developed by Reissner [2], [3]. In

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literature the name Mindlin-Reissner theory may often be found, although many authors impugn such a name claiming that the two theories differ considerably [4].

Some authors have tried to solve the problem relating to correction factors by introducing shear deformation shape functions [5-16]. This paper considers the problem of free vibrations of simply supported laminate plates by applying high-order shear deformation theories (HSDT) based on selected shape functions.

2. THEORETICAL ASSUMPTIONS

Geometrical non-linearity, in high-order shear deformation theories, is defined by the assumed displacements and there after functions are selected which are to be introduces in to displacements. The aim is to obtain simpler and less mathematically demanding functions, which are the closest to experimental results and the results obtained by the 3D elasticity theory.

The assumed shapes of displacement fields in this case are:

$$u(x,y,z,t) = u_0 = (x,y,t) - z\frac{\partial w}{\partial x}(x,y,t) + f(z)\,\theta_x$$

$$v(x,y,z,t) = v_0 = (x,y,t) - z\frac{\partial w}{\partial y}(x,y,t) + f(z)\,\theta_y \qquad (1)$$

$$w(x,y,z,t) = w_0 = (x,y,t)$$

where:

u_0, v_0, w_0 - displacement of the middle plane of the laminate, $\frac{\partial w}{\partial x}$, $\frac{\partial w}{\partial y}$ - rotation angles of the normal of plate, θ_x, θ_y - displacement due to transversal shear, $f(z)$ - shape function.

Table 1. *Shear deformation shape functions defined by different authors*

1.	Viola et al. [17]	$\frac{2h}{\pi}\tan\left(\frac{\pi}{2h}z\right)$
2.	Karama et al. [7], Aydogdu [8]	$ze^{-2\left(\frac{z}{h}\right)^2}$, $\left[ze^{\frac{-2\left(\frac{z}{h}\right)^2}{ln\alpha}}\right]$,$\forall\,\alpha > 0$
3.	Mantari et al. [83]	$z\cdot 2.85^{-2\left(\frac{z}{h}\right)^2} + 0.028z$
4.	El Meiche et al. [18]	$\xi\left[\frac{h}{\pi}\sin\left(\frac{\pi}{h}z\right)-z\right]$, $\xi = \left\{1, 1/\cosh(\frac{\pi}{2}) 1- \right\}$ ⍰
5.	Soldatos [6]	$h\sinh(z/h) - z\cosh(1/2)$
6.	Akavci and Tanrikulu [19]	$z\sec h\left(\frac{z^2}{h^2}\right) - z\sec h\left(\frac{\pi}{4}\right)\left[1-\frac{\pi}{2}\tanh\left(\frac{\pi}{4}\right)\right]$

7.	Grover et al. [21]	$z\sec\left(\frac{rz}{h}\right)-z\sec\left(\frac{1}{2}\right)/\left(1+\frac{r}{2}\tan\left(\frac{r}{2}\right)\right)$, r=0.1
8.	Mechab et al. [20]	$\frac{z\cos\left(\frac{1}{2}\right)}{-1+\cos\left(\frac{1}{2}\right)}-\frac{h\sin\left(\frac{z}{h}\right)}{-1+\cos\left(\frac{1}{2}\right)}$

In order to define components of unit loads, it is necessary to apply the relations between displacements and strains in accordance with the well known theory of linear elasticity. Using a generalized Hooke's law the following components of unit loads are obtained:

$$\mathbf{N}=\int_{h^-}^{h^+}\boldsymbol{\sigma}dz=\sum_{l=1}^{n}\left(\int_{h_l^-}^{h_l^+}\mathbf{Q}^{(l)}\mathbf{k}_0dz+\int_{h_l^-}^{h_l^+}\mathbf{Q}^{(l)}\mathbf{k}_1zdz+\int_{h_l^-}^{h_l^+}\mathbf{Q}^{(l)}\mathbf{k}_2f(z)dz\right),$$

$$\mathbf{M}=\int_{h^-}^{h^+}\boldsymbol{\sigma}zdz=\sum_{l=1}^{n}\left(\int_{h_l^-}^{h_l^+}\mathbf{Q}^{(l)}\mathbf{k}_0zdz+\int_{h_l^-}^{h_l^+}\mathbf{Q}^{(l)}\mathbf{k}_1z^2dz+\int_{h_l^-}^{h_l^+}\mathbf{Q}^{(l)}\mathbf{k}_2zf(z)dz\right), \qquad (3)$$

$$\mathbf{P}=\int_{h^-}^{h^+}\boldsymbol{\sigma}f(z)dz=\sum_{l=1}^{n}\left(\int_{h_l^-}^{h_l^+}\mathbf{Q}^{(l)}\mathbf{k}_0f(z)dz+\int_{h_l^-}^{h_l^+}\mathbf{Q}^{(l)}\mathbf{k}_1zf(z)dz+\int_{h_l^-}^{h_l^+}\mathbf{Q}^{(l)}\mathbf{k}_2\left(f(z)\right)^2dz\right),$$

$$\mathbf{R}=\int_{h^-}^{h^+}\boldsymbol{\tau}f'(z)dz=\sum_{l=1}^{n}\int_{h_l^-}^{h_l^+}\mathbf{Q}_s^{(l)}\mathbf{k}_S\left(f'(z)\right)^2dz,$$

where:

$$\mathbf{Q}=\begin{bmatrix}Q_{11}&Q_{12}&Q_{16}\\Q_{12}&Q_{22}&Q_{26}\\Q_{16}&Q_{26}&\bar{C}_{66}\end{bmatrix},\ \mathbf{Q}_S=\begin{bmatrix}Q_{44}&Q_{45}\\Q_{45}&Q_{55}\end{bmatrix},\ \boldsymbol{\sigma}=\left\{\sigma_{xx}\quad\sigma_{yy}\quad\sigma_{xy}\right\}^T,\ \boldsymbol{\tau}=\left\{\tau_{xz}\quad\tau_{yz}\right\}^T,$$

$$\mathbf{N}=\left\{N_{xx}\quad N_{yy}\quad N_{xy}\right\}^T,\ \mathbf{M}=\left\{M_{xx}\quad M_{yy}\quad M_{xy}\right\}^T,\ \mathbf{P}=\left\{P_{xx}\quad P_{yy}\quad P_{xy}\right\}^T,$$

$$\mathbf{R}=\left\{R_y\quad R_x\right\}^T,\ \mathbf{k}_0=\left\{\frac{\partial u_0}{\partial x}\quad\frac{\partial v_0}{\partial y}\quad\frac{\partial u_0}{\partial y}+\frac{\partial v_0}{\partial x}\right\}^T,\ \mathbf{k}_1=\left\{-\frac{\partial^2w_0}{\partial x^2}\quad-\frac{\partial^2w_0}{\partial y^2}\quad-2\frac{\partial^2w_0}{\partial x\partial y}\right\}^T,$$

$$\mathbf{k}_2=\left\{\frac{\partial\theta_x}{\partial x}\quad\frac{\partial\theta_y}{\partial y}\quad\frac{\partial\theta_x}{\partial y}+\frac{\partial\theta_y}{\partial x}\right\}^T,\ \mathbf{k}_S=\left\{\theta_x\quad\theta_y\right\}^T.$$

In the eq. (3), by grouping the terms with the elements of constitutive matrix, it is possible to define new matrices:

$$\left(A_{ij}, B_{ij}, \mathrm{D}_{ij}, \mathrm{E}_{ij}, F_{ij}, G_{ij}\right) = \sum_{l=1}^{n} \int_{h_l^-}^{h_l^+} Q_{ij}^{(l)} \left(1, z, f(z), z^2, zf(z), (f(z))^2\right) dz,\; i, j = (1,2,6),$$
$$H_{ij} = \sum_{l=1}^{n} \int_{h^-}^{h^+} Q_{ij}^{(l)} \left(f'(z)\right)^2 dz,\; (i,j) = (4,5). \tag{4}$$

Using the Hamilton principles, equilibrium equations become:

$$\begin{aligned}
&\delta u_0:\; N_{xx,x} + N_{xy,y} = I_1\ddot{u} - I_2\ddot{w}_{,x} + I_4\ddot{\theta}_x,,\; \delta v_0:\; N_{yy,y} + N_{xy,x} = I_1\ddot{v} - I_2\ddot{w}_{,y} + I_4\ddot{\theta}_y,\\
&\delta w_0: M_{xx,xx} + 2M_{xy,xy} + M_{yy,yy} = I_1\ddot{w} + I_2\left(\ddot{u}_{,x} + \ddot{v}_{,y}\right) - I_3\left(\ddot{w}_{,xx} + \ddot{w}_{,xx}\right) + I_5\left(\ddot{\theta}_{xx} + \ddot{\theta}_{yx}\right),\\
&\delta\theta_x:\; P_{xx,x} + P_{xy,y} - R_x = I_4\ddot{u} - I_5\ddot{w}_{,x} + I_6\ddot{\theta}_x,\; \delta\theta_y:\; P_{xy,x} + P_{yy,y} - R_y = I_4\ddot{v} - I_5\ddot{w}_{,y} + I_6\ddot{\theta}_y.
\end{aligned} \tag{5}$$

where:

$$I_{1\ldots6} = \sum_{l=1}^{n} \int_{h_l^-}^{h_l^+} \rho_l \left(1, z, f(z), z^2, zf(z), (f(z))^2\right) dz.$$

3. NUMERICAL RESULTS

The aim of this chapter is to check the correctness and efficiency of the presented theory for determining dimensionless frequency of simply supported cross-ply laminate plates. In order to do that, different numerical examples were done, and the obtained results were compared with the results available in the literature.

Analytical procedure requires defining of boundary conditions and assuming the solutions of dynamic equations of motion. Boundary conditions are defined as [22]:

$$\begin{aligned}
&v_0 = w_0 = \theta_y = N_x = M_x = P_x = 0,\ \text{at the edges } x = 0,\ x = a,\\
&u_0 = w_0 = \theta_x = N_y = M_y = P_b = 0,\ \text{at the edges } \mathrm{y} = 0,\ y = b.
\end{aligned} \tag{6}$$

Taking into consideration previously defined boundary conditions based on [19] it is possible to assume Navier solution to have the form:

$$
\begin{aligned}
u_0(x,y,t) &= \sum_{m=1}^{\infty}\sum_{n=1}^{\infty} U_{mn}\cos\frac{m\pi x}{a}\sin\frac{n\pi y}{b}e^{i\omega t},\\
v_0(x,y,t) &= \sum_{m=1}^{\infty}\sum_{n=1}^{\infty} V_{mn}\sin\frac{m\pi x}{a}\cos\frac{n\pi y}{b}e^{i\omega t},\\
w_0(x,y,t) &= \sum_{m=1}^{\infty}\sum_{n=1}^{\infty} W_{mn}\sin\frac{m\pi x}{a}\sin\frac{n\pi y}{b}e^{i\omega t},\\
\theta_x(x,y,t) &= \sum_{m=1}^{\infty}\sum_{n=1}^{\infty} T_{xmn}\cos\frac{m\pi x}{a}\sin\frac{n\pi y}{b}e^{i\omega t},\\
\theta_y(x,y,t) &= \sum_{m=1}^{\infty}\sum_{n=1}^{\infty} T_{ymn}\sin\frac{m\pi x}{a}\cos\frac{n\pi y}{b}e^{i\omega t}.
\end{aligned}
\qquad (7)
$$

where are arbitrary parameters which should be determined.

For thus defined boundary conditions and assumed form of analytic solutions, equations of dynamic equilibrium are reformed into:

$$
\left\{
\underbrace{\begin{bmatrix}
L_{11} & L_{12} & L_{13} & L_{14} & L_{15}\\
L_{12} & L_{22} & L_{23} & L_{24} & L_{25}\\
L_{13} & L_{23} & L_{33} & L_{34} & L_{35}\\
L_{14} & L_{24} & L_{34} & L_{44} & L_{45}\\
L_{15} & L_{25} & L_{35} & L_{45} & L_{55}
\end{bmatrix}}_{\mathbf{L}}
-\omega^2
\underbrace{\begin{bmatrix}
I_1 & 0 & -\alpha I_2 & I_4 & 0\\
0 & I_4 & -\beta I_2 & 0 & I_4\\
-\alpha I_2 & -\beta I_2 & I_3\left(\alpha^2+\beta^2\right)+I_1 & -\alpha I_5 & -\beta I_5\\
I_4 & 0 & -\alpha I_5 & I_6 & 0\\
0 & I_4 & -\beta I_5 & 0 & I_6
\end{bmatrix}}_{\mathbf{I}}
\right\}
\begin{Bmatrix} U_{mn}\\ V_{mn}\\ W_{mn}\\ T_{xmn}\\ T_{ymn}\end{Bmatrix} = \mathbf{0} \qquad (8)
$$

where , and coefficients obtained by analytical procedure. For obtaining non-trivial solutions of the equation (8) it is necessary that the determinant of the first matrix in the product is equal to zero, that is:

$$
\left|\mathbf{L}-\omega^2\mathbf{I}\right| = 0 \qquad (9)
$$

For presenting the obtained numerical values it is necessary to normalize the obtained values in accordance with [18] as $\bar{\omega} = \frac{ab}{h}\sqrt{\frac{\rho}{E_2}}$. Thus a dimensionless value of the frequency is obtained, which for *m=1 i n=1*, relates to the first oscillation mode. The results were obtained in the software Matlab by combining symbolic and numerical values of variables.

Material properties used in the numerical examples were the following [21]:

$$
E_1/E_2 = \text{open},\ G_{12}/E_2 = 0.6,\ G_{13}/E_2 = 0.6,\ G_{23}/E_2 = 0.5,\ \nu_{12} = \nu_{13} = \nu_{23} = 0.25
$$

Calculated values of the dimensionless frequency are given in the Tables 2 and 3. Table 2 presents dimensinoless values of the first oscillation mode of the laminate plate , for different values of the relation , at a fixed relation . It can be seen that for all proposed shape functions it is possible to obtain solution for dimensionless frequency. The differences in results obtained by various shape functions grow with the increase of the relation , which can most clearly be seen in the shape function proposed by Viola at al. Generally, the method which was implemented in Matlab provides good matching with the values presented in the papers of authors dealing with these problems [9], [22], [23], [24].

Table 2. *Values of dimensionless frequency* $\bar{\omega}$ *of symmetric cross-ply laminate* $[0°/90°/90°/0°]$ *at a changing relation* E_1/E_2*, and the fixed relation* $\frac{a}{h}=5$

Name of the author	E_1/E_2 $m=1,\ n=1$				
	3	5	10	20	50
Viola et al.	6.793	7.509	8.816	10.420	12.709
Karama et al., Aydogdu	6.592	7.245	8.399	9.743	11.494
Mantari et al.	6.592	7.246	8.400	9.746	11.494
El Meiche et al.	6.592	7.246	8.400	9.746	11.449
Soldatos	6.585	7.233	8.374	9.698	11.419
Akavci and Tanrikulu	6.587	7.232	8.367	9.683	11.409
Grover et al.	6.673	7.344	8.540	9.957	11.876
Mechab et al.	6.585	7.233	8.375	9.700	11.423

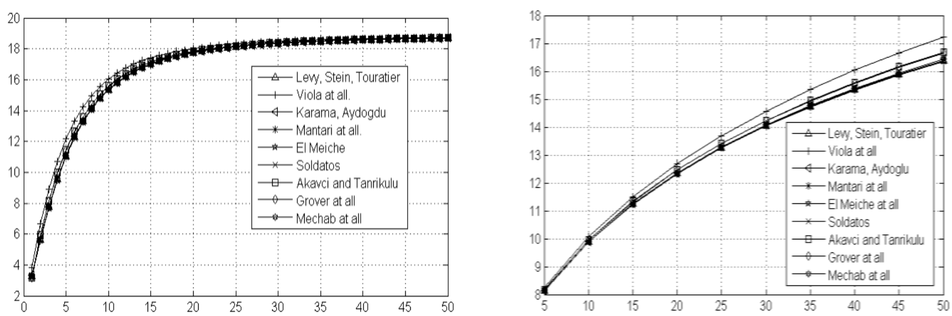
Table 3. *Values of dimensionless frequency* $\bar{\omega}$ *of symmetric laminate* $[0°/90°/90°/0°]$ *at a changing relation* a/h*, the fixed relation* $E_1/E_2 = 40$

Name of the author	a/h $m=1,\ n=1$				
	2	4	10	50	100
Viola et al.	6.67	10.711	16.030	18.740	18.853
Karama et al., Aydogdu	5.659	9.581	15.383	18.695	18.842
Mantari et al.	5.664	9.585	15.386	18.696	18.842
El Meiche et al.	5.664	9.585	15.386	18.696	18.842
Soldatos	5.586	9.520	15.327	18.691	18.840
Akavci et al.	5.578	9.517	15.299	18.688	18.840
Grover et al.	5.908	9.94	15.570	18.708	18.854
Mechab et al.	5.590	9.524	15.330	18.691	18.8414

Table 2 presents the values of dimensionless frequency $\bar{\omega}$ of symmetric cross-ply laminate plates $\left[0^0/90^0/90^0/0^0\right]$ at a changing relation a / h and the fixed relation E_1/E_2. With thick and moderately thick plates, where a / h <20 there are bigger discrepancies in the values of the dimensionless frequency. Great deviations have been noticed at functions defined by Viola et al., Grover et al. so that it can be said that these functions are not applicable to this type of problems. With thin plates where a / h ≥ 20 it can be seen that all theories give results which match in two decimals, which is in accordance to the fact that the influence of HSDT decreases with the increase of the relation a / h. During the process it has been noted that only in the cases of functions which are marked in the Tables 2 and 3, it is not necessary to use numerical integration, so that the accuracy of obtained results is the biggest. All other functions require the use of numerical integration, and they are, therefore, developed primarily for numerical methods like finite elements method or finite differences method.

Diagrams in the Figure 1 show pretty good matching of results obtained using almost all shape functions. Somewhat bigger deviations have been noticed at shape functions defined by Viola et al. Figure 1a presents the values of dimensionless frequency in the function of the change of the relation a / h at the fixed values of the relation E_1 / E_2. With thick and moderately thick plates, up to the relation a / h <20 the value of dimensionless frequency is growing. Above the mentioned limit for all shape functions, the values start to become asymptotic closer to some fixed value. When it comes to thin plates, the influence of shape function decreases, so that it can be concluded that using shape functions at thin plates is not crucial and satisfactory results could be obtained using theories of lower order.

Diagrams in the Figure 1 show pretty good matching of results obtained using almost all shape functions. Somewhat bigger deviations have been noticed at shape functions defined by Viola et al. Figure 1a presents the values of dimensionless frequency in the function of the change of the relation a / h at the fixed values of the relation E_1 / E_2 . With thick and moderately thick plates, up to the relation a / h <20 the value of dimensionless frequency is growing. Above the mentioned limit for all shape functions, the values start to become asymptotic closer to some fixed value. When it comes to thin plates, the influence of shape function decreases, so that it can be concluded that using shape functions at thin plates is not crucial and satisfactory results could be obtained using theories of lower order.



a / h E$_1$ / E$_2$

a) $E_1 / E_2 = 40$ *б)* $a / h = 10$

Figure 1. *Values of dimensionless frequency* $\overline{\omega}$ *in the function of the change of relations*
a) $E_1 / E_2 = 40$ *b)* $a / h = 10$

Figure 1b shows, through a diagram, functional dependence of dimensionless frequency at fixed value of the relation a / h = 10 and a changing relation of the elasticity module E_1 / E_2. Unlike the previous case, here there is no asymptotic approaching to some finite value. It can also be clearly seen that all shape functions, apart from the functions defined by Viola, Akavci and Tanrikulu, give curves which make one family of curves. With the growth of the relation of elasticity module, the mentioned two functions begin to increasingly diverge from the defined families of curves

4. CONCLUSIONS

Laminate materials, as materials of contemporary engineering structures have growing use in automotive industry. Accordingly, the paper presents the dynamic analysis of the problem of own vibrations of these materials from the aspect of the use of some proposed shape functions. The results obtained by applying the developed and implemented 2D high-order shear deformation theories give satisfactory accuracy, and the very method is much simpler than 3D elasticity theory. Thus the efficiency of macro-mechanical analysis is increased. It has been shown that all proposed shape functions are not applicable to the problem of free vibrations. It has also demonstrated that the use of these functions is important only for thick and moderately thick plates. Generally, the idea was to select the most simple shape function which would give satisfactory results. Comparative analysis has shown that for problems of own vibrations shape functions which are analytically integrable can be used. In that sense, the use of analytically integrable functions proved to require shorter calculation time. Shape functions which need numerical integration have not proved to be dominant over analytically integrable functions. With these functions for obtaining results it was necessary to go to some of the numerical integration methods. From this aspect, the best results with the shortest calculation time have been obtained using shape functions defined by Soldatos and Mechab. These two functions gave solutions of integrals in the closed form, and the procedure is therefore much faster and simpler. Commercial software for structure analysis using finite elements are mainly based on Mindlin's theory which requires correction factors which depend on geometry and shape. It has been shown here that it is possible to apply analytically integrable shape functions for free vibrations problems of simply supported laminate plates. The confirmation of this claim is to be found by creation of material model of laminate plates based on shape functions.

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THE VEHICLE AS A KEY FACTOR IN TRANSPORTATION ON THE EVE OF AN EPOCHAL PARADIGM SHIFT

Ralph Pütz[1]

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ABSTRACT: In the light of the 'megatrends' of electromobility and interconnection the car and commercial vehicle industry is facing dramatic changes which could lead to major upheavals. Triggered by ecological necessity and socially induced paradigm shifts, the understanding of mobility, the status of the environment, limited fossil resources, promising propulsion and fuel technologies as well as the increasing digitalisation and networking of all systems must inevitably be considered within a close system relationship. Sufficient technologies must therefore incorporate a corresponding sustainability in all areas: ecology, economy and social affairs for both subsystems as well as in the overall network context. Thus, for example, electromobility can only succeed in the transition to a comparable internal combustion engine in terms of economic and commercial maturity with a technology leap using post-lithium-ion battery technology. An improved lifecycle assessment can only be achieved in the medium to long term through extensive integration of regenerative energies in the electricity mix. Likewise, the interconnection which, at first glance, is inherent in and, ultimately, overarching within the transport system can probably only succeed in its ultimate aim of autonomous driving by overcoming high safety and regulatory hurdles in the medium to long term. In the context of these developments newly understood mobility and cross sector network synergy effects can be developed in the future on the way to a user perspective. In this respect, market shifts between the classic automobile manufacturers, innovative active suppliers and the IT industry are expected.

KEY WORDS: Electromobility, interconnection, lightweight design, megatrends, paradigm shift

VOZILO KAO KLJUČNI FAKTOR U TRANSPORTU NA POČETKU EPOHALNE PROMENE PARADIGME

REZIME: U svetlu "velikih zahteva" za korišćenje elektro pogona za kretanje, industrija putničkih i komercijalnih vozila suočava se sa dramatičnim promenama koje bi mogle dovesti do velikih preokreta. Podstaknuta ekološkom neophodnošću i socijalno indukovanim pomeranjima paradigme, Razumevanje mobilnosti, stanja okoline, ograničeni fosilni izvori, savremeni sistemi pogona i tehnologije goriva, kao i sve veća digitalizacija i umrežavanje svih sistema, neizbežno se moraju uzeti u obzir u međusobnim odnosima koji su pod uticajem ekoloških zahteva i promena u društvu. Zbog toga se adekvatne tehnologije moraju primeniti da bi se dobila održiva rešenja u različitim oblastima: ekologiji, ekonomiji

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i društvenim odnosima u oba podsistema, kao i u celokupnoj mreži. Tako, na primer, prelazak na elektrovuču sa uporednog motora sa unutrašnjim sagorevanjem može se ostvariti u ekonomskom i tehnološkom kontekstu tehnološkim usavršavanjem post-litijum-jonske baterije. Procenjuje se da se produženje životnog ciklusa baterija može postići samo srednjoročno i dugoročno kroz masovniju primenu različitih regenerativnih energija. Uspeh primene elektro vuče unutar transportnog sistema može se ostvariti ispunjenjem visokih sigurnosnih i regulatornih zahteva u srednjeročnom i dugoročnom periodu. U kontekstu ovih razvoja, nova shvatanja mobilnost i sinergijskih efekti međusektorskih mreža mogu se razvijati u budućnosti iz perspektive korisnika. U tom smislu očekuje se promena tržišta između klasičnih proizvođača automobila, inovativnih aktivnih dobavljača i IT industrije.

KLJUČNE REČI: elektromobilnost, međusobna veza, projektovanje lakih konstrukcija, veliki zahtevi, promena paradigme

THE VEHICLE AS A KEY FACTOR IN TRANSPORTATION ON THE EVE OF AN EPOCHAL PARADIGM SHIFT

Ralph Pütz [1]

1. INTRODUCTION

The car and commercial vehicle industry is facing dramatic changes in the light of mounting 'megatrends'. The ecological necessities caused through climate change, tighter air quality aims and limited fossil resources and the change in social mobility awareness in industrialised nations towards freely combinable forms of mobility in connection with an increasing digitalisation and interconnection induce a potentially significantly changed portfolio for the future development of vehicle technology, in which the megatrends such as electromobility and interconnection are pushed forward as potential solutions (see Figure 1). These developmental priorities are ideally encompassed in a complementary sense by other technologies identified as promising such as the supporting lightweight design of electromobility, off-board-diagnostics automated through intercommunication or autonomous driving. In this respect, in an integrative total concept technologies must also conform to a comprehensive sustainability in all areas: ecology, economy and social systems. Despite the public and, above all, political hype concerning megatrends, the combustion engine has still not come to the end of its development and will continue to dominate in the medium term.

During the course of the conference "MVM 2016 – Motor Vehicles and Motor" in Kragejuvec all facets and topics mentioned here will be covered from modern, conventional propulsion up to and including alternative concepts for vehicles deemed promising for the future.

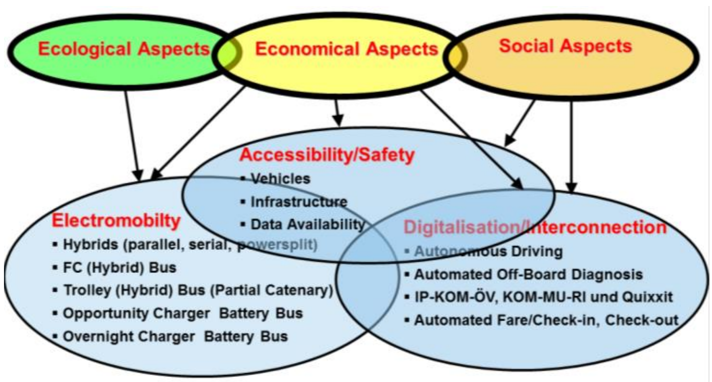

Figure 1. *Actual megatrends in automotive industry, derived from action topics; here: example bus transport system (Source: BELICON)*

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In the following, by way of introduction to the conference, attempts will be made to shed light on the implications of the new megatrends starting with modern, conventional technologies using the example of the bus transport system in public transport, which the author has been researching at his institute, Belicon.

1.1 Localization form and acoustic tensor

In the course of the future development of propulsion concepts motivated by the new EURO VI limit rankings alternatives to the diesel engine, which has hitherto dominated route operated buses, are coming to the fore. On the one hand, these include conventional power drives such as the natural gas engine in conjunction with biogas of different generations and electrified power trains with the diesel engine in the form of hybrid concepts and preliminary concepts for pure electromobility, on the other. Thus, a comprehensive consideration of the effect on the environment is unavoidable. In particular, the reduction of particulate matter rated as carcinogenic (PM10 and smaller groups) and the gas nitrogen dioxide (NO2), which is classified as an irritant, are the focus of the policy, along with CO2 and its associated reduction in fuel consumption. In this context, however, not only individual power drives exclusively should be considered, but also all subsystems including fuel supply chains, vehicle production (and disposal) as well as maintenance.

1.2 Combustion Engines for the near Future

Since 1st January 2014 the new EURO VI limit level for all engines for heavy commercial vehicles has been introduced throughout Europe. EURO VI is the most comprehensive regulation to date by the EU to reduce local emissions from commercial vehicles. As opposed to the previous limit level, EURO V or the optional ranking EEV (Enhanced Environmentally-friendly Vehicle), particle emissions and nitrogen oxide (NOx) emissions should be reduced by 50% and 80% respectively during an engine type-approval test WHDC (World-wide Harmonised Duty Cycle consisting of a transient and stationary test cycle). Extensive practice measures taken by the author have proved that through the introduction of these new, more characteristic, practically-oriented test cycles for public transport it is possible to confirm that the low emission levels anticipated through the EU EURO VI ranking are actually achievable in genuine bus operation (see Figure 2). It can be stated that the most efficient EURO VI vehicles now demonstrate a 'Near Zero Emission' level whereby the ambient air is actually cleaned during intake by the engine.

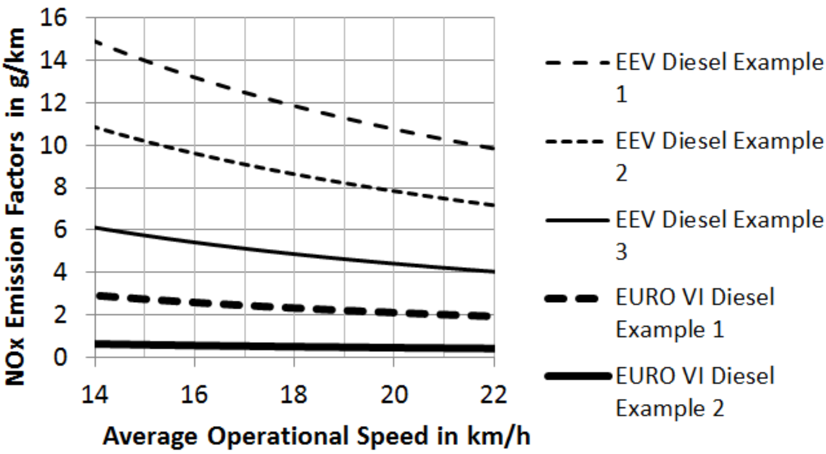

Figure 2. *NOx-Emissions in relation to the cycle speed for diesel solo buses under EURO V/EEV and EURO VI regulations (Source: BELICON)*

It is evident that with the EURO VI ranking propulsion systems with combustion engines demonstrate a highly significant improvement in local emissions (e.g. NOx) compared to previous levels. However, whilst a further reduction in global emissions and fuel consumption was verified by all manufacturers with diesel powertrains at

EURO VI, global emissions and fuel consumption with natural gas at EURO VI compared to EEV were likewise reduced depending on the input characteristics of the individual manufacturers, per contra with others it rose by around 30%. Figure 3 shows the ratios of selected EURO VI buses for typical German city transport with an average cycle speed of 18km/h, which corresponds to the SORT 2 (Standardised On-Road Test) cycles.

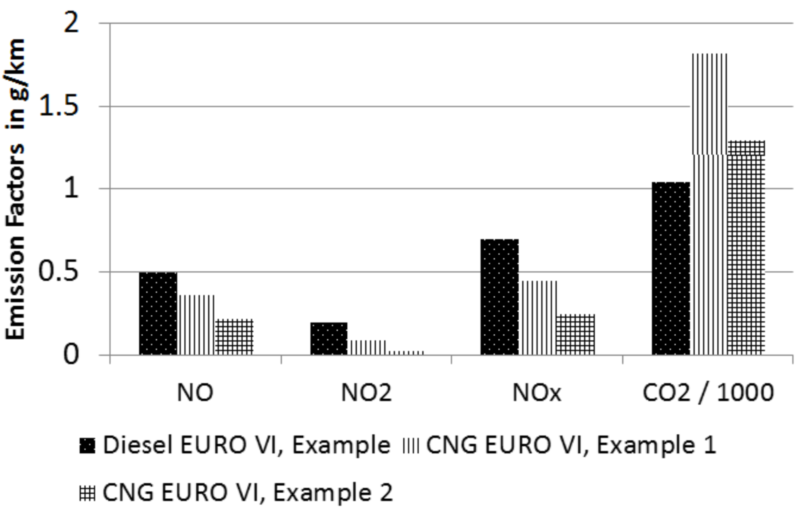

Figure 3. *Comparison of local and global emissions as well as consumption by buses under different limit levels at a nominated cycle speed of 18km/h on a comparable route (souce: BELICON)*

1.3 Development of the "Bridge Technology" Hybrid

The potential and opportunities for hybrid technology are closely linked to the characteristics of energy storage technology. The advantages of ultracaps (high performance condensors) are high power densities, i.e. a rapid energy input and output; the disadvantage here is the low energy density and the related limited total energy intake. By way of contrast to this, batteries demonstrate a high energy density and thus high energy storage capability although they have a lower power density. Current critical points are the still relatively low cycle stability, lifespan limitation due to greater sensitivity to temperature ratios and fluctuations in voltage, a higher control input and high costs. A compromise could be offered by so-called Li-Caps in the threshold between Ultacaps and Li-Ion batteries. Hybrid concepts can only then exhaust their full potential if, in addition to the actual brake energy recovery, additional functionalities such as downsizing the combustion engine, start/stop function, electrification of the auxiliary units and an overriding, route dependent energy management could consequently be implemented. If only brake energy recovery is anticipated, then the energy saving remains limited to a maximum of 10%. Only through the implementation of all the above mentioned hybrid functionalities can energy savings of around 30% be realised. The basic hybrid structure itself (serial, parallel, power split) has proved to be less critical in practice. In order to demonstrate the efficiency of current hybrid buses, the global emissions of currently used conventional and hybridised articulated buses based on SORT 2 (average cycle speed of 18km/h) are compared in the following Figure 4.

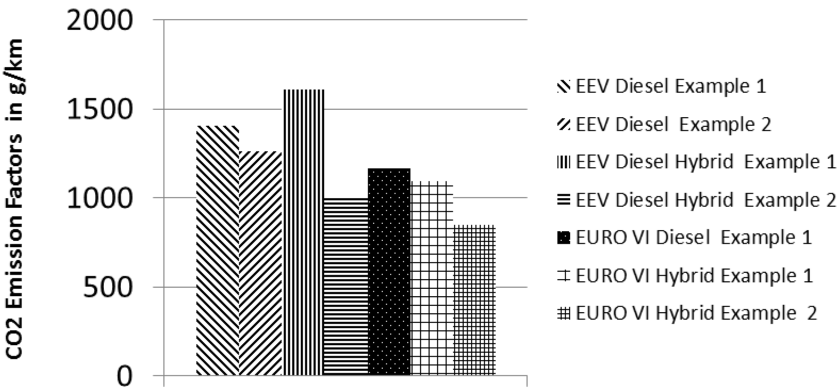

Figure 4. *Comparison of CO_2 emissions of selected articulated buses with a normalised cycle speed of 18km/h (source: BELICON)*

With an economic evaluation taking into account vehicle costs (vehicle procurement, maintenance and fuel) significant additional costs are reflected for hybrids despite fuel savings due to higher investment and maintenance costs. The comparatively moderate ecological improvements of hybrid technology compared with conventional EURO VI buses must be 'bought' over an input period of 12 years with significant additional costs. It should be noted that the current availability of hybrid buses is generally not at the same level as conventional vehicles and reserve vehicles must be kept in stock for heavy/frequent usage.

In order that the hybrid technology can achieve economic viability at the same level as conventional propulsion systems, the investment costs for this type of technology must be reduced significantly. By way of example, Figure 5 shows the conditions for the economic viability of a city hybrid solobus waiving public funding subsidies. According to this, with a comparable economic viability, the addtional vehicle investment costs compared to conventional buses are merely around €30,000 (by comparison: the additional investment costs of hybrid solo buses are currently between €75,000 and €130,000).

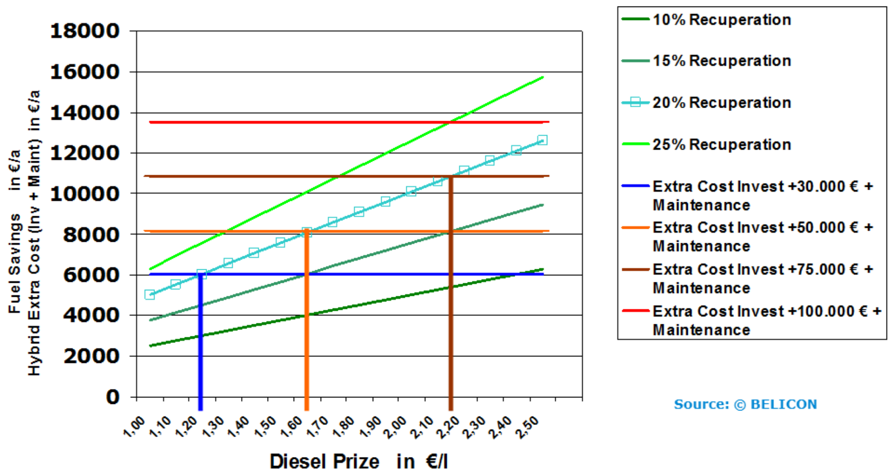

Figure 5. *Fuel saving versus additional hybrid costs depending on diesel price and the recuperation rate (example: city solobus) (source: BELICON)*

1.4 Actual Stage of Development and potential Advancement of Electromobility

As a rule, electromobility represents an individual system for each transportation company and its circumstances, whereby vehicle and power technology, battery type, energy intake and loading technology and operational pattern on the respective route topology must be determined. The input of battery and fuel cell buses is still very limited today although extensive marketing measures may make it appear otherwise. As this type of technology becomes more ready for operational mass production, its use will become increasingly accelerated in the future. Intensive use of battery and fuel cell buses is currently only possible for those transportation companies who can draw on extensive public funding.

In the following, promising alternative power systems for the 'electromobility' category will be assessed both ecologically and economically. These include:

- **Opportunity Charger** (**aka: E Bus Opportunity, OPC**); has a smaller battery and has to be recharged en route regularly. This requires fast charging with high power and voltage levels. Two charging stations per route with ten buses are generally used. A second battery during operational lifespan is also currently required.
- **Overnight Charger** (**aka: E Bus Overnight, ONC**); has a big battery and is therefore only charged slowly overnight with 400 V technology at the bus depot itself. A second battery during operational lifespan is also currently required.

- **Fuel Cell-Hybridbus** (**FCH**); conventional fuel cell buses are no longer relevant. A second battery during the operational lifespan is currently required. Due to the reduced fuel cell lifespan a replacement fuel cell stack can become necessary.
- **Trolley-Hybridbus** (**aka In-Motion-Charger, TRH**); conventional trolley buses will no longer be relevant in the future. A second battery is required during operational lifespan.

A total ecological evaluation is done here following the 2009/33/EG directive (directive on the promotion of clean and energy efficient road transport vehicles for public transport) using the totaling of external costs from local and global emissions of all subsystems including:

- Fuel supply (WTT; Well-to-Tank),
- Vehicle production
- Vehicle operation (TTW; Tank-to-Wheel) and
- Maintenance.

It thus characterises the environmental relevance of the different propulsion system variants investigated on an up-to-date basis. In this case, as is usual current practice, fuels from fossil sources were used for all variants. Regenerative fuels have not yet been introduced in electromobility projects and possibly accounted for in calculation. If the talk in different projects still refers to 'green electricity', then this merely relates to 'balanced green electricity'. The ecological total assessment (see Figure 6) demonstrates that, for a comprehensive sustainability, no improvements can currently be achieved by alternative electric propulsion variants taking into consideration local and global emissions as well as energy consumption. In the medium term therefore, diesel technology remains the first choice for public transport. In total the conventional power diesel EURO VI and natural gas

EURO VI equate to the opportunity and overnight buses. An additional ecological potential is offered through the use of biogas and biogenic synthetic diesel fuels as well as regenerative electricity and hydrogen which should be actively harnessed in the future. As a result of the energy transition through discontinuation of nuclear power stations and the substituted use of brown coal, the electricity mix in Germany has actually worsened ecologically albeit temporarily.

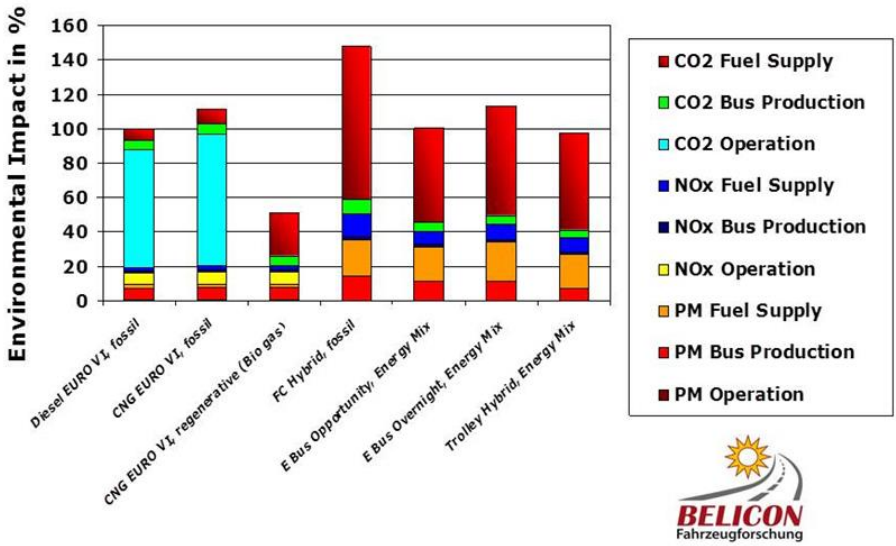

Figure 6. *System-related environmental relevance 2016 using external costs of a bus fleet in a total lifecycle (12 years) in accordance with 2009/33/EG (source: ©BELICON)*

In the following text there is an economic analysis of electrobus concepts currently under discussion compared to the EURO VI diesel bus for reference. The cost of the vehicles per bus kilometre is made up from the apportioned costs for:

- vehicles
- infrastructure
- replacement investment (e.g. for a change of battery during the lifespan of the bus)
- energy
- maintenance and repairs.

The assumed vehicle costs are pieced together to objectify the costs of the components used (vehicle configuration). Thus, calculations are made for electrobuses based on both automotive electro technology (electric motors, power electronics) with a 12 year expected lifespan as well as the sensitivity of use with a more cost intensive, but more durable (20 year lifespan) rail technology. If, in the future development of electromobility, there is a market penetration in accordance with experience from other key technologies in the automobile sector, then a market penetration over time as shown in Figure 7 would result. The time horizons 2015 (present day) and 2025 (medium term) are applied for the economic evaluations.

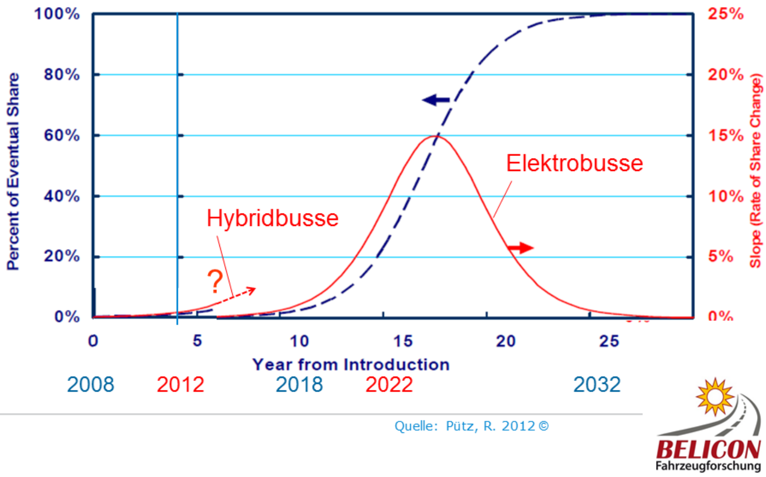

Figure 7. *Model approach towards expected market penetration of electromobility (source: BELICON)*

The total economic evaluation – differentiated on the basis of automobile and rail technology as well as for the time horizons of 2015 (present day) and 2025 (medium term) - is shown in Figure 8. With a trolley hybrid bus the overhead line is included for 50% of the total route.

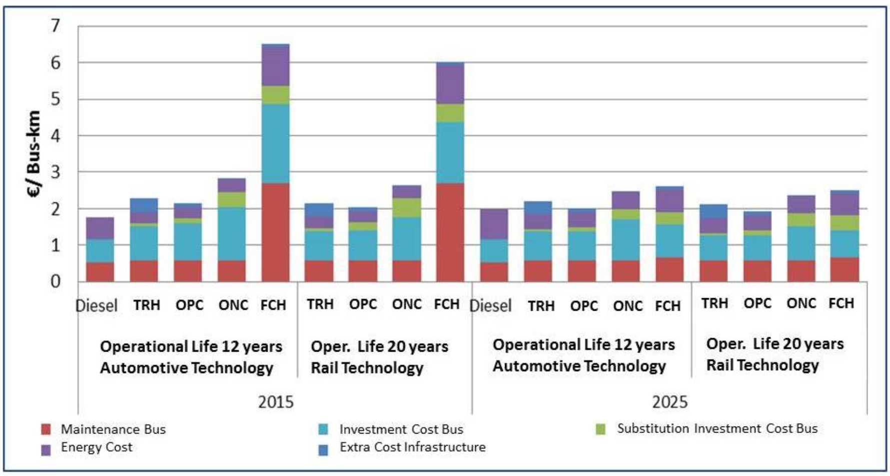

Figure 8. *Cost comparison of propulsion technologies of articulated buses (lifecycle costs without driver costs) (source: IFEU/BELICON)*

From this it is clear that all current electrobus technologies are significantly more expensive than the conventional EURO VI diesel articulated bus. In the medium term (in 2025) electrobuses will become more economically competitive - in particular, as a result of the assumed increase in diesel prices as well as a reduction in the cost of batteries. It is also recognisable that the costs of the electrobus concepts will align with one another in the long term. With regard to vehicle-km the Trolley-Hybrid (TRH) and Opportunity Bus (OPC) options are the most cost effective electrobus technologies both currently as well as in 2025. Concepts with a greater flexibility (no route-based infrastructure) such as fuel cell hybrid (FCH) and overnight bus (ONC) are more expensive in 2025 than TRH and OPC buses (25 ct/km or 41 ct/km compared to the GL [12 year lifespan]).

The additional costs of the trolley hybrid bus compared to the opportunity bus (2015: 13ct/km, 2025: 20 ct/km [12 Jahre Lebensdauer]) result, in particular, in greater expenditure for the overhead line infrastructure. Without infrastructure costs i.e. if an investment has already been done for this, then the trolley hybridbus (TRH) represents the most cost effective electrobus system within the entire study. As the trolley hybridbus can draw electricity for propulsion and for heating/air conditioning as well as charging the battery from the overhead line, this has operational advantages compared with the overnight and opportunity bus concepts since these must draw energy required for heating/air conditioning from the limited reserves of the battery storage unit, which can significantly reduce the overall coverage. A 20 year operation of electrobuses leads – despite higher procurement costs for this type of bus – to a reduction in costs per bus-km for all electrobus technologies taken into consideration. Nevertheless, this cannot close the economic viability gap with the currently established diesel bus (2015). At best, in the medium term (2025), a trend towards convergence can be expected.

An important advantage of all electrobus concepts is the reduced noise emissions compared with combustion engine drives. Measurements taken in practice confirm that, when leaving the bus stop electrobuses demonstrate a noise level which is 5 dB(A) lower, see Figure 9.

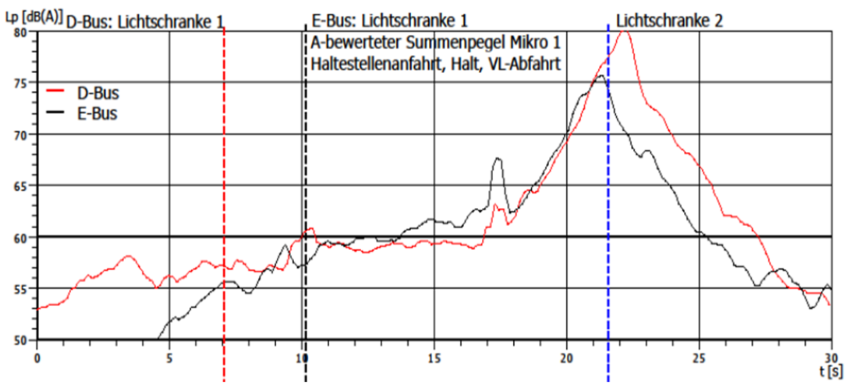

Figure 9. *Comparison of noise level of diesel and battery bus (source: BELICON)*

1.5 Conclusion on Propulsion System Development

The ecological and economic analysis of currently implemented or tested alternative propulsion technologies for route operation buses has demonstrated that conventional "near zero" powertrains with diesel and natural gas will continue to remain the first choice for route operation buses for the foreseeable future as it enables transportation companies to act both economically and taking the environment into consideration. It is clear that electromobility with batteries will likely only be able to penetrate the market following the anticipated technology leap towards Li-Ion successor technologies (Li-S?) after 2026 to 2030 (see Figure 10).

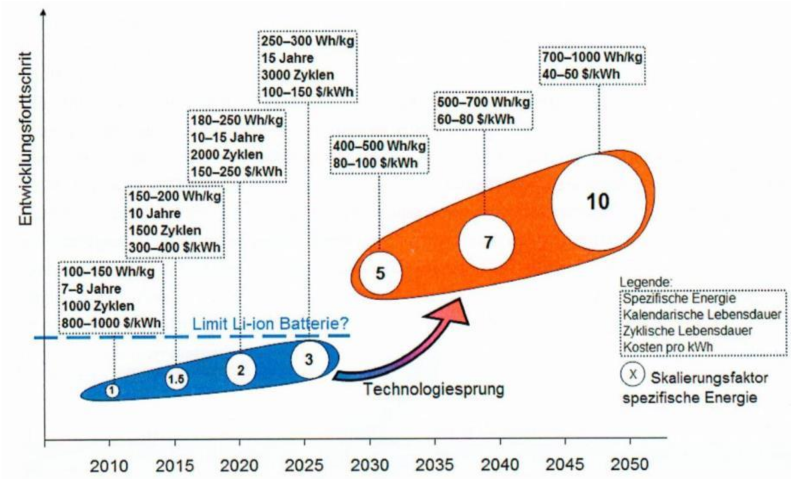

Figure 10. *Aggregated technology road map for Li-Ion batteries (source: Schulz, A., 2015)*

Nevertheless, the existing potential for alternative bus propulsion systems must be completely exhausted in the near future. Therefore, it is important that some transportation companies and local authorities are ready to test these buses and thus obtain relevant experience which will serve the further development of alternative power for all transportation companies (best practice in Serbia: Beograd Transport Company). This is, however, only possible if extensive means from public funding are continually made available.

What is undisputed is the fact that all sectors of our society – including local public transport – must be involved in the creation of a worthy environment for generations to come. A decisive factor in this case, however, is finding an economically practicable way towards this goal. Big transport companies have more favourable conditions to lead the way forward due to their greater potential and can become involved as pioneers in the testing of alternative power compared with smaller transport companies which could be overextended due to lower vehicle and personnel capacity. One should not ignore the fact that all current alternative propulsion technologies are significantly more expensive in terms of procurement and maintenance compared with tried and tested diesel and natural gas drives due to their development and number of units – even in the age of EURO VI. It should also be questioned as to whether the combustion engine can be replaced in the long term by electromobility. Rather more it is to be expected that certain areas of application will explicitly require coordinated drive technologies. In longer route areas the combustion engine will dominate in the long term. Nevertheless, the danger exists for the car and commercial vehicle industry that electromobility could become the “Trojan horse“ of classic vehicle manufacturers since the batteries occupy a large share of the value of the vehicles; however the manufacturers of the battery cells have established themselves in east Asia. Whether or not it will be sufficient for the vehicle manufacturer to be responsible merely for the quality monitoring and assembling of the battery cells remains open. An engagement with strategic partnerships in the development of post-Li-Ion battery technology would certainly be expedient. Also, the route towards electromobility could generate a migration from suppliers such as Bosch, Siemens or ZF – to name a few German companies by way of example here – to veritable vehicle manufacturers. The same applies to leading companies in the IT industry such as Apple or Google.

1.6 IT Technologies and Networking

Within the context of a change in understanding of mobility, in particular for the younger generation, the existing competition between individual and collective transportation companies has softened and been replaced by a service level cooperation. The customer is no longer interested in simply owning vehicles, but rather more in the preference of mobility. Thus, it can be expected that the classical transport operators as well as the classical car manufacturers concur and start to develop towards being a provider of mobility services. Car2Go and DriveNow are the first examples. So it is to be expected that the IT sector will become increasingly important since it can significantly support and operate the development of driver assistance categories and autonomous driving, telematics and off-board diagnostics as well as infotainment. In view of the enormous opportunities which can result within the context of electromobility and the trends towards vehicle networking the IT sector can be equally significant, if not more important, to the vehicle manufacturer in the car and commercial vehicle sector.

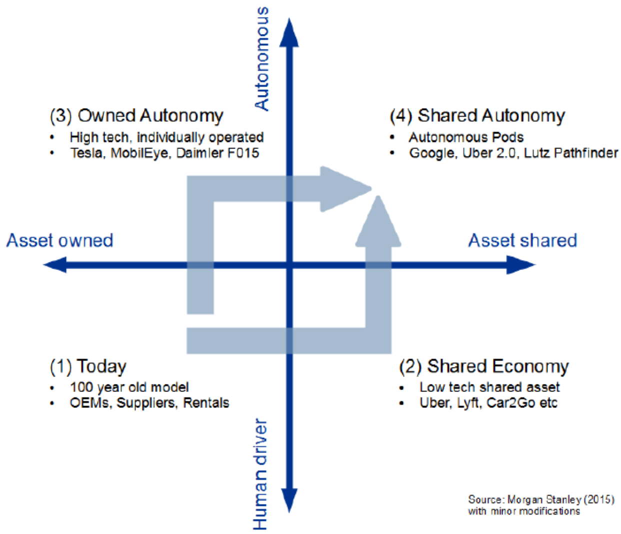

Figure 11. *Change in understanding of mobility encourages further IT developments as autonomous driving (source: Morgan Stanley, 2015)*

1.7 Driver Assistance Systems and Autonomous Driving

In controlled environments - such as agriculture or the mining industry – self-driven vehicles have already been implemented with success. Work cost savings of up to 90% and significant reductions in CO2 have resulted. Logistics can also use fully automated trucks, for example, to enable better fleet capacity utilisation and create more efficient supply chains. Practice tests by vehicle manufacturers confirm this. In addition to the positive economic and ecological effects, socio-economic improvements through a reduced risk of accidents and improved transport flows can also be expected. In actual fact, fully autonomous vehicles and robots are based on similar technologies so that synergies will accelerate development on both sides. Public service buses are, however, still a long way off from regular autonomous driving. The first step within the legal hurdles to overcome is driver assistance when approaching a bus stop. Securing a minimal distance from the kerb to improve passenger boarding is feasible in all cases. The bus driver should not initially be dispensed with since safety is paramount during practice runs so that the driver can intervene at any time. In the long term autonomous driving should significantly improve the life-cycle cost and availablility through dispensing with the need for a driver. Simultaneous use of a driver and technology for autonomous driving do not make sense objectively.

Attempts to realise autonomous driving have been made since the 1990s through mechanical, inductive and optical lane guidance projects. Autonomous driving is currently being publicised in the public service bus sector through EvoBus which has a system based on HighwayPilot which is also being tested in long distance driving for trucks on German motorways. Recognition of obstacles and pedestrians and the combination of priority at traffic lights are currently being tested worldwide, see Figure 14.

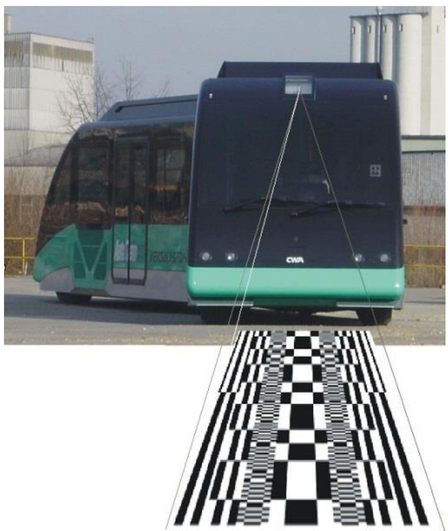

Figure 12. *The Autotram – autonomous driving with barcode signals (source: Fraunhofer IVI, 2005)*

Figure 13. *FutureBus – Autonomous driving project by EvoBus with 10 Cameras (source: EvoBus, 2016)*

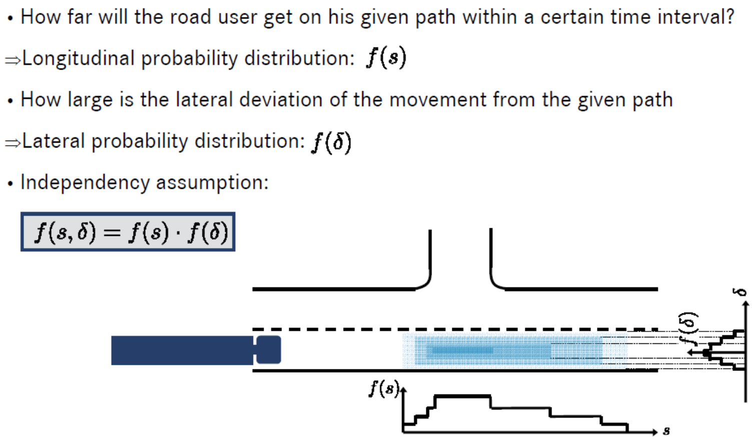

Figure 14. *Prediction for the (Ego) environmental performance (source: Daimler, 2011)*

On-demand public transport would offer a further level of migration, but it's still a long way off. In Hamburg, Germany, a possible test field is currently being developed for autonomous driving in cooperation with VW. The technical requirements of an autonomous urban bus are almost identical to those of an autonomous car; however, it is anticipated that buses will be on the road autonomously sooner than cars since the former often have their own separate lanes and, therefore, less interaction with other vehicles can be expected. Car-to-car communication with referenced, coordinated routes would be a further level of development.

Figure 15. *Example for autonomous shuttle bus (source: Postauto Schweiz AG, 2016)*

1.7 Automated Remote Maintenance

Automated off-board diagnostics such as those for fleets of aeroplanes on the basis of an open platform is one of the most promising options for further improving the efficiency of transportation companies. The prerequisite for automated off-board diagnostics is the willingness of the vehicle manufacturer to make accessible all relevant state variables which are available on the CAN databus (Controller Area Network) on an open diagnostic platform for evaulation in order to thus identify complex faults. These faults are then taken off board automatically by an EDP-supported maintenance planning and fed in for execution with automatic scheduling by maintenance personnel, materials, progress status and optimal timing. This leads to a reduction in time taken to detect faults and, thus, to a reduction in personnel ratios. Furthermore, serious faults can be prevented through early diagnosis and targeted indications to drivers which, in turn, results in reducing the subsequent costs of rectifying the faults as well as the amount of time the vehicle is out of service, so the vehicle has greater overall availability. The optimisation of maintenance schedules through predictable scheduling further reduces the personnel ratio. Ultimately, a "prematurely averted“ need for maintenance results in greater vehicle quality and availability. The prompt availability of spare parts by connected manufacturers´ logistic systems also leads to further best practice optimisation.

Through targeted instructions to transport personnel for economic driving with direct feedback in the central display of the driver cab, a reduction in fuel consumption of between 5 and 10% can be expected on the basis of values achieved in testing. Furthermore, due to the scheduling of maintenance work and higher vehicle quality with established off-board diagnostics, a reduction in the vehicle reserves is possible.

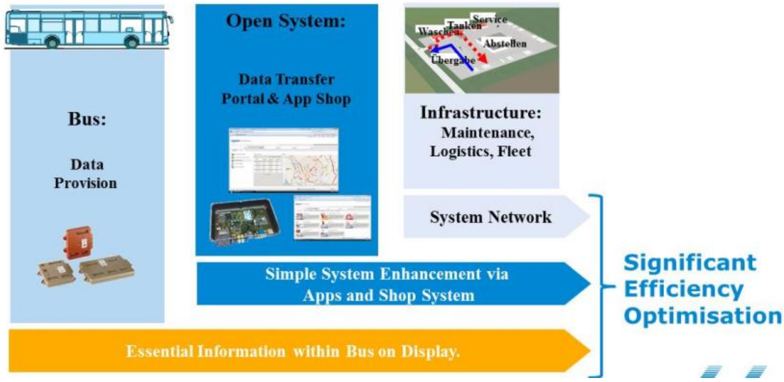

Figure 16. *Increases in efficiency through off-board diagnostics (source: Continental, 2011)*

1.8 Conclusion on IT Developments and Networking

The increased digitalisation and changed requirements of electrotechnology and IT between the mechanical engineering sector and the automobile industry resulting from the networking of systems open, in particular to the IT sector, new areas of business with the potential tendency of overall leadership even in the vehicle industry. These must be adapted to academic education since cross sectoral competencies will be unavoidable in the future.

1.9 Lightweight Design

One of the complementary key technologies in conjunction with electromobility is lightweight design which also plays an important role with conventional vehicles, but which is becoming increasingly significant in the electromobility sector. In order to achieve a greater scope without passenger capacity being adversely affected and without having to recharge en route it is an urgent necessity that the weight of the vehicle is reduced as far as possible. Carbon fibre reinforced plastic in conjunction with high strength steel and light alloys require new construction and manufacturing technology due to the hybrid structures. A one tonne reduction in weight would enable public service buses to save fuel and thereby reduce the related CO2 by 4%. In other words: a lightweight bus with a saving of 3 tonnes in weight has the same effect as an average hybrid system in public transport operation, which saves only 12% in fuel on average annually.

2. CONCLUSIONS

The car and commercial vehicle industry is facing dramatic changes due to looming „“megatrends“. Through climate change, air quality targets and limited fossil resources, previously mentioned ecological necessities and a changed commercial understanding of mobility in industrialised nations including freely combinable forms of mobility in conjunction with an increasing digitalisation and networking in an age of information trigger a significantly different portfolio of requirements for the future for the continued development of vehicle technology. This offers new actors from the IT industry sector and also from the supply industry the opportunity to endanger the established positions of classical vehicle manufacturers and to take on responsibility for the development as a whole. On the other hand, cross-departmental, competency-based partnerships can shift overall responsibility to the forefront. A conditio sine qua non on the way to networking would be a forced standardisation e.g. with the charging infrastructure with electromobility, with the cross-vendor automated off-board diagnostics etc. in order to provide developments on a wider basis and thus to improve the economic viability. European industry still has the opportunity – in the face of an obstructive background of an ageing population and a leap forward by east Asian concerns in battery technology – to maintain its technical-economic progress. For this, a new strategical alignment and a corresponding active design is essential. This also affects universities which have to adjust to the high level of European academic education towards an intensified interdisciplinary approach.

No one knows what will happen in the future, but the best way to predict the future is to actively create it yourself! In this sense, I would like to wish the delegates of this conference insightful lectures, interesting meetings and discussions and an engaged creativity in practice.

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