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Editors: Prof. dr ***Jovanka Lukić****; Prof. dr* ***Čedomir Duboka***

MVM *Editorial Board*
University of Kragujevac
Faculty of Engineering
Sestre Janjić 6, 34000 Kragujevac, Serbia
Tel.: +381/34/335990; Fax: + 381/34/333192

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FMECA OF BRAKE SYSTEM'S ELEMENTS OF LIGHT COMMERCIAL VEHICLES

Dobrivoje Ćatić [1]*, Jasna Glišović, Jasmina Blagojević, Sandra Veličković, Marko Delić*

UDC:629.018

ABSTRACT: The development history and basic principles of method Failure modes, effects and criticality analysis – FMECA are described in the introductory part of the paper. Failure analysis is particularly important for systems whose failures lead to the endangerment of people safety, such as, for example, the braking system of motor vehicles. For the failure analysis of the considered device, it is necessary to know the structure, functioning, working conditions and all factors that have a greater or less influence on its reliability. Features of elements of mechanical systems regarding failure intensity demand special approach of quantitative FMECA. The paper presents this approach, applied to the elements of mechanical systems and used for design of a software package. Criticality analysis of failure modes of light commercial vehicles' braking system elements was conducted based on exploitation results and with the use of previously mentioned method and program. In conclusion, it is points out the importance of methods for the analysis of failure of elements in order to improve the reliability and safety of operation, and therefore the quality of the technical systems.

KEY WORDS: Reliability, FMECA, Motor Vehicles, Braking System

FMECA ELEMENATA SISTEMA ZA KOČENjE LAKIH PRIVREDNIH VOZILA

UDC:629.018

REZIME: U uvodnom delu rada dat je istorijat razvoja i osnovne postavke metode Failure Modes, Effects and Criticality Analysis – FMECA. Analiza otkaza je posebno važna za sisteme čiji otkazi dovode do ugrožavanja bezbednosti ljudi, kao što je, na primer, sistem za kočenje motornih vozila. Za analizu otkaza razmatranog uređaja, neophodno je poznavati strukturu, način funkcionisanja, radne uslove i sve faktore koji imaju veći ili manji uticaj na pouzdan rada. Karakteristike elemenata mašinskih sistema u pogledu intenziteta otkaza zahtevaju poseban pristup kvantitativne FMECA. U radu je prikazan ovaj pristup, primenjen na elemente mehaničkih sistema i korišćen za izradu softverskog paketa. Analiza kritičnosti načina otkaza elemenata sistema za kočenje lakih komercijalnih vozila sprovedena je na osnovu podataka iz eksploatacije i uz korišćenje prethodno pomenute metode i programa. U zaključku rada ukazano je na značaj primene metoda za analizu otkaza elemenata za poboljšanje pouzdanosti i sigurnosti funkcionisanja, pa samim tim i kvaliteta tehničkih sistema

KLJUČNE REČI: Pouzdanost, FMECA, motorna vozila, sistem za kočenje

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FMECA OF BRAKE SYSTEM'S ELEMENTS OF LIGHT COMMERCIAL VEHICLES

Dobrivoje Ćatić[1], Ph.D, Full professor, Jasna Glišović[2], Ph.D, Assistant professor, Jasmina Blagojević[3], Ph.D, student, Sandra Veličković[4], Ph.D, student, Marko Delić[5], Ph.D, student

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INTRODUCTION

According to IEC standard [1], Failure Modes and Effects Analysis (FMEA) is a method for analysis of technical systems reliability. FMEA was developed for USA military purposes as a technique for assessment of reliability through determination of effects of different failure modes of technical systems. This method dates from November 9th, 1949, as an official document [2]. Application of FMEA in automotive industry projects followed no sooner than in the second half of the 1980's and it was related with introduction of quality regulations Q-101 by American Ford Company.

FMEA is a procedure for evaluation of reliability of a technical system that may be applied in all phases of its lifetime. FMEA is generally an inductive method. It is based on consideration of all potential failures of constitutive parts of the system and effects they have on the system. Criticality Analysis (CA) is a procedure for evaluation of criticality rating for all constitutive parts, where, by criticality, a relative measure of item's failure modes influence on reliable and safe operation of the system is meant. Joint FMEA and CA analysis are called Failure modes, effects and criticality analysis - FMECA. According to previous considerations, application of FMECA based on exploitation data is founded on the assumption that the intensity of all failure modes of system elements is constant, which is valid for electronic systems [3]. This assumption considerably simplifies the procedure for criticality assessment. However, application of this methodology in cases when failure intensity is a function of time may lead to distortion of real picture of elements' criticality. A proposal for procedure of quantitative FMECA of machine system's elements, originating from modification of the existing method, is given in paper [4].

For the safety of people and vehicles in traffic, the brake system of motor vehicles has a special significance. Performing detailed analysis of the causes and failure modes of the observed object requires knowledge of the structure, functioning modes and the relationship among the constituent elements. The significance of the braking system of the motor vehicle for the safety of people in traffic requires a detailed analysis of the constituent components in terms of occurrence of the failure. Based on exploitation data, using the method FMECA, the determination of the critical elements of the light commercial vehicle's braking system, which have restrictive influence on the reliable and safe operation of the

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[1] *corresponding author:Dobrivoje Ćatić, Faculty of Engineering, University of Kragujevac, Sestre Janjić 6, Kragujevac, caticd@kg.ac.rs*
[2] *Jasna Glišović, Faculty of Engineering, University of Kragujevac, Sestre Janjić 6, Kragujevac, jaca@kg.ac.rs*
[3] *Jasmina Blagojević, Faculty of Engineering, University of Kragujevac, Sestre Janjić 6, Kragujevac, jasminamikovic89@gmail.com*
[4] *Sandra Veličković, Faculty of Engineering, University of Kragujevac, Sestre Janjić 6, Kragujevac, sandravelickovic89@gmail.com*
[5] *Marko Delić, Faculty of Engineering, University of Kragujevac, Sestre Janjić 6, Kragujevac, delicmarko@gmail.com*

system is made in this paper.

IMPORTANCE, ROLE AND STRUCTURE OF THE BRAKING SYSTEM

An important part of the motor vehicle technology relates to braking. The ability of a vehicle to decelerate is one of the primary components of the preventive-active safety. Speed of the motor vehicle in certain traffic conditions, as well as the maximum speed on the open road, depends on the efficiency of the braking devices and the possibility of stopping a motor vehicle in the shortest possible distance. Vehicle with better braking performances may develop in service a higher average speed. Therefore, the braking characteristics of the vehicle can be considered an important part of the overall dynamic characteristics of the vehicle.

Braking system is a typical example of a complex system of motor vehicles, whose structure is determined by a complex objective function and certain current international and national regulations on the safety of vehicles in traffic. The main subsystems of the braking system are: service brake, secondary brake, parking brake and an additional brake or retarder. The basic structure of the braking system of motor vehicles is schematically shown in Figure 1 [5].

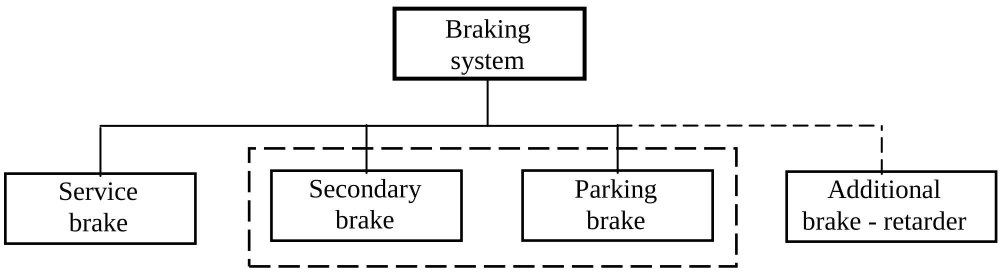

Figure 1: *The structure of the braking system of a motor vehicle*

The term "brake" in the names of individual subsystems has conditionally i.e. adopted meaning. In this case, it involves the entire subsystem with the specific purpose (for service, secondary, parking or additional braking), not just brake as the executive mechanical device of the braking system, as well as each subsystem individually.

Service brake takes over performing the most important tasks of the braking system, i.e. braking with the maximum deceleration (in case of emergency) and all mild, short braking under normal moving conditions.

The secondary or emergency brake is introduced solely to increase the security of the vehicle in traffic, i.e. in order to achieve higher reliability of the braking system. Its mission is to provide an opportunity for braking the vehicle in case if there is a failure in the service brake subsystem.

Parking brake has a task to provide permanent braking-holding the vehicle in place, so-called the parking brake. In addition, it is used for starting the vehicle on a hill. If this brake is design so that it can be also activated during the movement of vehicles, which is commonly the case, the parking brake can takes over tasks of the secondary-emergency brake. In this case, the emergency and parking brake are one same subsystem, which is showed in the block diagram in Figure 1.

Additional brake or retarder has a task to provide slightly, prolonged braking while vehicle moving on longer downs, with the goal of moving vehicles approximately with constant speed. Mandatory presence of the additional brake is prescribed only for vehicles with greater total mass, as indicated in Figure 1 with the dashed line.

Subsystems of the braking system are structurally design basically in the same way, and they include the same functional components: command, transmission mechanism and brakes.

Command is used to activate the appropriate subsystem of service, secondary and other brakes. Each subsystem must have its own command placed so that the driver can easily activate it.

Transmission mechanism has the task to transmit the impulse from the command to the executive devices-the brakes and thereby provides the necessary deceleration i.e. braking of the vehicle.

Brakes are the executive devices of the braking system, by which their objectives are realized. Therefore, their importance within the braking system is especially pronounced. Basically, the brakes are friction mechanisms, which convert the vehicle's kinetic energy into heat [10].

A complete failure of the braking system, due to the complexity of the structure, is rarely occurred. The largest number of failure modes of the constituent elements leads to a partial failure of this system. In the reference [6] by using Fault tree analisys method, a detailed analysis of potential failure modes of the braking system's elements of light commercial vehicles is performed. In this way, it was recorded the highest number of failure modes of elements that directly or indirectly lead to a reduction in performance of the braking system of motor vehicles.

QUANTITATIVE FMECA PROCEDURE FOR MACHINE SYSTEMS' ELEMENTS

Within the reference [6], the procedure of quantitative FMECA of mechanical system's elements is explained, which was created by modifying the existing procedure, taking into account the specificity of mechanical system's elements in terms of failure intensity. The modified version of the quantitative FMECA given in the paper consists of the following steps:

1. Determination of criticality $C_{ij}^{(k)}$ of failure mode *j* of element *i* is to be done by categories of failure effects *k* (*k* = 1, 2, 3, 4), using:

$$C_{ij}^{(k)} = \frac{\alpha_{ij} \cdot \beta_{ij}^{(k)} \cdot t_i}{t_{sri}}, \tag{1}$$

where α_{ij} is a relative rate (frequency measure) of failure mode *j* of element *i* ($0 \le \alpha_{ij} \le 1, \quad \sum_j \alpha_{ij} = 1$), $\beta_{ij}^{(k)}$ is conditional probability that failure mode *j* of element *i* will cause category *k* failure effect according to the adopted classification (values are taken from Table 1, according to recommendations from [1, 3], t_i is operating time of element *i* and t_{sri} is mean operating time until failure of element *i* occurs.

Table 1*: Values of conditional probabilities*

Degree of occurrence of the *k*-th failure effect category	$\beta_{ij}^{(k)}$ [-]
Certain event	1
Probable event	0.1 ... 1
Most probably would not happen	0 ... 0.1
Practically doesn't happen	0

Calculated values of $C_{ij}^{(k)}$ apart from being the starting point for determination of other quantitative properties of element's criticality, they make it possible to rank the element's failure modes according to effects in order to evaluate the most critical system's failure modes from the aspect of reliability and safety.

2. Determination of failure criticality of element *i*, which causes the *k*-th category of failure effects [7]:

$$C_i^{(k)} = \sum_j C_{ij}^{(k)} . \tag{2}$$

Calculation of $C_i^{(k)}$ enables the isolation of the most important elements whose failures lead to certain categories of effects.

3. Determination of criticality of the *k*-th category of the system's effects, by summation of criticalities of all elements failure modes for the specified effect category:

$$C_p = \sum_i \sum_j C_{ij}^{(k)} . \tag{3}$$

Calculated values of C_k are statistical indicators of the representation rating of the individual category of effects.

4. Determination of "absolute criticality" of element *i* according to [6]:

$$C_i = a_I \cdot C_i^{(I)} + a_{II} \cdot C_i^{(II)} + a_{III} \cdot C_i^{(III)} + a_{IV} \cdot C_i^{(IV)}, \tag{4}$$

where a_k is "weight" of the *k*-th (*k* = 1, 2, 3, 4) category of effects (values may be determined using subjective evaluation of effect's "weight" for each case, from the interval between 0 and 1) and $C_i^{(k)}$ is the *i*-th element criticality for the *k*-th category of effects.

By ranking obtained values C_i it can, in a direct way, be evaluating the degree of criticality of system elements from the aspect of durability and security with no complicated analysis.

A computer program for quantitative FMECA of mechanical systems' elements, according to the procedure described above, is established and will be used in future work.

ANALYSIS OF THE CRITICALITY DEGREE OF BRAKE'S ELEMENTS

Quantitative FMECA of braking system's elements of light commercial vehicles is conducted for detailed failure analysis of this system and obtaining information based on which the critical elements of the system, in terms of durability, and safety will be determined.

The basis of this analysis is a complex set of data, which is usually formed in the shape of the table. The process of collecting the data required for quantitative FMECA of the braking system's elements was conducted in the following steps [6]:

1. structural decomposition of the system (In the first step, based on the manufacturer's documentation [8], the structural decomposition of the braking system, the identification and encoding of constituent units are made.);
2. the adoption of structural level for conduction of quantitative FMECA procedure;
3. identification of all failure modes of elements;
4. determination of relative participation of individual elements' failure modes;
5. category definition of final failure effects;
6. categorization of element's failure modes according to effects and determination of conditional probabilities of final effects;
7. determination of mean operating time until element failure occurs and
8. calculation of the total operation time of elements.

Forming of input files for the program of quantitative FMECA of mechanical systems' elements was performed based on the data, which one part is shown in Table 2. To calculate the elements absolute criticality in accordance with (3), the following weighting factors of effect categories are adopted: $a_I = 1{,}00$; $a_{II} = 0{,}70$; $a_{III} = 0{,}30$ and $a_{IV} = 0{,}05$. Weighting factors were adopted by subjective assessment of the experts from the subject area.

By processing of the acquired data given in Table 2, by using the computer program for quantitative analysis of the criticality of the mechanical system elements, the results are obtained for: criticality of elements' failure modes without taking into account the effects (Table 3), criticality of elements with taking into account the effects (Table 4), criticality of final failure effects (Table 5) and absolute criticality of elements (Table 6).

To assess the criticality degree of units' failure modes (parts and assemblies of the braking system), it is considered a total of 35 different structural units and a total of 96 their failure modes. Output list of the program for the criticality degree of units' failure modes regardless of the effects contains the ranked failure modes according to criticality. Since the units' failure modes are sorted according to criticality in descending series, the first part of this list is an interesting for the analysis. Therefore, and due to limited space in the paper, Table 3 shows the initial part of the output list of the program.

In the braking system, as opposed to steering system [9], based on Table 3, one can observes greater uniformity of criticality of units' failure modes. The most critical failure mode of brake system's units, regardless of the result, is the wear of the shoe's brake lining with the category of effects of *k*.2 and criticality of $0.5677 \cdot 10^{-3}$. This should be assumed due to the extremely difficult operating conditions (high sliding speed, high operating temperature and large contact pressure). In the second is increased clearance of bearing bushings of brake command with criticality of $0.3996 \cdot 10^{-3}$, but the category of effects is *k*.4. In the third is the wear of walking surface of the command's rubber cover, also with the effects of *k*.4. Nonhermetic master cylinder is in fourth in the category of effects *k*.1. In the fifth is nonhermetic wheel brake cylinder. Nonhermetic cylinders occur due to wear of rubber sealing rings. Wear speed of the sealing rings depends on the external cylinder sealing i.e. on prevention the ingress of abrasive and corrosive impurities in the interior of the cylinders, then on the quality of the oil, working motion of the pistons, operating temperatures, etc.

Failure modes of drum occupy high places, too. Wear of the drum is in the sixth in order of criticality, and scratched working surface of drum is in eighth place. However, from twentieth place, the criticality of failure modes is over a hundred times smaller than the criticality of most critical failure modes.

Based on Table 4, for effect *k*.1 highest criticality have units whose failures lead to complete failure of service or parking brake (master cylinder, rear and front cable of the parking brake), or to the failure of one line in parallel connection of service brake (wheel brake cylinder, pipes and connectors of hydraulic installation, etc.).

Based on Table 5, the representation of units' failure modes with an effect's category *k*.3 with 2.10% is negligible compared to the other categories of effects. Failure modes with effects *k*.4, regardless of representation, because of the severity of effects, are not prevailed to the determination of the most critical unit in the braking system. Failure modes of units with the ultimate effects *k*.1 and *k*.2 are remained for consideration. The question is whether they are more important units' failure modes with a category of effect *k*.2 and the relative representation of 46.39%, or failure modes with the category of effect *k*.1 and relative representation of 18.98%. The dilemma can be resolved by calculating the absolute criticality of units. Table 6 contains the units that are ranked according to the absolute criticality. Based on this table, the biggest criticality has the brake shoe lining. Further follow: the master cylinder, wheel brake cylinder, drum, depressor, etc.

***Table 2**: Basics of the FMECA procedure for elements of the light commercial vehicle's braking system*

Element's name	Elem. code	Failure mode	Failure mode code	Rel. rate α_{ij} [-]	Loss prob. β_{ij} [-]	Final effect	t_{sr} [h] x10^3
Pedal of brake command	51111	Breakage of connection parts	N.32	0.003	0.4	*k*.1	14.96
Rubber cover of pedal	51112	Slipping off from the pedal	N.29	0.1	1.0	*k*.4	2.32
		Wear of step on surface	N.77	0.9	0.6	*k*.4	
Bearing bushing	51113	Increased clearance	N.35	0.995	1.0	*k*.4	2.49
		Get jammed	N.36	0.005	0.4	*k*.2	
Return spring of pedal	51101	Spring crack	N.06	0.1	0.6	*k*.2	13.67
		Insufficient elasticity	N.15	0.001	0.3	*k*.2	
		Fallout of spring	N.29	0.002	0.6	*k*.2	
Pull rod of piston pump	51102	Deformation	N.02	0.001	0.2	*k*.2	12.08
		Fork crack	N.06	0.001	0.7	*k*.1	
		Coil damage	N.07	0.03	0.4	*k*.2	
		Misalignment	N.62	0.2	0.8	*k*.2	
Reservoir for fluid	51201	Porosity	N.81	0.002	0.4	*k*.3	14.97
Flexible pipe of the reservoir	51202	A loose connection	N.31	0.06	0.7	*k*.3	13.93
		Broken pipe clamps	N.32	0.01	0.8	*k*.3	
		Pipe porosity	N.81	0.002	0.2	*k*.3	
Master brake cylinder	51210	Loose connection with body	N.31	0.001	0.2	*k*.3	3.31
		Pistons get jammed	N.36	0.02	1.0	*k*.1	
		Nonhermetic	N.58	0.9785	0.6	*k*.1	
		Body porosity	N.81	0.0005	0.3	*k*.3	
Brake booster	51220	Blocking	N.13	0.02	1.0	*k*.2	14.10
		Ineffective	N.30	0.005	1.0	*k*.2	
		Insufficient press. connect. elements	N.31	0.001	0.4	*k*.3	
		Nonhermetic	N.58	0.04	1.0	*k*.2	
Braking regulator	51240	Damage to the coil of plug	N.07	0.004	0.8	*k*.3	14.78
		Damage to seals	N.37	0.01	0.4	*k*.1	
		Body porosity	N.81	0.002	0.2	*k*.3	

***Table 3**: Criticality of elements' failure modes without taking into account the effects*

No.	Code	Element's name	Failure mode	Eff. name	α [-]	β [-]	t_{sr} [h]	t_i [h]	Criticality $C_{ij}^{(k)}$ [-]
1	51312	Shoe lining	Wear of the lining	*k*.2	0.8800	1.0	1.550E+03	1	0.5677E-03
2	51113	Bearing bushing	Increased clearance	*k*.4	0.9950	1.0	2.490E+04	1	0.3996E-03
3	51112	Rubber cover of pedal	Wear of the step on surface	*k*.4	0.9000	0.6	2.320E+03	1	0.2328E-03
4	51210	Master brake cylinder	Nonhermetic	*k*.1	0.9785	0.6	3.310E+03	1	0.1774E-03
5	51250	Wheel brake cylinder	Nonhermetic	*k*.1	0.8595	0.5	3.090E+03	1	0.1391E-03
6	51306	Drum	Wear of the work surface	*k*.2	0.5750	1.0	4.230E+03	1	0.1359E-03
7	51230	Depressor	Insufficient efficiency	*k*.2	0.9980	1.0	8.320E+03	1	0.1200E-03
8	51306	Drum	Scratched working surface	*k*.2	0.4000	0.7	4.230E+03	1	0.6619E-04
9	51112	Rubber cover of pedal	Slipping off from the pedal	*k*.4	0.1000	1.0	2.320E+03	1	0.4310E-04
10	51250	Wheel brake cylinder	Damage of the outlet valve	*k*.3	0.1200	1.0	3.090E+03	1	0.3883E-04
11	52204	Rear cable with cover	Lining get jammed	*k*.1	0.3000	0.6	8.140E+03	1	0.2211E-04
12	51102	Pull rod of piston pump	Misalignment	*k*.2	0.2000	0.8	1.208E+04	1	0.1325E-04
13	52201	Front cable with cover	Lining get jammed	*k*.1	0.2000	0.6	1.003E+04	1	0.1196E-04
14	51208	Other pipes and connectors	Cracking	*k*.1	0.2000	1.0	1.285E+04	1	0.1167E-04
15	51204	Pipes of servo commands (pneumatic)	Tube cracking	*k*.2	0.1500	1.0	1.306E+04	1	0.1149E-04
16	52204	Rear cable with cover	Cable stretching	*k*.2	0.2000	0.4	8.140E+03	1	0.9828E-05
17	52201	Front cable with cover	Cable stretching	*k*.2	0.2000	0.4	1.003E+04	1	0.7976E-05
18	51312	Shoe lining	Contamination of lining	*k*.2	0.0100	1.0	1.550E+03	1	0.6452E-05
19	51210	Master brake cylinder	Pistons get jammed	*k*.1	0.0200	1.0	3.310E+03	1	0.6042E-05
20	51250	Wheel brake cylinder	Pistons get jammed	*k*.1	0.0200	0.8	3.090E+03	1	0.5178E-05

Table 4: *Criticality of elements with taking into account the effects*

a) Criticality by effects *k*.1

No.	Code	Element's name	$C_i^{(k)}$ [-]
1	51210	Master brake cylinder	0.1834E-03
2	51250	Wheel brake cylinder	0.1443E-03
3	52204	Rear cable with cover	0.2703E-04
4	52201	Front cable with cover	0.1396E-04
5	51208	Other pipes and connectors of hydraulic install.	0.1261E-04
6	51312	Shoe lining	0.6452E-05
7	51206	Flexible pipes of hydraulic installation	0.3988E-05
8	51306	Drum	0.9456E-06
9	52202	Wheel with a fork	0.5277E-06
10	52206	Lever mechanism of the parking brake on the wheel	0.3362E-06
11	51240	Braking regulator	0.2706E-06

b) Criticality by effects *k*.2

No.	Code	Element's name	$C_i^{(k)}$ [-]
1	51312	Shoe lining	0.5794E-03
2	51306	Drum	0.2050E-03
3	51230	Depressor	0.1202E-03
4	51102	Pull rod of piston pump	0.1425E-04
5	51204	Pipes of servo commands (pneumatic)	0.1167E-04
6	52204	Rear cable with cover	0.9828E-05
7	52201	Front cable with cover	0.7976E-05
8	51220	Brake booster	0.4610E-05
9	51101	Return spring of pedal	0.4499E-05
10	51241	Regulator command	0.1434E-05

c) Criticality by effects *k*.3

No.	Code	Element's name	$C_i^{(k)}$ [-]
1	51250	Wheel brake cylinder	0.3887E-04
2	51202	Flexible pipe of reservoir	0.3618E-05
3	52205	Bracket of cable's cover	0.2683E-06
4	51240	Braking regulator	0.2436E-06
5	51205	One-way valve	0.2038E-06

d) Criticality by effects *k*.4

No.	Code	Element's name	$C_i^{(k)}$ [-]
1	51113	Bearing bushing	0.3996E-03
2	51112	Rubber cover of pedal	0.2759E-03
3	52111	Parking brake lever	0.3349E-06

Table 5: *Criticality of final failure effects*

No.	Final effect	C_k [-]	Rel. crit. %
1	*k*.2	0.9640E-03	46.39
2	*k*.4	0.6759E-05	32.53
3	*k*.1	0.3943E-03	18.98
4	*k*.3	0.4369E-05	2.10

Table 6: *Absolute criticality of elements*

No.	Code	Element's name	C_i [-]
1	51312	Brake lining	0.4120E-03
2	51210	Master brake cylinder	0.1834E-03
3	51250	Wheel brake cylinder	0.1559E-03
4	51306	Drum	0.1444E-03
5	51230	Depressor	0.8413E-04
6	52204	Rear cable with cover	0.3391E-04
7	51113	Bearing bushing	0.2054E-04
8	52201	Front cable with cover	0.1954E-04
9	51112	Rubber cover of pedal	0.1379E-04
10	51208	Other pipes and connectors of hydraulic install.	0.1265E-04
11	51102	Pull rod of piston pump	0.1004E-04
12	51204	Pipes of servo commands (pneumatic)	0.8168E-05
13	51206	Flexible pipes of hydraulic installation	0.4032E-05
14	51220	Brake booster	0.3235E-05

For purposes of separation of a small number of relevant units from a large number of less significant, the Pareto analysis of the absolute criticality of brake system's unit is performed. Figure 2 shows the percentage share of the top ten most critical units of the brake system. Criticality of the remaining 25 units is only 3.2%.

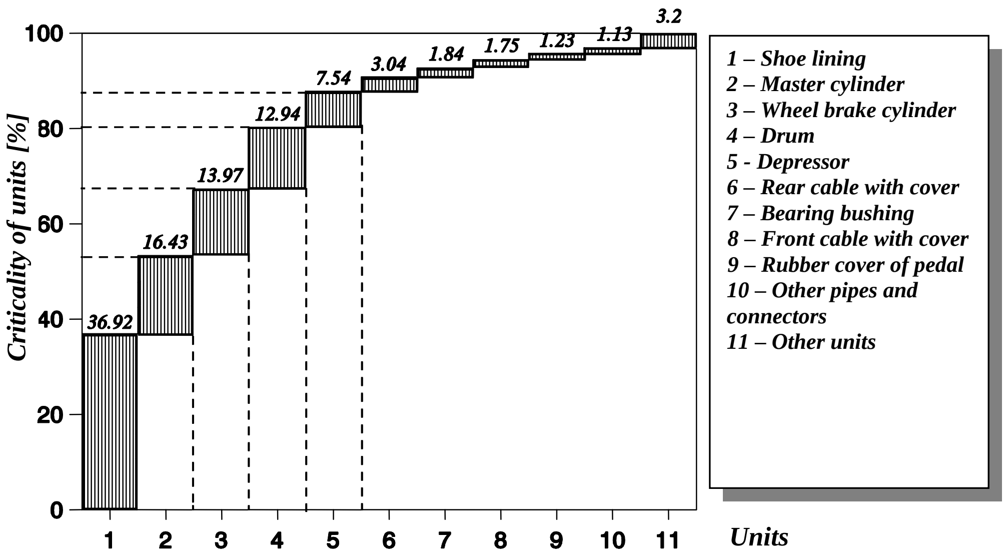

Figure 2: *Pareto analysis of the absolute criticality degree of whole brake system*

Based on the above analysis, the brake shoe lining is undoubtedly the most critical unit (element) of the braking system of the considered type of vehicle. A group of units according to the sequence shown in Figure 2 then follows.

CONCLUSION

By analysis of failure mode, effects and criticality analysis of machine systems' elements, based on data from exploitation, we get a range of information necessary for detailed knowledge of the system from the point of failure. In the case that there is data on medium operation time until failure and the relative frequencies of certain modes of failure of elements, or can be assessed by applying the quantitative analysis of modes, effects and criticality of failure may be made ranking of failure modes of elements by degree of criticality. Calculation of criticality failure modes of elements of mechanical systems and their ranking by degree of criticality is important because it points to the elements and their failure modes in which a criticality is the greatest. Analysis of the causes of critical failure modes of elements can be determined directions of undertaking concrete measures to minimize or completely eliminate the causes of failure, or lower the effects of failure. Thus increases the reliability of critical elements, and thus the reliability, dependability and quality of the entire system.

ACKNOWLEDGEMENTS

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RECENT RESEARCH RESULTS IN COMPOSITE MATERIALS AND ADHESIVE APPLICATIONS FOR VEHICLE LIGHTWEIGHT

Giovanni Belingardi[1], Brunetto Martorana

UDC:629.3.023.27

ABSTRACT: Vehicle weight reduction (and in turn reduction of fuel consumption, noxious gas and greenhouse gas emissions), manufacturing costs and riding comfort are pushing toward relevant growth the amount of polymeric materials employed in modern cars. At the same time the main performance of the car (and in particular safety and NVH comfort) should be maintained. In order to pursue this trend, it is important to carry out research and innovation on new polymer-based materials, with a high structural performance to weight ratio to replace standard materials, such as mild steel, for structural components. The base costs of composite materials are still relatively too high, therefore research activities are needed to reduce manufacturing costs of composite components. On the other hand the use of composites offer advantages not only in terms of lightweight but also in terms of parts integration, TTM reduction, etc. Innovative components can take advantage from new materials but need for proper design rules and proper manufacturing technologies.

Cycle times and production volumes are key factors. The production value chain and the research have to work in order to overtake some technological limits (joining technologies, recyclability, repairing, safety, costs, …) for a wider employment of lightweight materials.

This paper is presenting some recent results in the design of vehicle components with composite materials and is also presenting some recent achievements in the use of thermoplastic adhesives, nanomodified by ferromagnetic particles, sensitive to the electromagnetic field finalized to speed up both the manufacturing and the dismounting processes.

KEY WORDS: lightweight, composite material, CO2 emission reduction, adhesive joints, nanomodified adhesives

REZULTATI ISTRAŽIVANJA U OBLASTI PRIMENE KOMPOZITNIH I ADHEZIVNIH MATERIJALA KOD LAKIH KONSTRIKCIJA VOZILA

UDC:629.3.023.27

REZIME: Smanjenje težine vozila (i zauzvrat smanjenje potrošnje goriva, emisije izduvnih gasova i štetne emisije gasova staklene bašte), proizvodnih troškova i poboljšanje udobnost su ciljevi koji utiču na širu primenu polimernih materijala u savremenim automobilima. Istovremeno treba zadržati najvažnije performanse automobila (posebno sigurnost i NVH komfor). U cilju postizanja ovih zahteva, potrebno je sprovesti istraživanja i primeniti inovacije sa novim materijalima na bazi polimera, koji imaju visok odnos strukturnih performansi u odnosu na težinu, kojima treba zameniti standardne materijale, kao što je čelik, naročito kod strukturnih komponenata. Osnovni troškovi kompozitnih materijala su još uvek relativno previsoki, zato su potrebna istraživanja u cilju smanjenja troškova proizvodnje komponenata od kompozitnih materijala. Sa druge strane, primena kompozitnih materijala daje prednost, ne samo u smislu lakih konstrukcija, ali i u pogledu delova za

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spajanje, smanjenja TTM, itd. Inovativne komponente mogu iskoristiti prednosti novih materijala, ali je potrebno primeniti odgovarajuća pravila projektovanja i odgovarajuće proizvodne tehnologije. Vreme i obim proizvodnje su ključni faktori. Proizvodni lanac i istraživanja moraju da da se usklade kako bi se prevazišla neka tehnološka ograničenja (tehnologije spajanja, reciklaže, popravke, sigurnost, troškovi, ...) za širu primenu lakih materijala.

U ovom radu prikazani su rezultati istraživanja u razvoju komponenata vozila od kompozitnih materijala, i neka novija dostignuća u primeni termo-plastičnih adhezivnih materijala, nano-modifikovanih fero-magnetnim česticama, osetljivim u elektromagnetnom polju kako bi se ubrzali procesi proizvodnje i rasklapanja.

KLJUČNE REČI: lightweight, composite material, CO2 emission reduction, adhesive joints, nanomodified adhesives

RECENT RESEARCH RESULTS IN COMPOSITE MATERIALS AND ADHESIVE APPLICATIONS FOR VEHICLE LIGHTWEIGHT

Giovanni Belingardi[1],PhD, Proffesor, Brunetto Martorana[2]

UDC:629.3.023.27

INTRODUCTION

Automobile production has increased in the last 20 years, reaching the total amount of about 58 million units (excluding commercial vehicles) in 2000. According to the estimations made by the Organization for Economic Cooperation and Development (OECD), the total number of vehicles in OECD countries is expected to grow further by 32% from 1997 to 2020 [1]. The already evident consequences of high energy consumption for transportation of passengers and goods and this sharp forecasted increase in the number of circulating vehicles create concern in the society, as vehicles impact the environment in several ways throughout their life cycle. On one hand, the main energy source for automobile motion is the direct combustion of fossil fuels and this results in a large contribution to the global CO2 emissions. One must consider that burning 1 kg of petrol, diesel, kerosene and the like in a vehicle engine leads to approximately 3.15 kg of CO2 emissions. Among the circulating road transport means, emissions from the ‘‘light duty vehicles’’, i.e. passenger cars and vans, are responsible for approximately half of CO2 emissions [2]. On the other hand, currently, only about 75% of each vehicle, mainly its metallic components, is truly recycled at its end-of-life in the European Union, avoiding to further fill landfills and to waste precious resources. Therefore, the rest (~25%) of the vehicle material is wasted and generally is burnt or is sent to landfills contributing to make the landfill situation more and more critical. This generates between 8 and 9 million tons of waste every years in the European Union [3].

The transportation sector is responsible of nearly one-third of global energy demand and consequently is one of the major source of pollution and greenhouse gas emissions in urban areas. This stimulates a wide expectation for energy saving opportunities and for clean technology adoption. The environmental sustainability represents one of the major driving forces for the innovation considering European Commission’s regulation for CO2 emissions which sets stringent values for fuel economy depending on the average fleet weight as reported in figure 1. The EU directive No. 443/2009 [4], established in 2009, is prescribing that for the average fleet, in 2020 a target of 95 gCO2/km and in 2025 a target of 75 gCO2/km which represents a great challenge for vehicle development. Additional regulations for light commercial vehicles, introduced in 2011, require that they must not exceed emissions of 175g CO2 /km by 2017, and 147g CO2 by 2020The adoption of new materials and technologies can help greatly in this perspective. While in case of insufficient improvement, automotive OEM will have to pay a bill of 91€ for every gram of CO2 emitted above the threshold which may mean up to more than 3000€ per car. This represents a strong driving force to new lightweight materials in order to help in decreasing CO2 emission. Based on preliminary calculations, every 10% of weight saving will bring to a 3-

[1] *Giovanni Belingardi, Politecnico di Torino, Dep of Mechanical and Aerospace Engineering, corso Duca degli Abruzzi 24, 10129 Torino Italy – giovanni.belingardi@polito.it ; Visiting Professor at the Faculty of Mechanical Engineering of the University of Kragujevac, Serbia*

[2] *Brunetto Martorana, CRF - FIAT Research Center – GML Material Lab, strada Torino 50 Orbassano (Torino) – Italy – brunetto.martorana@crf.it*

5% of fuel economy and CO2 emission decrement, which can be translated into a cost acceptable increment in the range of 3-5 € per kg saved.

In additions, European Parliament and Council Directive 2000/53/EC on vehicle end-of-life set out specific measures to be actuated by Member States in relation to the collection, storage, dismantling, reuse and recycling of materials and components at vehicle end-of-life. As per this Directive, each Member State is required to achieve a recovery and recycle target of 95% (with a minimum of 85% material recycle) by 1 January 2015 and to ensure that all end-of-life vehicles are dismantled, treated and recovered by industry at no cost for the final owner of that vehicle and in a manner that does not cause environmental pollution [5].

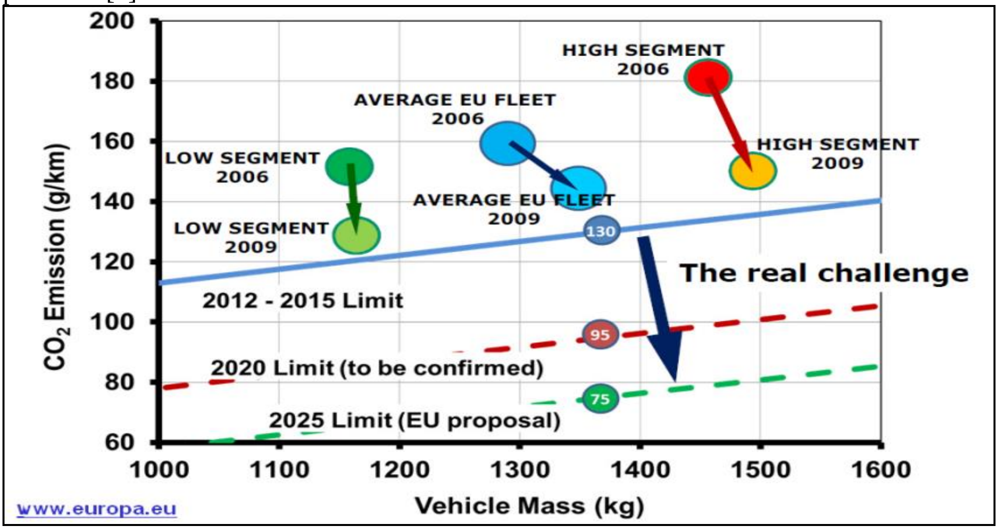

Figure 1 – Evolution of the CO2 emission limits in the EU for the next years

One of the most promising way to enhance operating efficiency is the use of lighter structural and semi-structural materials including advanced metals (high-strength steel, aluminum) and polymeric materials as glass fibers and carbon fibers reinforced plastic (GFRP, CFRP).

Material selection for component construction depends on the performance requirements of the component itself, on its location and functional role in the automobile. Thus components can generally be categorized according to the following three main groups that have peculiar characteristics: body and exterior, interior, and powertrain. In the short term, vehicle lightening can be achieved by replacing heavy steel components with components made by materials such as high-strength steel, aluminum, or fiber-reinforced polymer composites. The mechanical properties and manufacturing of these materials are well established. In the longer term, even greater lightening is possible (50%–75% weight reduction for some components) through use of carbon-fiber-reinforced composites as shown in figure 2a by means of a comparison between steel and different type of composites.

Composite materials are gradually increasing their employment on vehicles. For some special vehicle they are already used for the manufacturing of structural components such as for the Alfa Romeo 4C monocoque (see figure 2b) that debuted at the 81st Geneva International Motor Show in March 2011 (commercially available in 2013). The Alfa Romeo 4C is small lightweight rear wheel drive sports car using carbon fiber tub, front rear crash box and hybrid rear frame to keep its weight below 1000 kg.

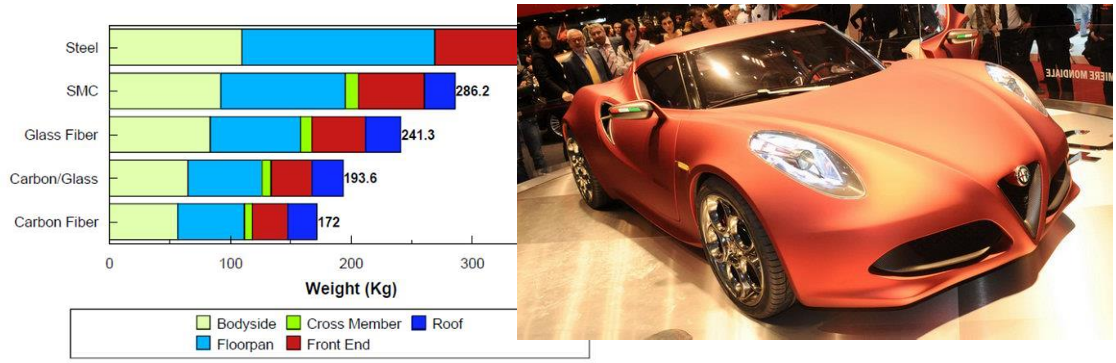

Figure 2 – a) Comparison between steel and composites for different car parts; b) Alfa Romeo 4C

The present work, that summarizes some of the recent results that has been obtained through the research cooperation between researchers of Politecnico di Torino and of FIAT, is dedicated to discuss the design capability of alternative novel materials for a couple of automotive components, a bumper beam and a engine subframe, that can contribute to significant improvements toward the solution of the above stated problems.

Bumper is an important structural component of automobiles to prevent or reduce physical damage to the front and rear ends of vehicles during low-speed collisions. In modern passenger car it has to satisfy two main structural requirements. On one hand, it needs to be deformable enough to absorb as much impact energy as possible to reduce the risk of injury for pedestrians or damage to other vehicles during low velocity collisions and on the other hand it needs to be stiff enough to protect nearby expensive-to-repair vehicle components such as fenders, hood, light groups, water cooler and intercooler. Therefore the material selection has to address both the above issues.

Random long glass fiber reinforced polypropylene Glass Mat Thermoplastic (GMT) is already widely used by the automotive industry for numerous applications. Current production applications include a number of noise shields and front end structures, as well as the Mercedes A Class rear hatch and double floor structure, the Volvo 850 rear seat structure and Volvo truck dashboards [6]. Kumar and Johnston [7] studied and compared the performance of C- and I-section bumper beams made of GMT composite using a variety of compression-molds. Gilliard et al [8] developed the I-section beam with 40% (mass fraction) of chopped fiber glass GMT. They found that the I-section bumper design has improved static strength and dynamic impact performance by means of the use of lower cost mineral filled/chopped fiber glass GMT. Belingardi and co-workers [9] have developed a specific study for the design of the bumper beam made by GMT as a possible solution for the front bumper in alternative to the present steel solution. The GMT solution, being based on thermoplastic matrix composite material, essentially polypropylene (PP), has better recycling performance with respect to other possible solutions made with composite materials based on thermosetting matrix such as epoxy resin [10].

Engine sub-frame is used to support the engine into the engine compartment and to connect through the engine mounts the engine to the body structure. Strength and stiffness are main targets for the frame design as well as its vibration response as it is directly submitted to the vibration excitation applied by the motor engine during its operation. The reference engine sub-frame basically consists of two longitudinal and two cross beams, these parts are made of steel. The two longitudinal beams and the rear cross beam are made of two half-shells that, after deep-drawing, are joined together by spot welding, while the front cross beam is made with extruded profile. Both the engine and vehicle front suspension systems are assembled on the rear cross beam and rear parts of longitudinal beam, respectively. To get robust stiff assembled engine sub-frame, two vertical links are generally introduced at the middle of longitudinal beams to connect with BIW. In order to support the cooling system, additional horizontal cross links are incorporated on the frontal cross beam of sub-frame.

Composite material solution has been developed by choosing a CFS003/LTM25 Carbon/Epoxy fabric prepreg, i.e. a material with high structural performance. Stacking sequence has been optimized in order to get the best results both in terms of frame bending stiffness and in terms of strength. Further, appropriate increment in the wall thickness and structural reinforcements has been designed in order to solve the structural problems in the most stressed zones.

In relation to the use of composite material, especially in the case of multi-material solutions, adhesive joining is considered as the main joining technology even if, in order to join plastic components, also mechanical fastening and welding [11,12, 13] can be considered.

Traditional mechanical joining involves the use of fasteners such as metallic and polymeric screws. This technique has the advantage of a rapid and effective disassembling process both for inspection and part substitution. Unfortunately, this type of mechanical joining is associated with an increase of the final weight and, very often, with an increase of the manufacturing time and costs. In welding, the plastic materials are fused together by the proper combination of heat and pressure; heat is applied to melt the polymeric material on the joint surfaces, to enable polymer intermolecular diffusion across the interface and chain entanglements to give the joint strength, and surfaces are pressed together for polymer solidification and consolidation.

Adhesive joining is a process whereby an adhesive is placed between the parts (adherends) where it serves as the material that joins the substrate and transmits the load through the joint. The principal benefits deriving from the use of adhesive joining involve: low cost, design flexibility, improved stiffness of the joint, ability to damp noise and vibrations, uniform distribution of stresses over the assembled areas, possibility to join dissimilar materials and no direct contact between parts. Having in mind the end-of-life recycle problems, the use of thermo-plastic adhesive could be of particular interest.

Adhesives and induction welding could be combined to achieve special benefits and obtain unique joining combination by means of the use of an electromagnetically nano-activated adhesive; this choice is relevant for reversible assembling/disassembling technologies.

This innovative technology is based on the embedding of electromagnetically active susceptors in an adhesive matrix. Suitable choices are iron particles, iron oxide, stainless steel, ceramic, ferrite or graphite [14, 15]. Once an alternating electromagnetic field is applied, the magnetic particles within the adhesive activate and rapidly heat: the amount of the generated heat depends on the nature, the quantity and the morphology of the particles.

The increasing temperature is thus able to melt the thermoplastic adhesive matrix and the assembling process of polymer-made automotive components is possible. Once the joint is created, it can also be quickly and effectively disassembled by simply use of the same apparatus and conditions.

VEHICLE WEIGHT REDUCTION

This topic has already been considered in a previous paper [16] presented at the MVM 2012 Conference. The interested reader can make reference to that paper. However some further elements can be brought to underline the evolution of the vehicle weight in the years. Figure 3 gives a rough information, for sake of exemplification, for medium size FIAT cars.

Figure 3 – Evolution of the vehicle weight for a FIAT medium size car

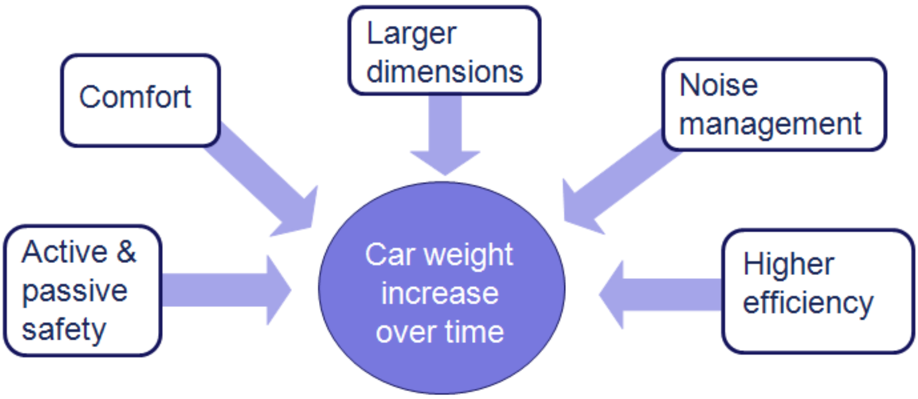

Figure 4 – Main contributions to weight increment for European cars.

Naturally this dramatic change in weight can be explained, as shown in figure 4, by the growth of the requirements both in term of costumer satisfaction (riding comfort, noise reduction, internal climatisation, info-mobility and so on) and in term of regulation requirements (reduction of noxious gas emissions, improvement in safety, driving assistance and so on). But this increment in the vehicle performance has not been accompanied by appropriated changes in the architecture and in the mix of the used materials. Car makers tend to go on with soundly experienced structural solutions that give high guarantee of good quality in the vehicle overall manufacturing.

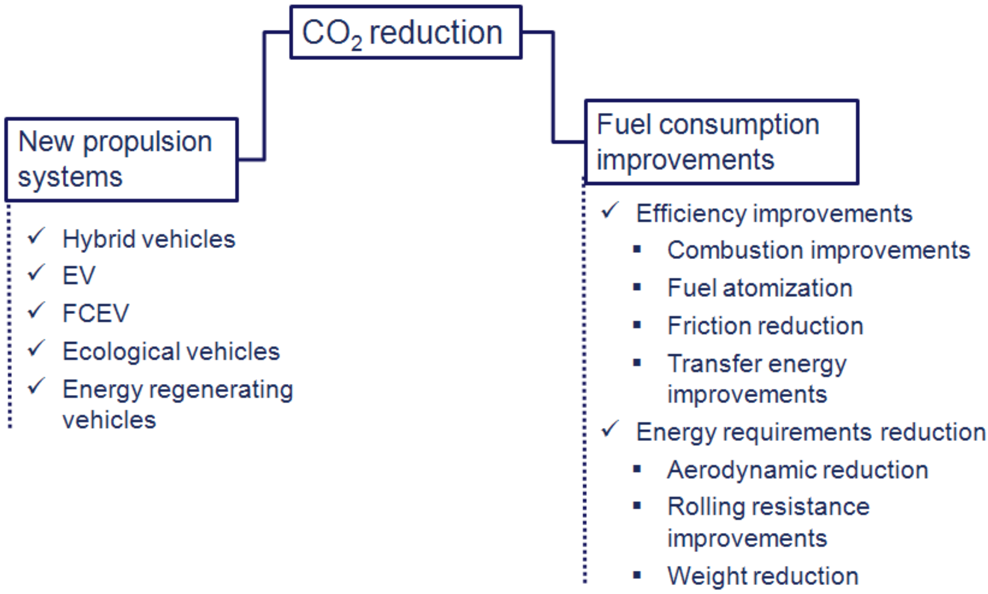

Figure 5 – Main strategies toward reduction of CO2 emission

Figure 5 is giving a general view of the main strategies that a car manufacturer can pursue toward the relevant reduction of the CO2 emission required by the EU regulations.

On the left side of the diagram it is visible the evolution in the propulsion system, from the presently adopted Internal Combustion Engines (ICE), with different possible types of energy sources such as methane, natural gas, GPL, Hydrogen and so on, toward Hybrid Vehicles (HV) and purely Electric Vehicles (EV).

On the right side of the diagram the two main choices (that are not mutually exclusive but could be synergic) that can be pursued are listed: an increment in the vehicle efficiency and a decrement of the amount of energy required for the vehicle ride. The first choice is related to the engine, that can be further optimised with respect to its thermo-fluido-dynamic performance, but also to the transmission line. A huge amount of energy is wasted as a consequence of the friction loss inside the engine itself, in the gearbox (teeth mating), in the differential box (gear geometry and teeth mating) and finally into the transmission joints. The second choice is related to the vehicle and finalised to reduce all the terms that contribute to the power required to ride the car [16] and in particular the aerodynamic drag, the rolling resistance for the tires but, as main contribution, the vehicle weight.

Table 1 is giving some order of magnitude in the advantage that can be obtained by means of a performance improvements of the above mentioned factors. While reading the results shown in the table one must take into account that the hypothesized improvements has been set equal to 10% for all the factors, despite the possibility of really achieving this improvements.

For what concern the improvements for the engine a lot of work has already been done and a very valuable reduction of the fuel consumption (that is strictly linked to the CO2 emission amount) has already been achieved, as shown in table 2, but this improvement has been accompanied by a big increment in the vehicle weight.

Table 1 – Main factors toward reduction of fuel consumption and CO2 emission and effect estimation.

Factor	Improvement	Impact on fuel consumption
Tires rolling resistance	- 10%	- 1,5%
Aerodynamics (Cx frontal area)	- 10%	- 2,7%
Weight	- 10%	- 3,5%
Powertrain efficiency (engine, gearbox, transmission)	+ 10%	- 10%

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Table 2 – Comparison between the performance of two vehicles of the same class after ten years

	FIAT BRAVO 1.9 Diesel 100hp - 1999	FIAT BRAVO 1.6 Diesel 105hp - 2009	Δ
Fuel consumption - combined cycle (l/100km)	6.3	4.5	- 28.6%
Weight (kg)	1155	1320	+ 14 %

Table 3 – Comparison of the weight reduction and of the cost increment that comes out if components made with the materials listed in the second column are redesigned with the materials listed in the first column

Lightweight material	Material replaced	Mass reduction (%)	Relative cost (Assuming HSS=1)
High strength steel	Mild steel	10 - 25	1
Aluminum	Steel, cast iron	40 - 60	1.3 - 2
Magnesium	Steel or cast iron	60 - 75	1.5 - 2.5
Magnesium	Aluminum	25 - 35	1 - 1.5
Glass FRP composites	Steel	25 - 35	1 - 1.5
Carbon FRP composites	Steel	50 - 60	2 - 10+
Al matrix composites	Steel or cast iron	50 - 65	1.5 - 3+
Titanium	Alloy steel	40 - 55	1.5 - 10+
Stainless steel	Carbon steel	20 - 45	1.2 - 1.7

Table 3 gives a rough estimation of the mass reduction and of the variation (increment) of cost that is coming out if components that in the normal present production are made of the "traditional" materials listed in column 2 of the table are redesigned with the adoption of the "innovative" materials listed in column 1. Only in a few situations (see column 4) the cost change is very small, most of the times we have a relevant increment of the cost up to twice and even more. But at the same time (see column 3) a relevant reduction in the component mass can be achieved, in several cases up to 40% and in some cases even up to 60%.

TWO EXAMPLES OF VEHICLE COMPONENTS MADE OF COMPOSITE

The bumper beam

Figure 6 shows the present solution for the front bumper system of the FIAT 500. The main structure consists of a transverse beam made of deep drawn steel, covered by a layer of polypropylene foam and a polypropylene shield (the so called fascia) that has mainly aesthetical and aerodynamic functions. The transverse beam is connected to two longitudinal crash-boxes that have the aim of absorbing energy in case of low velocity impacts, while preserving the other body front structure and the engine compartment components and devices.

Figure 7 shows the solution that has been studied taking advantage from the particular mechanical characteristic of the GMT material in its base configuration and in a modified configuration with some layers of unidirectional or fabric reinforcement. One of the main advantage in using this type of material relays on the manufacturing technology that can be adopted and is based on die-forming procedure. This technology enables the designer not only to obtain an interesting solution for the bumper transverse beam but to integrate in the same part the two crash-boxes, as is shown in figure 7 [9]. The crash-box has a thin-walled prismatic tapered shape. By choosing appropriately the dimensions (length, side width and wall thickness) in relation with the specific material strength, it is possible to obtain a crumpling behaviour, in case of impact, with energy absorption of the expected amount.

It is worth of note that the integration of the two crash-boxes and the bumper transverse beam into one single piece is of the greatest interest because it avoid to manufacture a number of different pieces (more than 10), to handle these pieces along the production lines, to dedicate some working stations for their assemblage operations.

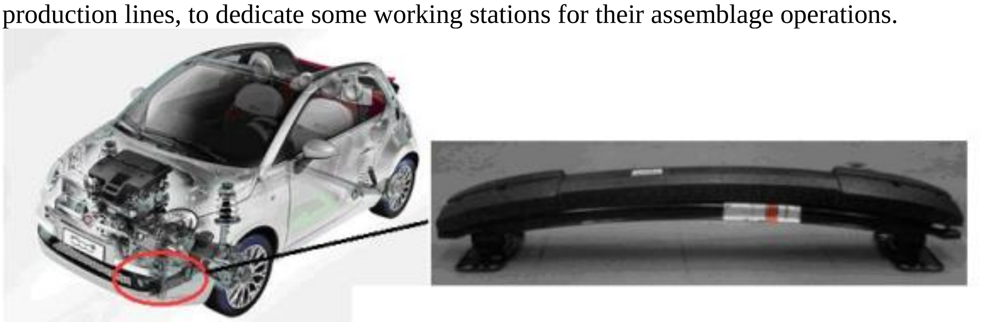


Figure 6 – The present solution for the front bumper system with the bumper beam and the crash boxes made by steel, through the assembly of different parts

The manufacturing process and the tooling result to be largely simplified and a relevant reduction of the production cost can be obtained. This can be a typical example of the need of using a wider view when comparing the costs of two alternative solutions based on the use of different materials: it is needed to account not only the cost of the materials but also the costs of the manufacturing process. Very often the composite material solution allow for integration and thus large simplification of the process.

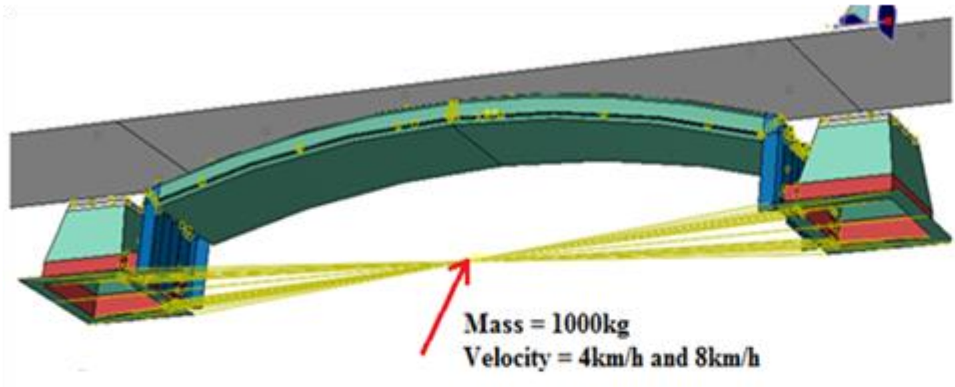


Figure 7 – The proposed solution for the front bumper system with the bumper beam and the crash boxes made by composite (GMT) material, the solution is integrating the different parts into one piece [9].

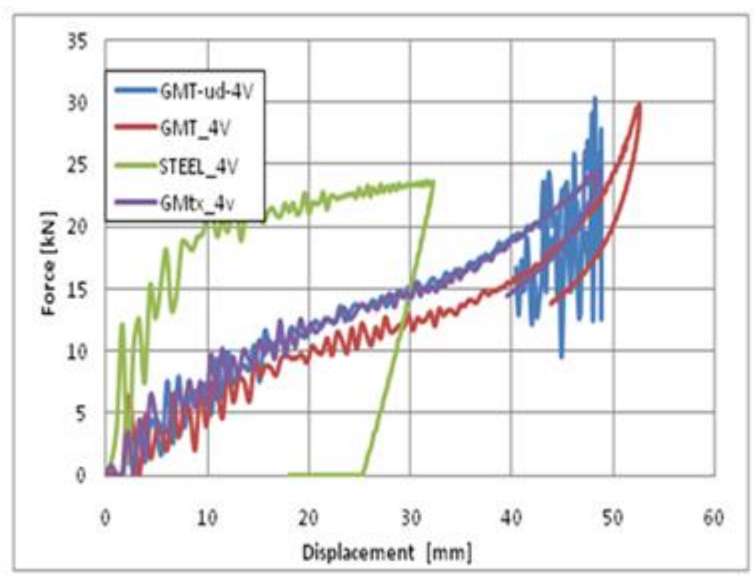


Figure 8 – Comparison of the force-displacement diagrams obtained through numerical simulation of the impact performance of the front bumper. One curve is describing the results related to the NP solution, the other three curves the composite material ones.

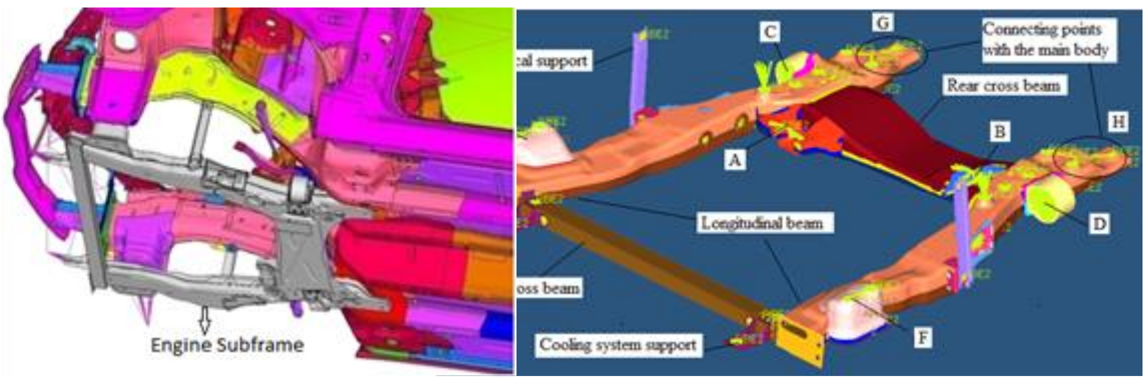
Finally figure 8 shows the comparison of the force-displacement curves for the case of the front bumper impacting at a velocity of 4 km/h against a rigid wall. The vehicle is supposed to have 1000 kg mass. In the figure four curves are superimposed, one is for the bumper beam made with steel (i.e. the NP solution) and the other three are for the composite solution of figure 7, made with different GMT materials: a simple GMT (that is the red curve, as expected, being this the less performing material, the curve is the lower one), a GMT-tex (that is the GMT reinforced with the fabric made of long glass fibers) and a GMT-ud (that is the GMT reinforced with unidirectional long glass fibers). These two latter alternatives result to be equivalent, being the curves nearly superimposed. The maximum displacement for the composite solutions, although larger than the steel one, does not exceed 50 mm and thus the intrusion into the engine compartment is not critical.

The advantage in terms of mass for the composite solutions with respect to the steel one is of the order of magnitude of -52 %, that is about 4 kg.

The engine subframe

Figure 9 shows the present solution for an engine sub-frame. It consists of two longitudinal and two cross beams, all these parts are made of steel. The two longitudinal beams and the rear cross beam are made of two half-shells that, after deep-drawing, are joined together by spot welding, while the front cross beam is made with extruded profile. In figure 9b the points E,F,G and H are the connection points of the frame with the body structure, points C and D are the connection points with the oscillating arms (left and right) of the front suspension system, finally points A and B are the connection points with the engine mounting and suspension system. In figure 8b also the water cooling system supports are visible.

This frame is a quite complex structure with multiple functions. In some solutions the longitudinal beams are extended toward the front of the vehicle to constitute a further load path very useful in case of frontal impact.



a) b)

Figure 9. Engine subsystem: a) Assembly of engine sub-frame with Body-In-White; b) Detail view of engine sub-frame.

Figure 10 shows the solution that has been studied taking advantage from the particular mechanical characteristic of a CFS003/LTM25 Carbon/Epoxy fabric prepreg, i.e. a material with high structural performance. By means of repeated virtual simulations the stacking sequence has been optimized in order to get the best results both in terms of frame bending stiffness and in terms of strength. Further, appropriate increment in the wall thickness and structural reinforcements has been designed in order to solve the structural problems in the most stressed zones.

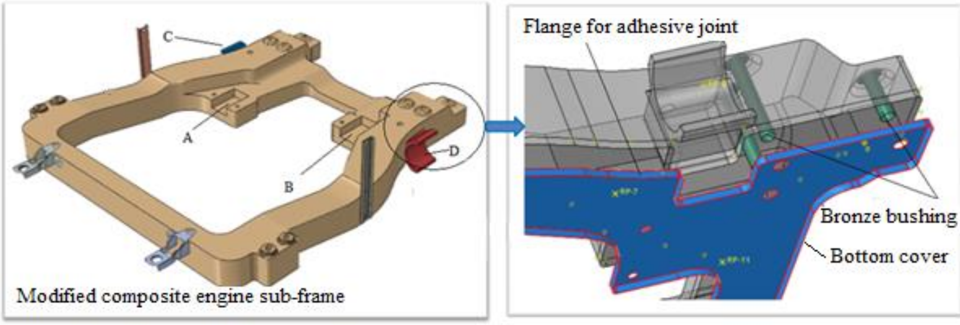


Figure 10. Conceptual design of the composite engine sub-frame [17]

By a comparison of the composite solution depicted in figure 10 and the NP solution depicted in figure 9, it is coming out with evidence that the composite solution is structurally simpler as it integrates into one single part a number of different parts that constitutes the steel solution. Some local reinforcements (for example the bronze bushings needed for the connection of the sub-frame with the vehicle structure, as shown in figure 10b) can be co-stamped and co-cured while the composite structure is manufactured.

Figure 11 is showing the distribution of the maximum principal stresses in the composite material, for the load case of the maximum torque given by the ICE. The calculated values for the stress are fully compatible with the strength of the adopted material.

Figure 11. Maximum principal stress distribution on engine sub-frame with reinforcements [17]

The advantage in terms of mass reduction for the composite solutions (that have a mass of less than 6 kg) with respect to the steel one (that has a mass of about 16 kg) is of the order of magnitude of 10 kg that is about - 62 %.

ONE EXAMPLE OF INNOVATIVE ADHESIVE JOINING

As mentioned in the introduction, in this paragraph we want to present some results obtained during a particular research activity about the use of adhesive for structural joints. The main concerns that has stimulated this type of research are to make experience with a thermo-plastic adhesive, to use nano-particles sensitive to the electro-magnetic field for reduce the polymerization time (and thus the duration of the production cycle), to use the same physical principle used for a selective melting of the adhesive for dismounting purposes (i.e. for separating the parts that has been joined both for easier repair and for easier end-of-life recycling).

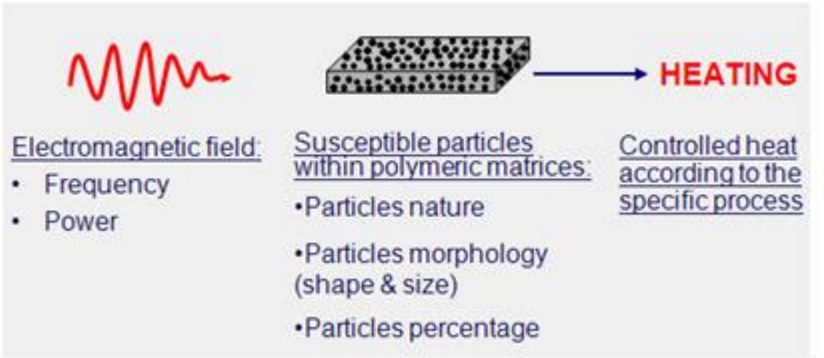


Figure 12. Physical principles of the electromagnetic activation of the nano-modified adhesive and design variants.

Figure 12 is recalling the physical principle for the activation of the adhesive nano-modified by means of susceptible particles dispersed into the polymeric resin [15]. The electromagnetic field acts as source of energy for the polymer heating. Both the parameters of the electromagnetic field (power and frequency) and the nano-particles (material type, particle shape and size, particle percentage) are design variables for the manufacturing process.

At the moment this process can be applied for joining components made of plastic materials. After having performed a number of laboratory tests in order to assess the methodology and to analyse the effects of the main design variables [15], the case of tail gate of the Lancia Musa was chosen for performing a real part application.

Figure 13 shows some detail of the application. The tail gate external trim consist of two shells made of polypropylene that have to be joined in order to obtain the lower trim of the rear door.

Figure 13. The Lancia Musa tail gate as chosen vehicular application.

Figure 14 shows the special tooling that has been prepared to join the two shells and produce the tail gate trim adopting the described innovative technology. A copper circuit has been laid along the joining area to act as electromagnetic inductor, activated by an alternate electric current with the selected values of power and frequency.

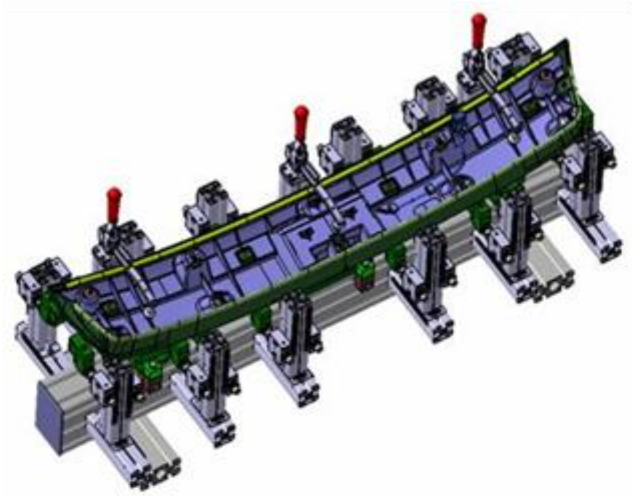


Figure 14. Scheme of the tooling for the manufacture of the innovative adhesive joints applied to the Lancia Musa tail gate [18].

Figure 15 – Disassembled low tail gate [18]

Finally figure 15 is showing the tail gate that has previously manufactured by joining with the described tooling and procedure, and then submitted to similar heating procedure for the dismounting. The supplied power raises the adhesive temperature, because of the reaction of the metallic nano-particles, and, when the appropriate temperature is reached, near the polymer melting threshold, the shells detachment is easily obtained.

CONCLUSIONS

The paper has addressed the present concern in the automotive engineering related to the environmental problems, with particular reference to the fuel consumption and to the noxious and GH gas emissions. Transportation is recognized as one of the main source of the carbon bioxide CO2, that is considered the main GH gas and consequently cause of the current, evident climate change.

The international European legislation is forcing the reduction, on the basis of the average fleet performance, of the fuel consumption reduction. For the CO2 emissions a progressive decrease is targeted, with relevant penalties for the car manufacturer in case of exceed.

The car makers have different possible strategies to develop their products in order to match these normative limits. These strategies can be developed in a concurrent way. One of the strategic line is the lightweight of the vehicles. Some options are at disposal of the designer, the most promising is the substitution of the traditional material (generally low-carbon steel) with more performing metallic materials or with fiber reinforced plastics, as it is widely done in the aeronautical industry sector.

It is the authors' opinion that the first step toward lightweight will consist in the use of more performing metallic materials, but the most important results will be obtained by the extended use of fiber reinforced plastics. This second step is requiring some more research activities in order to extend the already relevant knowledge of the behaviour of this class of materials, with particular reference to the mechanical characteristics (fatigue and impact response), the manufacturing technologies, the reparability, the recycling possibility at the vehicle end of life.

The cost of production is always of concern. In the evaluation of the costs one has to take into account not only the greater cost of the base material (typically fiber reinforced composites have larger costs with respect to metallic materials) but also the generally lower cost in the tooling, the cost reduction that can be obtained by structural integration of the several (very often tenths) metallic pieces, assembled together to construct one single component, into even single piece that can be obtained by plastic die manufacturing.

The paper has presented and discussed two particular examples that have been developed within the fame of the research cooperation between FIAT and Politecnico di Torino.

Further some results have been presented about an innovative adhesive joining technology, based on the use of an adhesive nonmodified by means of the dispersion of metallic particles that are sensitive to the electro-magnetic field. The proper application of the electro-magnetic field is resulting in the polymer heating and this can be used both to accelerate and control the adhesive polymerization during the joining procedure as well as to make possible and easy the disassembly of the joint, in case of repair or dismount. Preliminary results in the application to the Lancia Musa rear door low tail gate have been shown.

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ERGONOMIC ANALYSIS OF MOTOR VEHICLES

Maria Pia Cavatorta[1]

UDC:629.331;572.087

ABSTRACT: Up to the 1950s, motor vehicles were a product determined by technology. Engineers conceived the functional aspects of the vehicle, which was then dressed up by body work specialists and craftsmen. The purchaser himself was mainly interested in performance and technological innovations. Attention to user characteristics and needs came later. The evolution of the market intensified competition among manufacturers, who started to invest in image. Image soon became an important factor in driving customer choices.

The ergonomic aspects of motor vehicles are not explicitly treated by the European Community directives. The Society of Automotive Engineers, through its standards committees, sustain a series of recommended practices, that codify tools and methods. In particular, the SAE norms define the anthropometric standards for the dimensional relationship between man and vehicle, which are at the base of any assessment on habitability, accessibility, reachability, internal and external visibility, and postural comfort.

KEY WORDS: ergonomics, motor vehicle, anthropometric databases, digital human models

ERGONOMSKA ANALIZA MOTORNOG VOZILA

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REZIME: Do 1950. godine, motorna vozila su bila proizvod određen tehnologijom. Inženjeri su razmatrali funkcionalne aspekte vozila, koji su onda prosleđivani stručnjacima za karoseriju i modelarima. Sam kupac je uglavnom zainteresovan za performanse i tehnološke inovacije. Pažnja na karakteristike i potrebe korisnika došla je kasnije. ‚Evolucija tržišta intenzivirana konkurencije među proizvođačima, koji su počeli da ulažu u slici. Slika je ubrzo postala značajan faktor u vožnji izbora kupaca.

Ergonomski aspekti motornih vozila nisu eksplicitno tretirani direktivama Evropske zajednice. Društvo automobilskih inženjera (SAE), nastoji da preko svojih odbora standarda, omoguće primenu preporuka iz prakse, da kodira alate i metode Konkretno, SAE norme definišu antropometrijske standarde za dimenzionalne odnos između čoveka i vozila, koja su osnova svake procene prikladnost za boravak, dostupnost, mogućnosti dohvata, unutrašnje i spoljne vidljivosti, i udobnosti položaja.

KLJUČNE REČI: ergonomija, motorno voozilo, antropometrijska baza podataka, digitalni model čoveka

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ERGONOMIC ANALYSIS OF MOTOR VEHICLES

Maria Pia Cavatorta[1]*PhD, Professor*

UDC:629.331;572.087

INTRODUCTION

Design of motor vehicles had not initially focused around humans [2]. Vehicles were merely designed to perform basic mechanical tasks. Only later designers took into account the human element, even though, in the beginning, ergonomic principles were often introduced as an interventional option at the end of the design process. The aim of ergonomics was mainly introducing further qualities, which were often perceived as accessories or part of the brand image. Only in the past decades, vehicle occupant packaging became a necessary design phase [3].

The primary focus in occupant packaging is the driver's workstation, that is the location and adjustment ranges of the steering wheel and seat with respect to the pedals, the physical location of controls and displays with which the driver interacts, the analysis of interior and exterior driver visual areas, both direct and through mirrors.

The objective of packaging is usually stated in terms of percentage accommodation on particular measures. Accommodation is quantified as the fraction of the driver population achieving some target level of fit or comfort [7].

Beginning in the late 1950's, the Society of Automotive Engineers (SAE International) started considering standardized tools and procedures for packaging [23]. SAE Recommended Practices, first approved in 1962, defined a weighted three-dimensional manikin for measuring seats, known as the H-point machine. The manikin defines and measures the location of the H-point, a reference point that approximates the hip. In the early 1960s, the first percentile accommodation model, known as the eyellipse, was introduced. The eyellipse is a graphical construction that describes the expected distribution of driver eye locations. In the late 1990s, the model was upgraded to take into account the effect of steering wheel position on eye location. Other important statistical models include the seating accommodation model and the driver head clearance contour. In each case, the model provides a geometric design guide that represents a specified percentage of the relevant measure from the population of drivers [15].

An increasing common approach to occupant packaging employs manikins to represent driver requirements. Use of three-dimensional computer graphic models has followed the development of low cost computers. Early human modelling software programs such as Sammie have been followed by Ramis, Jack and Safework among others. These digital human models (DHM) are now widely used for vehicle interior design and have often replaced SAE packaging tools.

Manikins are fundamentally population models, in that they describe percentiles of a population, not the behaviour of any individual within the population. A panel of manikins would be needed to attain good estimates of population characteristics. In the attempt to reduce the number of computer analyses that must be performed, designers select the extremes that span a large percentage of the range of body dimensions in the target population [4,10].

1 Maria Pia Cavatorta, Department of Mechanical and Aeronautical Engineering, Politecnico di Torino. Corso Duca degli Abruzzi 24, 10129 Torino – Italy. maria.cavatorta@polito.it

The five elements to be considered in the ergonomics of motor vehicles are: habitability, accessibility, reachability, internal and external visibility, and seating comfort. The elements are briefly described hereafter.

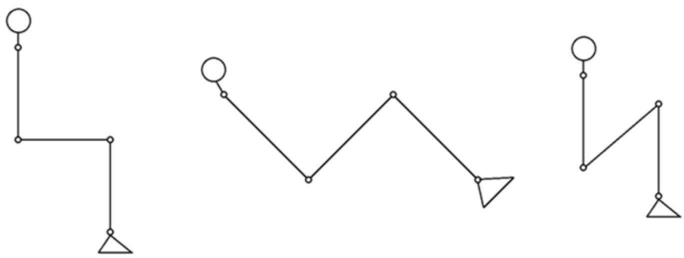
Habitability

Habitability is generally defined as the ability of the vehicle to accommodate the user; it comprises postural comfort, spaciousness and perceived habitability. In the study of a new vehicle, or in a benchmark analysis, the habitability study is often considered as the starting point.

Habitability study consists in positioning the virtual mannequin inside the vehicle so that it reflects natural human body physical angles [18].

Depending on the vehicle segments, designers decide between three basic positions: sit, reclined and cramped. These three positions have advantages and disadvantages (Table 1), related to the vehicle package and to the human body physiology.

Table 1 The three basic positions: main advantages and disadvantages



	SIT POSITION	RECLINED POSITION	CRAMPED POSITION
PROS	longitudinal size	vertical size	vertical size
	control reach	load on backbone	longitudinal size
	visibility		
CONS	load on backbone	longitudinal size	control reach
	vibration and fatigue	accessibility	vibration and fatigue
	vertical size	visibility	accessibility
			visibility

In most cars, the reclined position is used for the driver and the front passenger, while the cramped position is considered for the rear passengers. This choice guarantees a good comfort level for the driver and reduces the longitudinal size of the front and back seats, allowing to reserve a good trunk space [24].

Sit position is the best suitable for trucks. It guarantees a good front visibility on road, allows an easy reach of the dashboard controls with a reduced longitudinal driver size.

After the basic position of the driver has been chosen, a suitable driving limb position during driving is considered. Obviously the stature of the driver has a significant impact on the driving position and therefore on the room left for the rear passengers. Studies on different percentile combinations for driver and rear passenger are usually carried out, also in relation to the car segment and main car usage.

Spaciousness must be considered for the driver and the front and rear passengers. Spaciousness is to be evaluated in the transverse, vertical and longitudinal directions. Designers have to take into account both true geometrical dimensions and clearances, as well as the perception of space. Perceived habitability plays a key role in terms of marketing and value of the vehicle and must be considered carefully.

The spaciousness required by the upper body refers to restrictions of the trunk and arms and their movement; The spaciousness required by the lower body refers to the restrictions of the legs and their movement. Obviously, the requirement of spaciousness becomes more and more stringent as the size of the driver and passengers increases. Also age and state of health of driver and passengers are important parameters, as well as what is likely to be the main usage for the vehicle (city car vs. family car).

The perception of space is a determining factor in the sensation of comfort. It is provided by a complex relation of the physical dimensions of the inside of the vehicle to the ease of movements inside the vehicle, and to perceiving of the external world through the windows and the windshield.

It is worthwhile noticing that there are several targets to achieve to ensure habitability and that often target's achievement cannot be optimal for all tasks; in fact, the true difficulty for the designer consists in setting all these issues together to find the best solution possible. Needless to say that the car segment, and therefore the intended user and usage of the car, are important factors in determining the constraints to the optimization problem.

The posture of the driver is conditioned by several constraints imposed by the act of driving: awareness of the road, awareness of the dashboards and the displays, operating the steering wheel and other controls, operating the pedals. Some aspects, such as the front visibility, are car parameters subject to homologation.

For passengers, both in the front and in the back, body posture may be quite different with respect to that of the driver and it is only slightly constrained by the criteria of safety norms and regulations (i.e. the use of safety belts).

In habitability studies, there are some relevant dimensions to consider, which are coded according to SAE standards (Figure 1). These dimensions are relative both to the vehicle and to the future occupants.

Car manufacturers have always looked at the design solutions of competitors; historically, the only way to retrieve the information was to purchase the different vehicles and, through reverse engineering, obtain the measures of interest. At the end of 1980, different manufactures decided to set up the GCIE LIST (i.e. European Car Manufacturers Information Exchange Group). Through registration and payment of membership fees, the different vehicle manufacturers share data in a coded format and accessible to others.

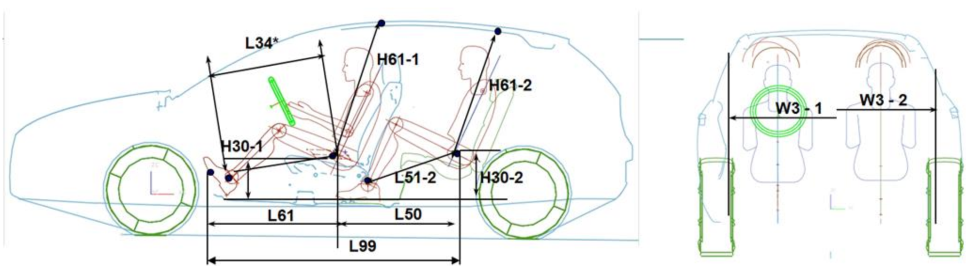
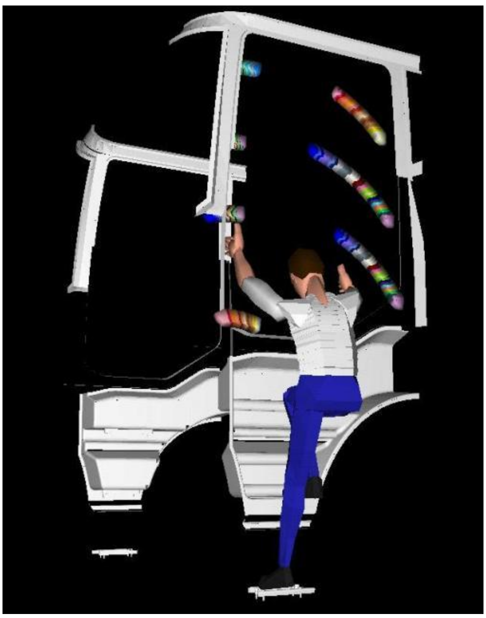


Figure 1 An example of vehicle and occupants' dimensions considered in habitability studies

ACCESSIBILITY

Accessibility refers to the absence of restrictions of movement in entering and exiting the vehicle. The ease of getting into and out of passenger cars and light trucks is a critical component of customer acceptance and product differentiation. A minimum of postural change and the maximum possible naturalness are searched for. For the upper body, freedom of movement may be conditioned by the thickness of clothes, by the mobility they allow, and by the presence of objects being carried (bags, umbrellas,...), while for the lower body, freedom of movement is mainly influenced by the clothes and shoes being worn.

In commercial vehicles, the health and safety of drivers is affected by the design of the steps and handholds they use to get into and out of the cabin. Ingress/egress assessment is often approached through digital human models (Figure 2). Digital modelling is difficult due to the complexity of the design space and the range of possible biomechanical and subjective measures of interest, which often require large-scale subject testing with physical mock-ups. Motion strategies are composite and strongly affected by the geometrical constraints and driver's characteristics, posing great challenges in creating meaningful simulations [23]. Subjects with different physical characteristic are generally tested in a wide range of vehicle conditions. Subjective responses are gathered along with motion measurements. Several people can choose, usually in an unconscious way, different strategies: the virtual path is created by choosing the most common among the different strategies. The primary advantage of this approach to simulation is that the resulting motion can have a very realistic appearance. A principal limitation is that the effects of important occupant covariates, such as stature, body weight, age, and gender, are not modeled explicitly [23].



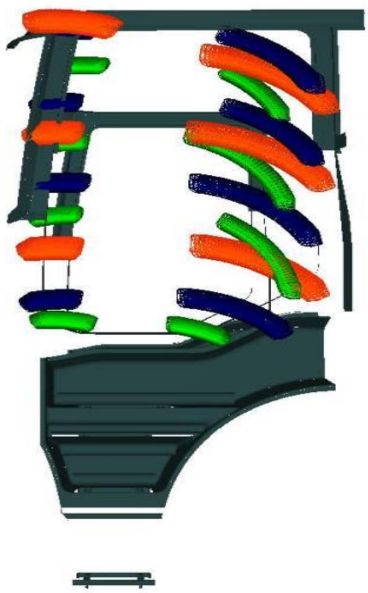


Figure 2 Different areas of reachability of the handles from each step for various percentiles, (5th percentile: green; 50th percentile: blue; 95th percentile: orange)

REACHABILITY

Check on the level of reachability of the different controls and devices on the dashboard, as well as of vehicle compartments, is also part of an ergonomic analysis of the motor vehicle. Reaching in postural comfort must be possible for different percentiles of users, that is, regardless of the driver's size, the joint angles for the different body segments and for the torso must be kept within comfortable bounds. Also no physical interference between the arms and the steering wheel or other cabin parts must prevent correct reachability.

In unrestrained positions, reachability generally represents a bigger issue for small individuals (Figure 3). However, this is not necessary the case for the driver of a vehicle, since bigger individuals, due to the longer legs, must position the car seat further away from the pedals, and are therefore more distant from the steering wheel and the different parts of the dashboard (Figure 4).

Assessment of reaching capabilities using human models is commonly performed by evaluating each joint of the kinematic chain, terminating in the hand, through the associated ranges of motion [21]. The result is a reach envelope determined entirely by the segment lengths, joint degrees of freedom and joint ranges of motion.

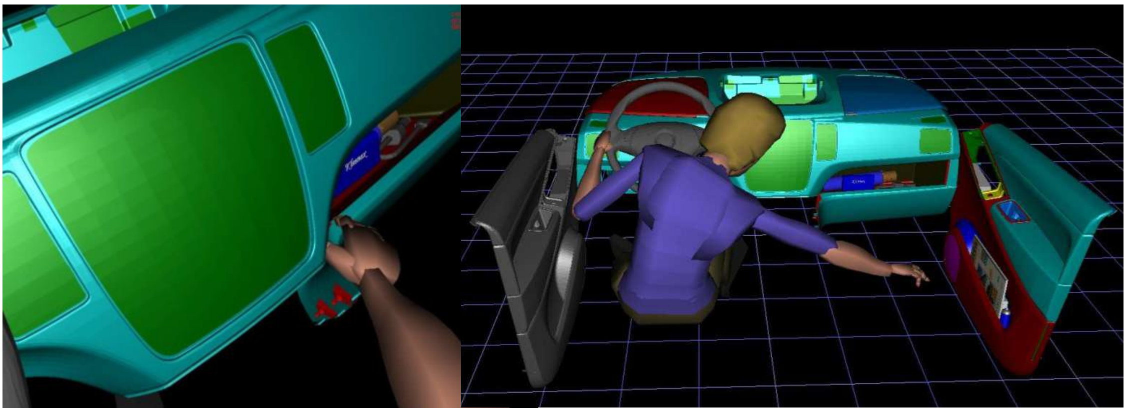


Figure 3 Reachability check of internal compartments. 5th percentile female

Software tools provide the ergonomist with the ability to simulate the vehicle occupant reaching to controls or other targets, by articulating the joints of a virtual human. For many vehicle interior analyses, computer simulations with manikins are used instead of statistical reach models. In typical applications, the range within which an occupant can reach is obtained by iterating through its range of motion each joint of the upper extremity, from the shoulder joint to the wrist. Analytical methods have also been developed to calculate the surfaces defining the reach envelope [1]. Earlier studies have examined the validity of reachability simulations for pilots with fixed-length torso restraints [9].

Belt restraints in modern road vehicles are commonly equipped with emergency locking retractors. With this type of belt system, the belt does not substantially restrain the occupant's torso during normal reaching activities. Hence, a vehicle occupant's reach envelope is determined by torso mobility in addition to upper extremity dimensions and range of motion. However, most designers currently use the reach envelopes obtained with fixed length, highly restrictive torso belts. Experience has shown that controls located within the more restrictive envelops approximate, comfortable reach for less restrictive conditions [17,23].

The ongoing increase in the number of in-vehicle controls, particularly in commercial vehicles, is exposing the problems of this type of approach. With a large number of controls to be placed and a limited area within the traditional design curves or within the reach envelopes generated using human models, it is unavoidable that some controls are placed in zones that are considered "unreachable" [5,6].

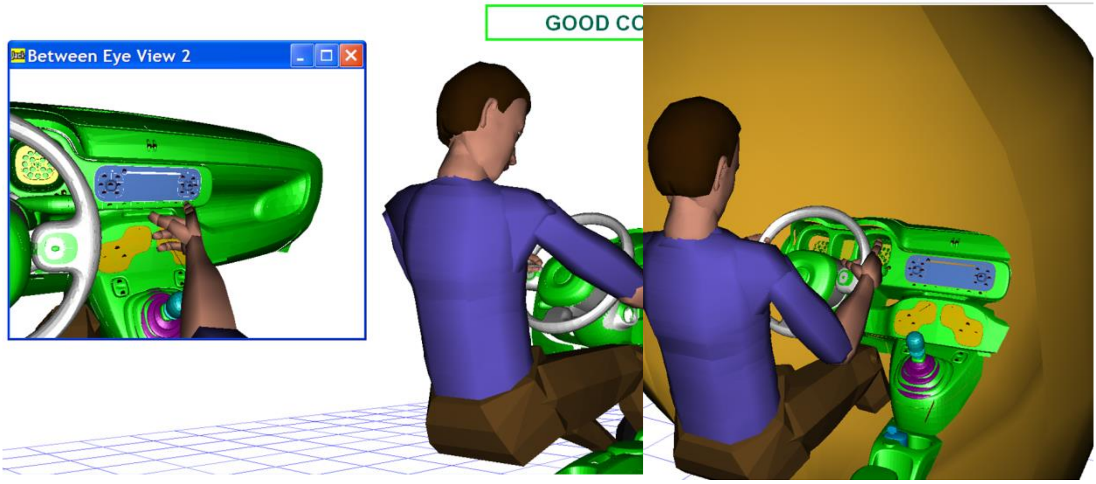


Figure 4 Reachability check for a 95th percentile male.

The reach envelope on the right allows to verify which parts of the dashboard fall within driver's reach

INTERNAL AND EXTERNAL VISIBILITY

Visibility is one of the most important vehicle performance. To guarantee good external visibility does not simply represent an ergonomics target to achieve, but an homologation parameter. The main visibility parameters are the SAE and the European regulations. In any case, it's possible for single countries to require vehicles to meet additional national requirements.

There are also other issues concerning visibility. In particular, designers also have to ensure that the interior devices and controls are visible for all percentiles of users.

In visibility checks, experimental testing as well as virtual analyses are performed. Experimental testing is usually carried out with expert users who perform a specific task. Movements are observed and registered in order to be analyzed and for defining strategies to be implemented in the simulation. Virtual analyses include virtual reality tools as well as simulation through software packages such as Jack and Ramsis. In virtual reality tools, users can perform a specific task interfacing with a mock-up of the vehicle interior, which is part physical and part digital. A realistic reproduction of external scenarios is also projected.

External visibility comprises static and dynamic aspects. The static external visibility refers to a stationary vehicle. Usually three aspects are checked: a) rotation of the point of view, b) analysis of wiper/screen printing, c) visibility of a child located outside the vehicle (Figure 5).

The dynamic external visibility is usually checked on four different tasks: a) right turn, b) left turn, c) exiting an underground parking through a ramp, d) reverse parking. For all manoeuvres, external agents (other vehicles, children and pedestrians) that move around the scenario, independently from the driver's choices, are present (Figure 6).

External visibility must also be checked in terms of reflected visibility, that is what the driver sees through the rear view and side mirrors. Usually two manoeuvres are simulated: reverse parking and passing on the motorway. The problem of reflected visibility is highly critical for industrial vehicles.

Internal visibility takes into account possible elements of visual obstruction and what parts of the dashboard drivers of different sizes may see or not see. The dashboard includes controls and displays of key importance, as they are used in the primary task of driving, as well as secondary displays and controls, which may be used for example in controlling the climate inside the car, switching on/off the radio...[6]

Ergonomics software programmes like JACK or Ramsis give designers the possibility to watch the rendered environment from the left, the right eye and from a point that approximates a binocular point of view, called "between eye view". In this way, by changing the point between eye due to the percentile being examined, it's possible to analyze what different percentiles see (Figure 4).

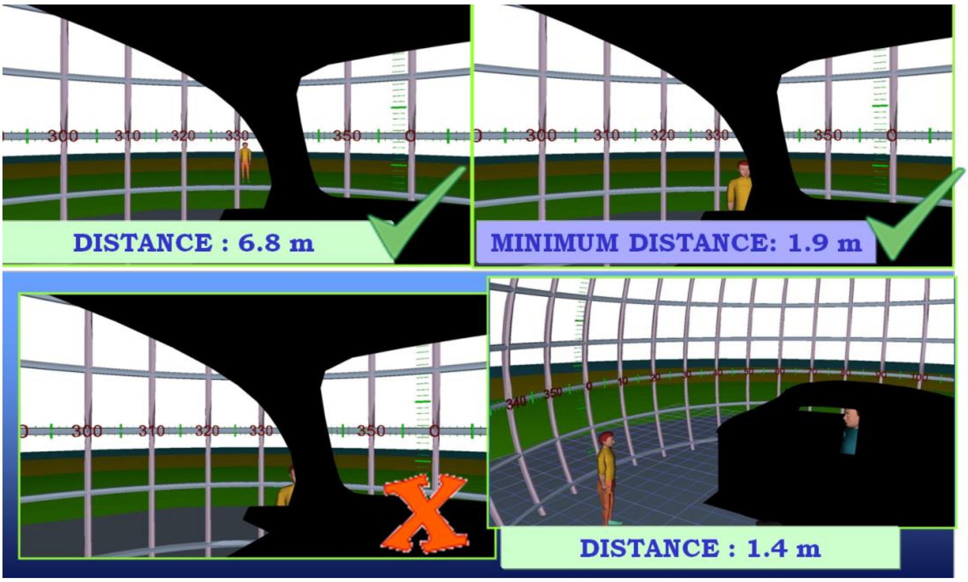


Figure 5 Visibility of a child located outside the vehicle. 50th male; driver's trunk rotation 30°

Reflexes are also important to consider and prevent. Non-homogeneous materials and lights are the main cause for reflected images on the windscreen. Both in a car and a truck, the dashboard upper surface is the most reflected on the windscreen. In particular, the annoyance comes from edges between different surfaces, because physiological perception is focused on discontinuity. Making the dashboard surface as homogeneous as possible decreases the chance of reflections. Sometimes reflexes can appear from illuminated objects. One of the most common examples is the gearlever illuminated by navigator screen and then reflected on windscreen.

Reflexes on cluster are usually created by instrument lights on the interior surface of the cluster's eyelid. This problem can be avoided by choosing a material with no lucid surface finishing. The same material with a rough or embossed surface is known to completely stop reflection.

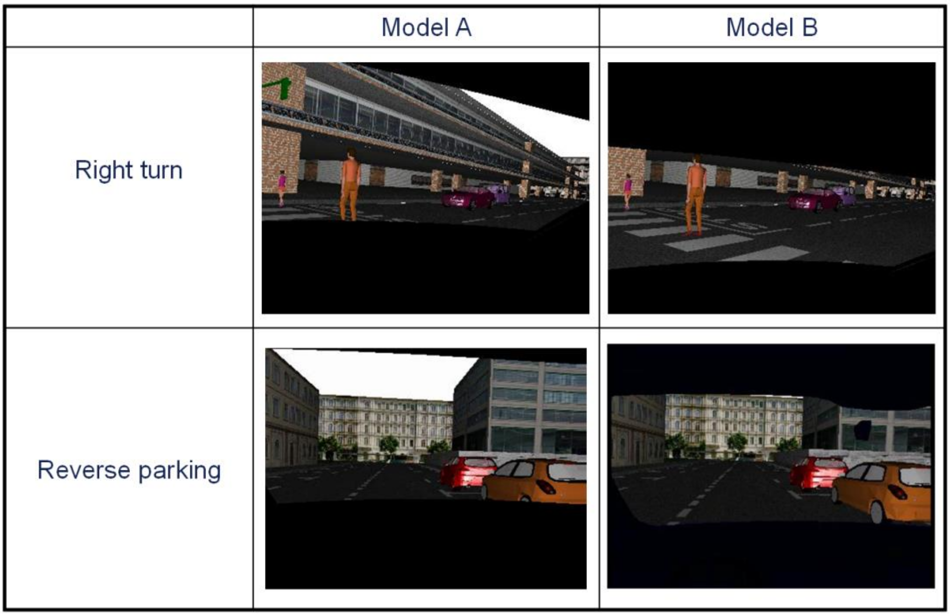


Figure 6 A comparison between two car models in different standardized manoeuvres

Before software analyses on reflexes were possible, the reflex issue was checked in the dark room requiring a prototype with almost final surface finishing. This wasn't possible in the first project phase and neither when materials where decided, but only after prototypes arrived and were mounted. The evolution of rendering software programmes made it possible for a highly realistic rendering of surfaces and a virtual representation of the dashboard as it will look like in reality.

COMFORT AND SEAT DESIGN

Comfort is the general state of well-being that derives from the reduction or absence of perceived disturbances. It is a passive and sensorial concept that is also linked to sensorial pleasantness. Sensorial pleasantness cannot be measured as it is an active and cognitive aspect that responds to customer expectation.

Comfort comprises quite different aspects: vibration, acoustic, thermal, tactile, vision and smell. The last three aspects are now considered important factors, but they have generally been studied in less detail.

Vibration comfort is related to the effects of the mechanical vibrations induced by the motor and the road profile, and transmitted through the suspension system.

Acoustic comfort depends on the effects produced by the mechanical parts and the noise induced by air turbulence and road surface. It is influenced by the mechanical characteristics of the vehicle and by the degree of sound proofing of the vehicle interior.

Thermal comfort is related to the quality of the microclimate and the thermal sensation of the contact surfaces.

Seat design is an important aspect for postural comfort as well as for reachability and visibility issues [14,16].

Today car manufacturers have to consider drivers of very different sizes. Stature range is constantly increasing, requiring seats to be moveable for almost 30 centimeters. While the steering wheel can be adjusted axially, the dashboard cannot move along with it. Thus, optimizing an interior design is to find the best compromise for the variety of possible drivers, while maintaining the corporate identity in interior design.

Since not all combinations can be evaluated with real test persons and physical mock-ups, virtual humans become more and more present. By placing a virtual human in different virtual scenarios, a much broader set of alternatives can be investigated in early stages of the design.

Most of the research findings concerning industrial and office chair design can be applied to car seats. However, there are several important considerations, unique to the mobile environment, that should influence design recommendations. In particular, the control locations and line of sight requirements serve to constrain postures to a greater extent than in most other seated environments. Safety concerns dictate that the driver be alert and continually responding to changing road conditions, and be positioned in such a way that the occupant restraint systems offer maximal protection in a crash. Passenger cars generally require a more extended knee posture than it is necessary in other types of seating. This has important implications with regards to the orientation of the pelvis and the lumbar spine. Additionally, vibrations impose tissue stresses that are not generally present in a stationary environment.

When attempting to specify design characteristics of a comfortable seat, it is important to bear in mind a functional definition of comfort as it applies to seating. Research has pointed out that it is unreasonable to assume that comfort extends in a continuum from unbearable pain to extreme feelings of well-being. Since a seat is not likely to convey a positive physical feeling, the continuum of interest reaches from indifference to extreme discomfort. The best a seat can do is to cause no discomfort. This definition is useful, not only in the design of subjective assessment tools such as questionnaires, but also in consideration of strategies to improve comfort. The aim of car seats should be to reduce or eliminate factors causing discomfort, rather than to elicit feelings of well-being.

Most virtual models used in ergonomic analyses provide postural comfort ratings based on joint angles, through a single whole body comfort score or on a joint-by-joint basis (Figure 7). The source data for these ratings is generally derived from laboratory studies that link posture to subjective ratings. What is lacking in many of these models is a thorough treatment of the distribution of ratings in the population of users. Information about rating distributions is necessary to make cost-effective tradeoffs when design changes affect subjective responses.

VIRTUAL DESIGN AND USE OF ANTHROPOMETRIC PERCENTILES

From a physical point of view, the biggest issue in designing a product for people is considering the variability of the target population through the use of percentiles. In first production age, craftsmen fulfilled the buyers' needs building around them the car as a tailor creates a suit. Following the industrial production age, business was based on mass production. No longer the case buyers "pull" the productive engine, the production chain is "pushed" to create a product that may suit the largest possible number of users [16].

Designers incorporate scientific data on human size into the design of systems and equipments through the use of anthropometric percentiles (Figure 8). The population is divided into 100 percentage categories, ranked from minimum to maximum dimensions, so that for example, when referring to stature. the 5th percentile is a value whereby 5% of the population is shorter and 95% is taller, the 50th percentile is the median stature and the 95th percentile is a value whereby 95% of the population is shorter and 5% is taller.

The same concept applies to different body segments as well as to weight and strength of the population. Manikin weight can be important as bigger transverse dimensions of the body can determine a reduced range of movement, posing problems of accessibility and reachability.

Parameter	Recommendation
Pressure Distribution	
• Seat cushion patterns	Peaks should be located only in the areas of the ischial tuberosities. No other local maxima should be found.
• Backrest patterns	Peaks should be located only in lumbar area. No local maxima should be found in the shoulder area.
• Peak levels	Peak levels should be determined by subjective comfort testing with target populations. Large differences in pressure distributions and sensitivity among individuals make specifying a quantitative "optimal pressure distribution" difficult.
Surface Shear	Surface shear on the seat cushion should be minimized by increasing the cushion angle and/or by contouring the cushion to achieve the same effect.
Temperature and Humidity	The seat covering should allow heat transfer of at least 75 W/m^2 by conduction and diffusion of water vapor. Foam should not be compressed to more than 80% to allow for maximum vapor diffusion.
Vibration	The seat should minimize the transmission of frequencies between 4 and 8 Hz.

Figure 7 Recommendation on pressure distribution patterns [23] and optimal pressure levels [25]

Since the late 1970's there have been many surveys, large and small, to obtain anthropometric data on a variety of subjects . Traditionally, the largest number of data have been taken on military personnel and the most noticeable survey belongs to U. S. Army. The army anthropometry databases are widely used because of the large number of measurements and the rigorous methodology [8]. Some other surveys dealt with smaller samples of factory workers. One large document covering the results of many surveys, Adult Data, was prepared by Nottingham University and published in 1998 by the Department of Trade and Industry of the United Kingdom.

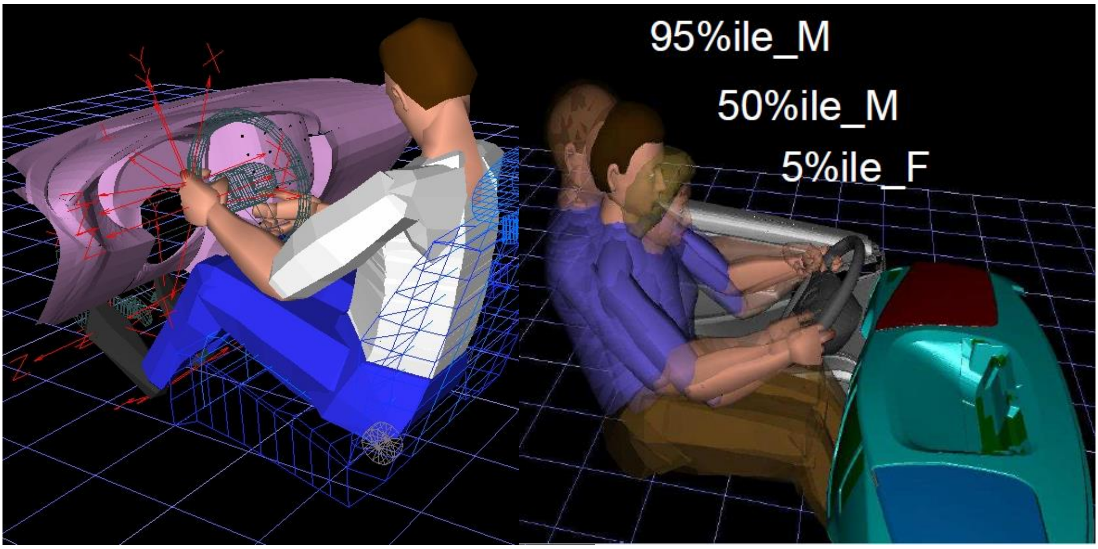


Figure 8 A virtual simulation in Jack through the use of different manikin sizes

In 2008, the International Organization for Standardization (ISO) released the Technical Report 7250-2, "Basic human body measurements for technological design - Part 2: Statistical summaries of body measurements from individual ISO populations." This technical report contains summary statistics for a number of anthropometric dimensions from various countries around the world. Available anthropometric data from a variety of countries are presented in a single source. Informative annexes contain information specific to Asia and Europe, so that designers of products to be marketed in those regions can use appropriate dimensional criteria.

The strategies for applying anthropometric data in design include:

- find the relevant data for the intended occupants with respect to their origin, occupation, age, gender, disability;
- make any necessary allowance for secular growth and clothing;
- determine the design limits. Traditionally these have been stated as the 5th percentile female value and the 95th percentile male value. Some authors [10] consider these limits somewhat out-of-date, given the concern for life quality and safety, and recommend using the 1st percentile female to the 99th percentile male values whenever possible. This wider range is particularly important when several dimensions are critical for accommodation or when safety is of concern;
- design for extreme individuals when appropriate. Clearance dimensions that must accommodate or allow the passage of the body or parts of the body shall be based upon the 95th percentile of the male distribution data. On the contrary, when reachability is an issue, generally it is the 5th percentile of the female distribution data that must be considered;
- design for the adjustable range when minimum fatigue, optimum performance, comfort and safety is required (e.g. vehicle seats, steering wheels, seat belt mountings);
- design for the 'average' person when adjustability is not feasible, but never use median values for clearance, reach or strength. The 'average value' should be used only when it is likely to cause less inconvenience and difficulties to the user population than a larger or smaller value would do.

Even though some general guidelines can be given, designers shall be aware that, even if the concept of percentile is easy to understand, fallacy arises because it is assumed that application of percentile data is equally easy. The first trap is referring to mythical people such as a 5th percentile female or a 95th percentile male. Anthropometric dimensions are poorly correlated, which means that people of the same stature can have markedly different leg and arm lengths, weight, torso breadth and so on. Percentiles are univariate and only refer to one dimension at a time. A percentile value should never be used without obtaining details of the age range, nationality and occupational groups included in the original survey data. The date of the survey is important too, due to the secular growth issue.

A common mistake is to assume that designing from 5th percentile female to 95th percentile male dimensions will accommodate 95% of people. This is true if only one dimension is relevant to the design solution (i.e. univariate accommodation, such as standing headroom). However, vehicle interior design is likely to require simultaneous accommodation on a large number of dimensions (i.e. multivariate accommodation). Since correlation between body dimensions is poor, it follows that those males who are designed out because of limited headroom (5% of males in theory for a large random sample) will not necessarily be the same 5% who are designed out for having arms that are too long or the 5% with legs too long, hips too broad and so on. Similarly, those females who are designed out because they have legs, arms, sitting eye height, etc. that are too small will not constitute just 5% of the females. Several literature studies demonstrated the complexity and seriousness of the anthropometric mismatch problem [10] that shall never be underestimated.

CONCLUSIONS

Habitability, accessibility, reachability, internal and external visibility, and seating comfort are the five elements in the ergonomics of motor vehicles, that are directly linked to the dimensional relationship between man and vehicle. The objective of the ergonomic analysis is usually stated in terms of the percentage accommodation on particular measures, where accommodation is quantified as the fraction of the population achieving some target level of fit, reachability or comfort.

Today digital human models are widely used for vehicle interior design and have often replaced SAE packaging tools. A panel of manikins is needed to attain good estimates of population accommodation. However, in the attempt to reduce the number of computer simulations, analysts often select the percentile extremes.

In percentile selection, designers shall be well aware that while percentiles are univariate, vehicle interior design is likely to require multivariate accommodation. Poor correlation between body dimensions, together with the increasing need of common platforms in a globalized market, pose a great challenge to design for all.

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THE MECHANICAL BEHAVIOUR MATERIAL IN AUTOMOTIVE ENGINEERING REINFORCED BY STRONG FIBRES

Gordana Bogdanović[1], Dragan Milosavljević, Ljiljana Veljović, Aleksandar Radaković, Dragan Taranović, Mila Mihajlovic

UDC:620.184.6;629.021

ABSTRACT: Laminate is made from layers mutually bonded to form multilayered composite. Composite materials consist two or more constituents such as fibres and matrix. Matrix bond fibres together, gives shape of composite, have role in transfer loads to fibre. Usually fibres are 60-70% of composite volume and they are made of carbon, glass, aramid (such as kevlar) or metal.

In the present paper we study wave propagation bulk waves. The properties of these waves are determined by the dependence between the propagation direction and constitutive properties of media. Here we study slowness surfaces, as indicators of dynamical behavior, in order to obtain information about wave propagation in arbitrary directions. The surfaces associated with wave front surfaces are slowness surfaces, with slowness defined by the inverse of the wave front speeds. Constitutive equations are developed for material which is made of unidirectionally reinforced thin sheets, which form model of material.

Degrees of wave surfaces deviations depend on the degrees of anisotropy, and may give valuable information about dynamic deformations. The materials used in the present analysis are fibre reinforced materials with two families of continuous elastic and mechanically equivalent fibres, having axes of symmetry along bisectors of the fibre directions and along the normal to the plane tangent to fibres.

KEY WORDS: Waves, Slowness surfaces, Fibre reinforced materials, Polarization, Constrains

REZULTATI ISTRAŽIVANJA U OBLASTI PRIMENE KOMPOZITNIH I ADHEZIVNIH MATERIJALA KOD LAKIH KONSTRIKCIJA VOZILA

REZIME: Laminat čine slojevi koji su medjusobno povezani i tako formiraju višeslojni kompozit. Kompozitni materijali se sastoje dva ili više konstituenta, kao što su vlakna i matrica. Vlakna su osnovni nosivi element, matrica daje oblik kompzitnom materijalu i ima funkciju u prenosu opterećenja na vlakno. Vlakna obično čine 60-70% zapreminskog udela u kompozitu i najčešće su od ugljenika, stakla, aramida (kao što je kevlar) ili metala.

U ovom radu je proučeno prostiranje zapremiskih talasa. Osobine ovih talasa su određene su relacijama između pravca propagacije i konstitutivnih osobina sredine. Ovde su analizirane površi sporosti, kao pokazatelji dinamičkog ponašanja, kako bi se dobila informacija o prostiranju talasa u proizvoljnim pravcima. Talasni front zajedno sa površima sporosti definisani su inverznim brzinama talasnog fronta. Konstitutivne jednačine su razvijene i za materijal koji je napravljen od jednodirekcionih ojačanih tankih slojeva, koji predstavljaju materijalni model.

Stepeni devijacija talasnih površina zavise od stepena anizotropnosti i mogu dati značajne informacije o deformaciji. Materijali koji su korišćeni u analizi su vlaknima ojačani

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materijali sa dve familije kontinualnih elastičnih i mehanički ekvivalentnih vlakana, koja imaju ose simetrije duž simetrala povučenih izmedju dve familije vlakana i duž normale na ravan tangente vlakana.

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KLJUČNE REČI: Talasi, povrči sporosti, vlaknima ojačani materijali, polarizacija, ograničenja

THE MECHANICAL BEHAVIOUR OF MATERIALS IN AUTOMOTIVE ENGINEERING REINFORCED BY STRONG FIBRES

Gordana Bogdanović[1], Dragan Milosavljevic[2], Ljiljana Veljović[3], Aleksandar Radaković[4], Dragan Taranović[5], Mila Mihajlović[6]

UDC:629.021;620.184.6

INTRODUCTION

Today, with the increase of the consumer market, new products have been introduced in order to replace materials such as metals, cement etc., which are very heavy, corrosive and less environmentally friendly. One such material is the fibre reinforced composite. In the past 30 – 40 years fibre composites have been competing with materials such as steel, aluminium and concrete in cars, aircraft, military, buildings, bridges, bicycles and everyday sports goods. A very important aspect of fibre reinforced materials is their mechanical behaviour.

Here is considered orthotropic materials modeled as fibre reinforced materials with one and two families of mechanically equivalent fibres. Constitutive equations employed here are developed for material which is made of unidirectional reinforced thin sheets, whose combinations form model of material. Here we study slowness surfaces, as indicators of dynamical behavior, analytically and numerically to obtain valuable information about wave propagation in arbitrary directions. Degrees of deviations of wave surfaces depend on degrees of anisotropy, and may give valuable information about dynamic deformations.

n_2/v

The propagation condition in elastic waves propagation is shown by Nayfeh [6]. Failure criterions for materials reinforced by two families of strong fibres are given by Milosavljevic et al. in [5]. Numerical results, for various propagation directions, are given in details by Bogdanovic [1], based on material constants, for one family, measured by the ultrasonic method by Markham [4], and adopted for the case considered here

CONSTITUTIVE EQUATIONS – LINEAR ELASTICITY

The most of dynamical systems are naturally nonlinear. Because of that, it is not easy to find closed solutions of such systems. There we consider infinite domains so that we can omit questions concerned with the nature and interpretation of the correct boundary conditions, as well as the appropriate form of the stress tensor and the associated tractions. It may be shown that the equation describing the initial weak discontinuity, assuming that

[1] *Gordana Bogdanović, Assistant Professor, Faculty of Engineering University of Kragujevac,,Sestre Janjić 6, 34000 Kragujevac, gocab@kg.ac.rs*
[2] *Dragan Milosavljević, Full Professor, Faculty of Engineering University of Kragujevac,,Sestre Janjić 6, 34000 Kragujevac, dmilos@kg.ac.rs*
[3] *Ljiljana Veljović, Assistant Professor, Faculty of Engineering University of Kragujevac,,Sestre Janjić 6, 34000 Kragujevac, veljovicljilja@yahoo.co.uk*
[4] *Aleksandar Radaković, teaching assistant, State University of Novi Pazar, Vuka Karadžića bb, 36300 Novi Pazar, Serbia, sale@1311gmailt.com*
[5] *Dragan Taranović, Assistant Professor, Faculty of Engineering University of Kragujevac, Sestre Janjić 6, 34000 Kragujevac, tara@kg.ac.rs*
[6] *Mila Mihajilovic, master architect engineer, Direkcija za urbanizam, Kragujevac, milarhitekta@gmail.com*

tangent stiffness tensor on both sides of the surface of discontinuity has the same value, has the following form

$$c_{ijkl} n_j n_l p_k = 0, \qquad c_{ijkl} = \frac{\partial^2 W}{\partial e_{ij} \partial e_{kl}}, \tag{1}$$

where c_{ijkl} represents the tangent stiffness tensor, n_j the unit normal of singular surface, and p_k is the polarization vector. Localization tensor is the second order tensor

$$\Gamma_{ik} = c_{ijkl} n_j n_l . \tag{2}$$

The classical localization condition in the considered case may be expressed as

$$\mathbf{det}\,\Gamma_{ik} = \left| c_{ijkl} n_j n_l \right| = 0 . \tag{3}$$

The equations of motion governing wave propagation in a generally isotropic elastic medium are given by many authors. The equation of motion may be expressed for infinitesimal displacements u_i, Cartesian coordinates x_i, density ρ, stress tensor σ_{ij} and body forces per unit mass f_i, in the form

$$\sigma_{ij,j} + f_i = \rho \ddot{u}_i \tag{4}$$

where "$,_j$" denotes a partial derivative with respect to x_j and the Einstein summation convention is employed.

Equations of motion have the usual form, considering anisotropic linear elastic material neglecting body forces

$$c_{ijkl} u_{k,lj} - \rho \ddot{u}_i = 0, \tag{5}$$

where c_{ijkl} are the components of stiffness tensor of the considered material.

After some transformations, we get Riemann - Christoffel's equation

$$(c_{ijkl} n_j n_l - \rho v^2 \delta_{ik}) p_k = 0 \tag{6}$$

and system of homogeneous equations (6), has nontrivial solutions, provided that

$$\left| \Gamma_{ik} - \rho v^2 \delta_{ik} \right| = 0, \qquad \Leftrightarrow \qquad \left| \Lambda_{ik} - v^2 \delta_{ik} \right| = 0, \tag{7}$$

where

$$\Lambda_{ik} = \Gamma_{ik} / \rho = c_{ijkl} n_j n_l / \rho = \lambda_{ijkl} n_j n_l . \tag{8}$$

The equation (7), as an eigenvalue problem, leads to three values of phase velocity that correspond to the three polarization vectors $p_k^{(\alpha)}, \alpha = 1,2,3$. The components of Riemann - Christoffel's tensor may be expressed as

$$\begin{aligned} \Gamma_{il} = C_{ijkl} n_k n_j = C_{i11l} n_1 n_1 + (C_{i12l} + C_{i21l}) n_1 n_2 + (C_{i13l} + C_{i31l}) n_1 n_3 \\ + C_{i22l} n_2 n_2 + (C_{i23l} + C_{i32l}) n_1 n_3 + C_{i33l} n_3 n_3 . \end{aligned}, \tag{9}$$

The localization tensor is referred to as the acoustic tensor, in the study of wave propagation. If the tangent stiffness tensor is taken as the elastic stiffness tensor, the eigenvalues of the corresponding acoustic tensor (8) divided by the mass density are squares of the speed of elastic waves propagating in the direction n_i. This equation represents the propagation condition of bulk waves as a set of three homogeneous linear equations. The Riemann-Christoffel's equation may be solved analytically only for the simplest cases of material symmetry.

NUMERICAL ANALYSIS OF SLOWNESS SURFACES FOR MATEIAL REINFORCED BY TWO FAMILIES OF MECHANICALLY EQUIVALENT EXTENSIBLE FIBRES

The material reinforced with two families of continuous fibres has the plane of symmetry tangent to both families of fibres, as the monoclinic symmetry and, therefore, has thirteen independent material constants. When two families of fibres are mechanically equivalent, the material behaves like orthotropic Axes of symmetry along the bisectors of the fibre directions and along the normal to plane tangent to fibres, reducing further number of independent material constants to nine.

The best way when developing constitutive equations for elastic materials is to find an equation for the strain energy density of the material as a function of the strain. The strain energy density, if the material is isotropic, can be a function of strain measures that do not depend on the direction of loading with respect to the material. That the strain energy can be a function of invariants of the strain tensor only that is, combinations of strain components that have the same value in any basis. The strain tensor always has three independent invariants, which could be the three principal strains, or the three fundamental scalar invariants, which are more convenient to use in practice.

Strain energy , for linear elastic materials, may be defined as quadratic of strain in form

$$W = \frac{1}{2} C_{ijkl} \varepsilon_{ij} \varepsilon_{kl}, \qquad (i, j, k, l = 1,2,3). \tag{10}$$

When is material reinforced by two families of mechanically equivalent fibres material behaves as orthotropic and has nine independent material constants. The local fibre directions are denoted by the unit vectors and for bidirectional reinforcement. In that case we say that the vectors and are "mechanically equivalent" if the response is unaltered when and are interchanged. When materials have axes of symmetry along bisectors of the fibre directions and along the normal to plane tangent to fibres, Spencer [7, 8] has shown that the most general quadratic form of expression for strain energy function is

$$\begin{aligned} W = {} & \frac{1}{2}\lambda(tr\mathbf{e})^2 + \mu tr\mathbf{e}^2 + \gamma_1\left[(\mathbf{a}\cdot\mathbf{e}\cdot\mathbf{a})^2 + (\mathbf{b}\cdot\mathbf{e}\cdot\mathbf{b})^2\right] + \gamma_2(\mathbf{a}\cdot\mathbf{e}\cdot\mathbf{b})^2 + \\ & \gamma_3(\mathbf{a}\cdot\mathbf{e}\cdot\mathbf{a} + \mathbf{b}\cdot\mathbf{e}\cdot\mathbf{b})tr\mathbf{e} + \gamma_4\cos 2\phi(\mathbf{a}\cdot\mathbf{e}\cdot\mathbf{b})tr\,\varepsilon + \\ & \gamma_5\cos 2\phi(\mathbf{a}\cdot\mathbf{e}\cdot\mathbf{a} + \mathbf{b}\cdot\mathbf{e}\cdot\mathbf{b})(\mathbf{a}\cdot\mathbf{e}\cdot\mathbf{b}) + \gamma_6(\mathbf{a}\cdot\mathbf{e}\cdot\mathbf{a})(\mathbf{b}\cdot\mathbf{e}\cdot\mathbf{b}) + \gamma_7\left(\mathbf{a}\cdot\mathbf{e}^2\cdot\mathbf{a} + \mathbf{b}\cdot\mathbf{e}^2\cdot\mathbf{b}\right), \end{aligned} \tag{11}$$

where are even functions of , and angle between the two families of fibres.

The elasticity tensor may be calculated by taking double partial derivation of with respect to strain tensor, which leads to the expression for the stiffness tensor as follows

$$
\begin{aligned}
\mathrm{C}_{ijkl} = \frac{\partial^2 W}{\partial e_{ij}\partial e_{kl}} &= \left[\lambda\ \delta_{kl} + \gamma_3\left(a_k a_l + b_k b_l\right) + \gamma_4 \frac{1}{2}\left(a_k b_l + a_l b_k\right)\cos 2\phi\right]\delta_{ij} + \mu(\delta_{ik}\delta_{jl} + \delta_{jk}\delta_{il}) \\
&+ \left[\gamma_3\delta_{kl} + 2\gamma_1 a_k a_l + \gamma_6 b_k b_l + \gamma_5 \frac{1}{2}\left(a_k b_l + a_l b_k\right)\cos 2\phi\right]a_i a_j \\
&+ \left[\gamma_3\delta_{kl} + 2\gamma_1 b_k b_l + \gamma_6 a_k a_l + \gamma_5 \frac{1}{2}\left(a_k b_l + a_l b_k\right)\cos 2\phi\right]b_i b_j \\
&+ \frac{1}{2}\left[\gamma_4\delta_{kl}\cos 2\phi + \gamma_5\left(a_k a_l + b_k b_l\right)\cos 2\phi + \gamma_2\left(a_k b_l + a_l b_k\right)\right]\left(a_i b_j + a_j b_i\right) \\
&+ \gamma_7\left[a_r\left(a_j\delta_{rk}\delta_{il} + a_i\delta_{rk}\delta_{jl}\right) + b_r\left(b_j\delta_{rk}\delta_{il} + b_i\delta_{rk}\delta_{jl}\right)\right].
\end{aligned}
\tag{12}
$$

When two families of fibres are initially straight, then the fibre geometry may be described in the Cartesian coordinate system , where is the normal to the plane of the fibres the unit vectors, which represent fibres, may be written as

$$
\begin{aligned}
(a_i) &= (\cos\varphi,\quad \sin\varphi,\quad 0) \\
(b_i) &= (\cos\varphi,\quad -\sin\varphi,\quad 0)\ .
\end{aligned}
\tag{13}
$$

If stiffness tensor is defined then for arbitrary propagation direction may be calculated phase velocities for all three waves, whose reciprocities represent points of corresponding slowness surfaces. In general, it is necessary to calculate wave surfaces numerically. The simplest way of calculation is, if crystallographic axes are known, to coincide axes of symmetry with coordinate axes. Numerical calculation was performed for material with material constants deduced from measurement of unidirectional carbon fibre epoxy resin composite material, measured in [2], with numerical values whereas density is given as

$$
\begin{aligned}
&\lambda = 5{,}65\cdot 10^9\,Nm^{-2},\ \mu = 2{,}46\cdot 10^9\,Nm^{-2},\ \gamma_4 = -1{,}28\cdot 10^9\,Nm^{-2},\gamma_7 = 3{,}20\cdot 10^9\,Nm^{-2}, \\
&2\gamma_1 = 110{,}45\cdot 10^9\,Nm^{-2},\ \gamma_2 = \gamma_3 = \gamma_5 = \gamma_6 = 0,
\end{aligned}
\tag{14}
$$

Slowness surfaces, for material reinforced by two families of fibres in [3], are calculated in program pack MATLAB.

Case when propagation is in the plane tangent to both families of fibres

In this paper slowness curves are calculated for waves propagating in the plane tangent to both families of fibres, that is in the plane of symmetry. For a fibre inclined for and slowness curves calculated in the plane of the fibres, for considered material for which is given in Figures 1. and 2. In these figures quasi-longitudinal waves are represented with solid lines, whereas two quasi-transversal waves are represented with broken lines.

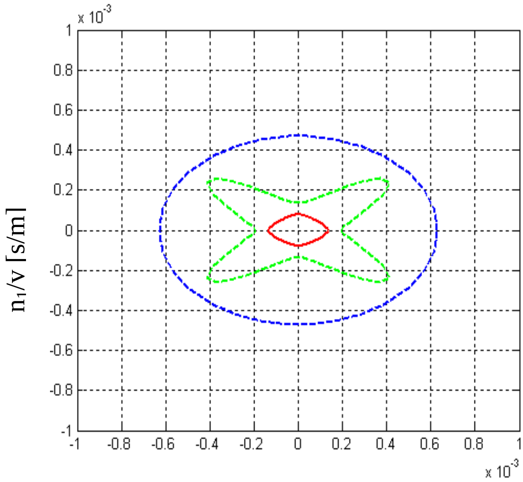

Figure 1 Two families of fibres propagation in the plane of fibres

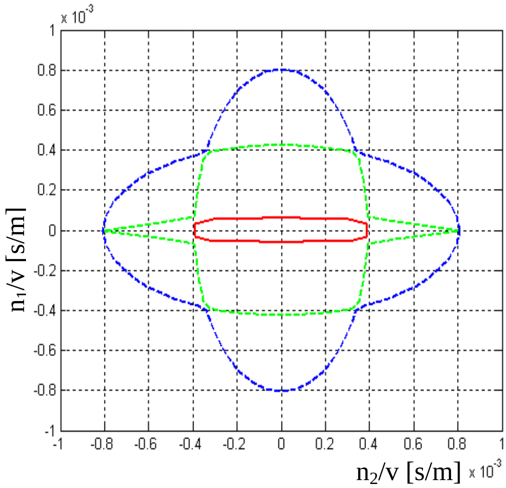

Figure 2 Two families of fibres, propagation in the plane of fibres

For considered material acoustic tensor has been formed, and determined, for different directions of wave propagation.

CONCLUSIONS

In the present paper mechanics of continuum treat material on macroscopic level as an anisotropic continuum and general conclusions about an anisotropic material behavior, in mechanical sense, are drawn from considering of bulk waves propagation. This approach may be used as a first approximation of dynamical behavior of the real parts with anisotropic characteristics. Numerical results show that a coordinate free formulation may give answers about the influence of fibres' direction as well as about the influence of fibres' strength on the wave propagation.

ACKNOWLEDGMENTS

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FULLY ELECTRIC BUSES ARE PROMISING TECHNOLOGY IN THE FUTURE

Zlatomir Živanović[1]*, Slobodan Mišanović*

UDC:629.1.46; 629.021

ABSTRACT: The problems of today's air pollution in cities caused by gas emissions from vehicles, especially buses, depletion of natural resources, and rising prices of fossil fuels, have imposed the intensive development of alternative fuels and propulsion systems for use in the city bus transport.

Electrification of the bus drive train systems is one of the ways that these problems can be reduced or completely eliminated. Battery electric buses often referred to as "pure" or "full" electric buses have become commercially available very recently. It is one of the best medium term options for zero tailpipe emissions. The use of electricity from renewable sources as the energy source for vehicles is another option to decarbonize the fuels used in the transport sector.

Some specific electrification of vehicle propulsion systems and architectures of electric vehicle drive trains are presented. Special attention is paid to the current status of development of batteries as a power source, charging systems, and electric buses, including their trials and demonstration tests across Europe.

KEY WORDS: Full electric buses, drive trains, battery packs, charging systems, realized solutions

ČISTI ELEKRTRIČNI AUTOBUSI SU TEHNOLOGIJA KOJA OBEĆAVA U BUDUĆNOSTI

REZIME: Problemi današnjeg zagađenja vazduha u gradovima izazvanih emisijom izduvnih gasova iz vozila, posebno autobusa, iscrpljivanje prirodnih izvora i porast cene fosilnih goriva, nametnuli su intenzivan razvoj alternativnih goriva i pogonskih sistema za korišćenje u gradskom autobusnom saobraćaju.

Elektrifikacija pogonskog sistema autobusa je jedan od načina da se ovi problemi smanje ili potpuno eliminišu. Baterija električnog autobusa često apostrofiraju na "čist" ili "pun" električni autobus koji je postao komercijalno dostupan tek nedavno. To je jedna od najboljih srednjoročnih opcija za nultu emisije izduvnog sistema. Primena električne energije iz obnovljivih izvora za vozila je još jedna mogućnost za dekarbonizaciju goriva koja se koriste u sektoru transporta.

Neki specifične elektrifikacije pogonskih sistema vozila i arhitekture električnih sistema prenosa snage su prikazani u ovom radu. Posebna pažnja posvećena je trenutnom statusu razvoja baterija kao izvora energije, sistema punjenja i električnih autobusa, uključujući i ispitvanja i demostaracione testove širom Europe.

KLJUČNE REČI: čist električni autobus, pogonski most, sistem baterija, sistem punjenja, realizovana rešenja

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FULLY ELECTRIC BUSES ARE PROMISING TECHNOLOGY IN THE FUTURE

Zlatomir Zivanović[1]PhD, BSc, Slobodan Mišanović[2],MSc,T.E.

UDC:629.1;62.838

INTRODUCTION

Fossil fuels remain the dominant sources of primary energy worldwide. Since 2010 more than a third of the primary energy is derived from oil, and around 62% of the final energy consumption is associated to the transportation sector [1]. In Europe, in the European Union member countries (EU-27) in particular, the transport sector represented approximately 33% of the total energy consumption and was responsible for about 24% of CO2 emissions in 2011 [1]. Given that, governments have been introducing a large number of policies and measures across all modes in an effort to improve efficiency of energy use. European decision makers have established political goals in order to address these complex issues. Kyoto protocol, 2003/30/EC European, 20-20-20 targets are some examples of a global trend to diminish emissions from the transportation sector that is under effect [1].

According to a UITP (International Association of Public Transport) report published in 2011, buses account for 50-60% of the total public transport offer in Europe, and 95% use diesel fuels. However, a wide range of alternative fuels and technologies, at different levels of technical and market maturity are now available for bus operators. If CO2 emission and local pollution targets are to be met, it is clear that alternative vehicle solutions must be found [2].

When purchasing buses, public authorities and operators of public transport services are obliged to follow the conditions laid out in the Clean Vehicles Directive (2009/33/EC), by taking into account energy consumption, CO2 emissions, and other harmful emissions (NOx , NMHC and particulates). In addition, all new bus models sold on the market since 1. January 2014 must meet the stringent Euro VI standards for harmful emissions [2].

Within the transport sector three main reduction routes are available that can contribute to meeting the target [3]:

- Improving the energy efficiency of vehicles, specifically of internal combustion engine vehicles by more efficient engines and drive trains, weight reduction, improved aerodynamics and a range of other measures;
- Application of alternative, low CO2 energy carriers, such as electricity, hydrogen or synthetic methane from renewable sources, and gaseous and liquid biofuels;
- Behavioral measures including energy efficient driving styles, improved logistics and curbing the growth of travel demand.

Both electro mobility (pure electric vehicles, fuel cell vehicles, and plug-in hybrid configurations) and advanced internal combustion engines (powered by advanced liquid or gaseous fuels) will play significant roles in achieving this target. The energy carriers for these vehicles will need to be produced increasingly from renewable, low-carbon energy sources [3].

[1] *Zlatomir Živanović, University of Belgrade, Institute of Nuclear Sciences "VINČA", Department for I.C. Engines and Vehicles, 11001 Belgrade, PO Box 522, E-mail: zzivanovic@vinca.rs*
[2] *Slobodan Mišanović, City Public Transport Company "Belgrade", Kneginje Ljubice 29, 11000 Belgrade, E-mail: slobodan.misanovic@gsp.co.rs*

Long-term decarbonization efforts obviously include electric buses but also second-generation biofuels from biomass and waste valorization. The fragmentation of this 5% share of alternative fuels and technologies today (CNG, LPG, biofuels and biogas, ethanol and electric) or tomorrow (hydrogen, hybrids, full battery electric, fuel cells etc.) places the manufacturing industry in an uncomfortable position when prioritizing R&D investments; which technology will be the 'mainstream successor' of diesel [4]

Bus electrification appears to be a highly promising option in terms of reducing fuel consumption, mitigating the environmental footprint and diversifying energy sources. But it is still hampered by a number of technical hurdles. Electric buses still have a long way to go before they reach maturity. At present, all-electric buses can only be used for short distances due to their low range and the high cost of batteries. Batteries are critical components in hybridized and electrified buses to achieve their potential.

Battery-electric buses are often referred to as "pure" electric buses because the propulsion system is powered only by the electric energy stored in the battery. The battery pack is recharged when the batteries are discharged. The first battery electric bus propulsion systems are primarily targeted to smaller buses, such as those used for shuttle service or other bus routes that are short and low speed. This is due to the limited range and power of current commercial battery technologies. Because of the potential benefits of using zero emission buses in public fleets, there has been much R&D funding devoted to improving the battery technology over the last decade. As a result, today there are some of manufacturers offering battery electric buses, primarily for short distances and relatively small ranges [5].

Electric drive trains are up to three times more energy efficient than conventional drive trains, they have zero tailpipe emissions, and they can transmit the energy originally found in a wide range of renewable and fossil energy resources into vehicle power through the electric energy batteries. Most electrified vehicles under development today obtain electricity from the power grid and store it onboard in batteries [6].

The paper content is processed through several thematic sections:

In section 2, electrification of vehicle drive trains is considered as a possible option to decarbonization of fuel in the transport sector. Depending on the level of electrification, possible alternative drive train solutions are given. On the basis of available analysis, expectations in terms of their development to year 2050 are presented.

In section 3 are given basic information about the full electric vehicles drive train architecture, some characteristics of electric motors, power electronics, and batteries as a power source. Special attention is paid to lithium-ion batteries as the current technologies for vehicles, their costs, performances, and prediction of further development.

In section 4 is shown state of the development of fast charging battery systems and given some typical solutions.

In section 5 is presented the state of development of electric buses, their presence in the market, and expectations regarding further increasing of the fleet. The basic information on some existing solutions of full electric buses, including the latest information about the trials, demonstrations, and projects are presented. E.g. from exploitation of several full electric buses, positive effects compared to diesel buses are shown.

In section 6 are given some information about electric buses that are related to their cost, emissions, LCA analysis, and energy efficiency compared to the diesel buses and other alternative technologies.

ELECTRIFICATION OF VEHICLE PROPULSION SYSTEMS

In order to comply with the established targets, to reduce the energy consumption and CO2 emissions, new fuels, as well as the respective production pathways improvement, and new vehicle technologies become extremely important to study [1]. At present, the energy carriers to power the vehicles are such hydrocarbons as gasoline or diesel fuel. The promising energy carriers capable of replacing these hydrocarbons are new energy sources like natural gas, synthetic fuels, biofuels (e.g. ethanol, biodiesel, biogas, and methanol), electricity and hydrogen, Figure 1. Some solutions regard technology improvements like hybrid electric vehicles (HEV), plug-in hybrid electric vehicles (PHEV), extended-range electric vehicle (E-REV), battery electric vehicles (BEV), and fuel cell electric vehicles (FCEV). In this framework, with the growing importance of sustainability policies, the vehicle industry is experiencing the gradual penetration of alternative technologies and fuels [1].

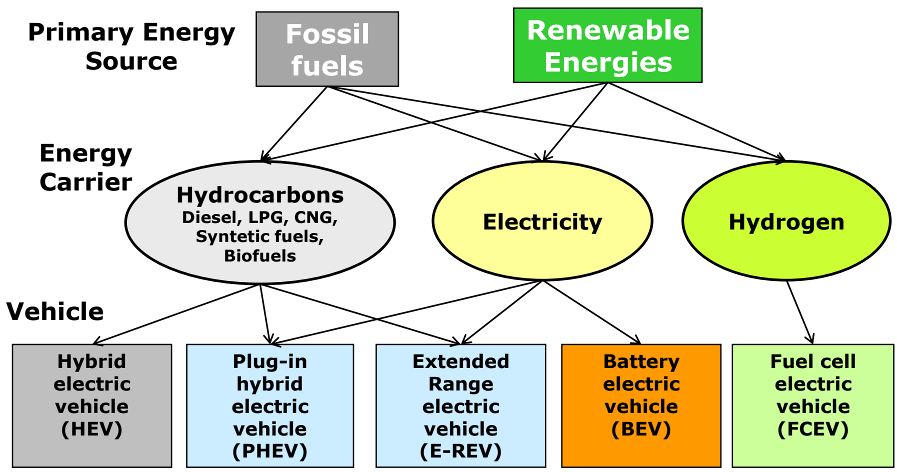


Figure 1 Energy flows to vehicles with various drive trains

The electrification of a vehicle is an option to decarbonize the fuels used in the transport sector. Vehicle electrification enables the improvement of urban air quality (no local emissions), diversification of primary energy sources (electricity can be generated from a wider range of sources, not necessarily with fossil origin), and allows the use of technologies that may improve energy-efficiency (such as regenerative braking and low consumption electric driven components). Hybridization is the first step towards drive train electrification.

Depending on the share of the electric motor to the traction power, most electric vehicles can be classified as a micro hybrid electric vehicle, mild hybrid electric vehicle, full hybrid electric vehicle, plug-in hybrid electric vehicle, extended range electric vehicle, and battery electric vehicle [7]. All electric options are applied in hybrid electric buses except micro and mild hybrid. Electric vehicle with fuel cell power packs can be classified as a fuel cell electric vehicle. These different classifications with respect to the level of electrification can be seen in Figure 2.

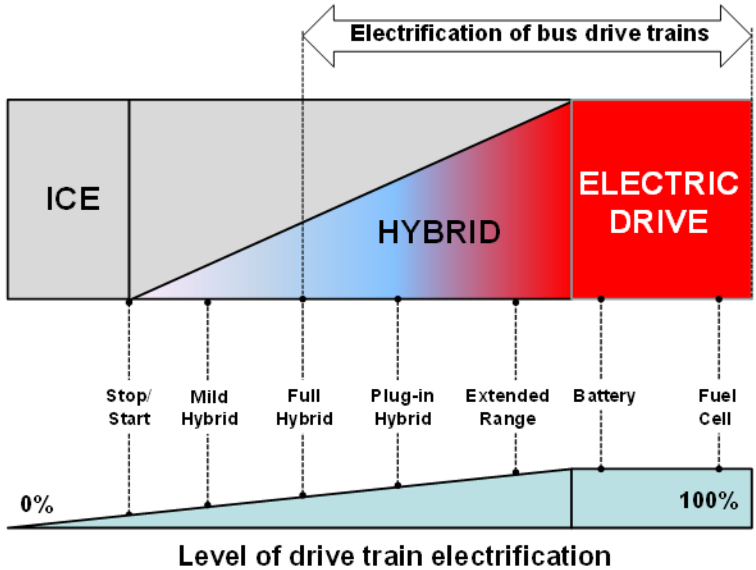


Figure 2 The range of electrification options for vehicles

A micro HEV is a vehicle with an integrated alternator that uses start/stop technology. Start/stop technology is where the vehicle shuts down the IC engine at a complete stop and then restarts when the driver releases the brake pedal. During cruising, the vehicle is propelled only by the IC engine.

A mild hybrid electric vehicle is the least electrified type of HEV. In a mild hybrid, the IC engine must always be on while the vehicle is moving. However, the motor/generator can be used to enable idle stop in which the engine is turned off while the vehicle is at idle. A mild HEV generally has an electric drive system rated at less than 20 kW of power and an IC engine power rating high enough to provide satisfactory vehicle performance when electrical power is exhausted [8].

A full HEV has an electric drive system rated at a relatively high power (usually >50 kW) allowing for the engine to be downsized [8]. The differences between a mild and full HEV are that a full HEV typically uses a smaller engine, has the ability to propel the vehicle solely off the electric motor, and utilizes a more sophisticated control system to optimize efficiency [9].

A Plug-in Hybrid Electric Vehicle (PHEV) or Plug-in Hybrid Vehicle (PHV) is a hybrid vehicle which utilizes rechargeable batteries, or another energy storage device, that can be recharged to full by connecting a plug to an external electric power source. A PHEV shares the characteristics of both a conventional parallel hybrid electric vehicle and of an all-electric vehicle, having a plug to connect to the electrical grid.

Extended-Range Electric Vehicles (E-REV) have a plug-in battery pack and electric motor, as well as an internal combustion engine. The difference with a plug-in hybrid is that the electric motor always drives the wheels, with the IC engine acting as a generator to refill the battery when it is discharge. Range extender is an auxiliary power unit built-in or externally attached to an all-electric (BEV) or plug-in hybrid electric vehicle (PHEV) to increase its all-electric range. The range extender can also be powered by a fuel-cell or other energy sources.

An Electric Vehicle (EV), either full or battery electric vehicle (BEV), is a vehicle that relies 100% on electricity (from either the grid or an off-grid source) for motion power. The wheels are propelled solely by electrical power from the energy storage device. As a result, BEVs usually have a limited driving range [8].

A Fuel Cell Vehicle (FCV) or Fuel Cell Electric Vehicle (FCEV) is a type of vehicle which uses a fuel cell to power its on-board electric motor. Fuel cells in vehicles create electricity to power an electric motor, generally using oxygen from the air and hydrogen. Fuel cell vehicles can be equipped with other advanced technologies to increase efficiency, such as regenerative braking systems, which capture the energy lost during braking and store it in a battery. Fuel-cell electric vehicles (FCEVs) are another type of zero-emission vehicle producing no CO2 or other emissions.

There are some major advantages of electric drive technologies but there are also some disadvantages. Table 1 summarizes the advantages and disadvantages of the hybrid-electric, plug-in hybrid electric, battery electric, and fuel cell drive systems [10].

Table 1 Advantages and disadvantages of electric drive technologies

Technology	Advantages	Disadvantages
Hybrid electric	Lower fuelling costs; Reduced fuel consumption and tailpipe emissions; Recovered energy from regenerative braking	Higher initial cost; Complexity of two drive trains; Component availability
Plug-in Hybrid Electric	Cleaner electric energy thanks advanced technologies or renewable; Reduced fuel consumption and tailpipe emissions; Optimized fuel efficiency and performance; Recovered energy from regenerative braking; Grid connection potential; Pure zero-emission capability	Higher initial cost; Complexity of two drive trains; Component availability-batteries, drive trains, power electronics; Cost of batteries and battery replacement; Added weight
Battery Electric	Use of cleaner electric energy; Zero tailpipe emissions; Overnight battery recharging; Recycled energy from regenerative braking; Lower fuel and operational costs; Quiet operation	Mileage range; Battery technology still to be improved; Possible need for public recharging infrastructure
Fuel cell	Zero tailpipe emissions; Higher energy efficiency than the IC engine; Recovered energy from regenerative braking; Potential of near-zero well-to-wheel emissions when using renewable fuels to produce hydrogen; No dependence on petroleum. Increased reliability and durability;	Higher initial cost; Hydrogen generation and onboard storage; Availability and affordability of hydrogen refueling; Codes and standards development; Scalability for mass manufacture;

The development of alternative fuels and drive trains in vehicles has began several years ago with intensive use of natural gas as a fuel, and more recently the development is characterized by increasing electrification of drive trains. Predictions of further development of propulsion systems to 2030, in which they included the renowned vehicle manufacturers, have resulted in a variety of scenarios. One of such scenarios, which are shown in Figure 3, is given by Daimler [11].

According to this scenario, starting from 2010 the increase of market share of CNG, hybrid, and electric propulsion systems is clearly shown, while commercialization of vehicles with fuel cell technology is expected after the 2020.

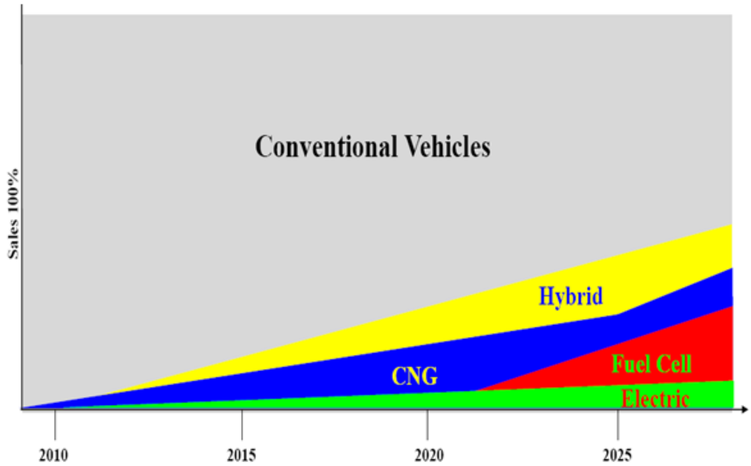


Figure 3 Increasing market share of alternative propulsion systems

BATTERY ELECTRIC VEHICLE DRIVE TRAIN

The drive system for a battery-electric vehicle, Figure 4, consists of:

- an electric motor (EM),
- a control system or power electronics that governs the vehicle operation, and
- a battery pack to provide energy storage.

Electric motors and power electronics

Electric motors offer greater efficiency and less noise than internal combustion engines. They provide their highest torque at low speeds, which results in better acceleration from a stop. Electric motors also increase energy efficiency by enabling regenerative braking: when the vehicle decelerates, the motor becoming an electricity generator that can recharge the battery pack during braking regime.

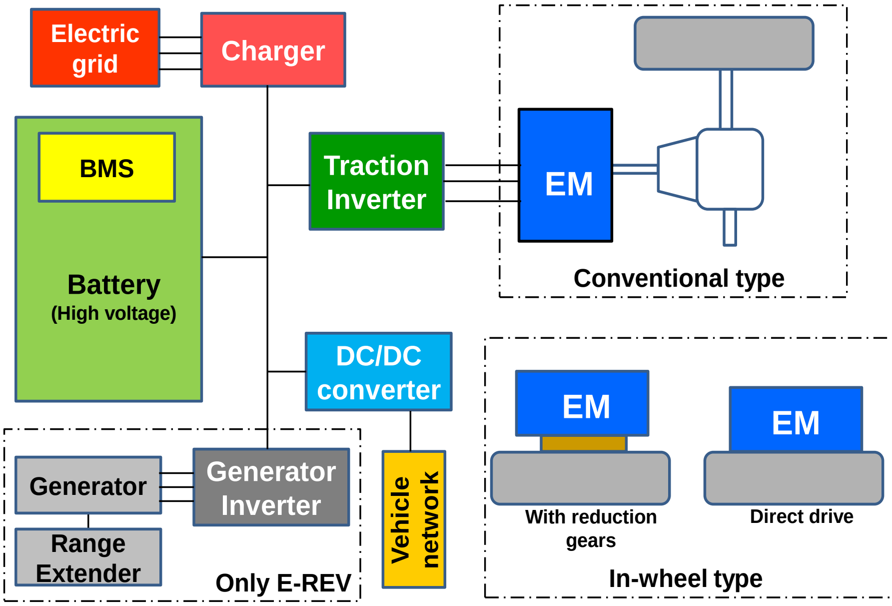


Figure 4 Electric vehicle drive train

Electric motors are already a mass-market product with a wide range of applications. They are produced by well-established manufacturers. However, the requirements for electric motors for vehicles differ from those of regular electric motors. In particular, electric motors for heavy vehicles and buses are subject to greater weight and packaging restrictions, have higher efficiency needs (due to the limited energy supply), superior power requirements, and need a broader speed range [12].

Several types of electric motors can be used to propel the vehicles, Table 2. Essentially, they can be divided in two groups: alternating current motors (AC) and direct current motors (DC). Each category has its disadvantages and benefits. The electric motors used in vehicle applications are mainly AC motors.

There are three types of electric motors that can be used in electric vehicle traction drive systems [13].

- Induction motors (IM) have high starting torque and offer high reliability. Their power density and overall efficiency are lower than that of IPM motors. Induction motors are of simple construction, reliability, ruggedness, low maintenance, low cost, and ability to operate in bad environment conditions.
- Internal permanent magnet (IPM) motors or permanent magnet synchronous motors (PMSM) have high power density and maintain high efficiency over a high percentage of their operating range. Therefore, almost all hybrid and plug-in electric vehicles use rare earth permanent magnets in their traction motors. These motors are relatively expensive due to the cost of the magnets and rotor fabrication.
- Switched reluctance motors (SRM, SM) offer a lower cost option that can be easy to manufacture. Also, switched reluctance motors are less efficient than other motor types, and require additional sensors and complex motor controllers that increase the overall cost of the electric drive system. SRM drives can inherently operate with an extremely long constant-power range.

Table 2 Current status of electric motor technology [12]

Input/stator current	AC			DC
Rotor speed relative to stator field	Asynchronous	Synchronous		Synchronous
Rotor field generation	Induction	Permanent magnet	Current excited	Permanent magnet
Type	IM	IPM, PMSM	SRM, SM	DC motor
Manufacturing cost	Low	High	Medium	Medium
Vehicle application	Yes	Yes	Yes	No
Key reasons	Low cost	Low weight, compact design	No permanent magnet	Low efficiency, heavy motors

DC motors are the only type of motor that is generally ruled out from vehicle application, as their low specific power and efficiency make them very unattractive for application in vehicles. Only innovative, brushless DC motors could potentially make a difference here [12]. Permanent Magnet Brushless DC Motor Drives are specifically known for their high efficiency and high power density. By using permanent magnets, the motors can eliminate the need for energy to produce magnetic poles. So they are capable of achieve higher efficiency than DC motors, induction motors, and SRMs [14].

Electric motors can be mounted in different ways into the vehicle, Figures 4, 5, and 6:

- On conventional type (where the electric motor is mounted instead of an IC engine, the transmission and summarizing differential remaining) and
- In-wheel type (where electric motor is mounted in the wheel with direct drive or with reduction gears).

Both alternative solutions have now found application in battery electric buses and have their own advantages and disadvantages.

Electric motors installed in the wheels contain integrated power electronics and the rims, brakes, sensors for temperature, ABS and tachometers. Along with the in-wheel hub motors driving the wheels, they can also be used as generators for regenerative brakes (recuperation). The installation space and fitting dimensions are usually compatible with common standard portal axles for low-floor buses.

Vehicle power electronics primarily process and control the flow of electrical energy in electric drive vehicles. They also control the speed of the motor, and the torque it produces. Finally, power electronics convert and distribute electrical power to other vehicle systems such as heating, ventilation, and lighting. Power electronics components include inverters, DC/DC converters, and chargers [17]

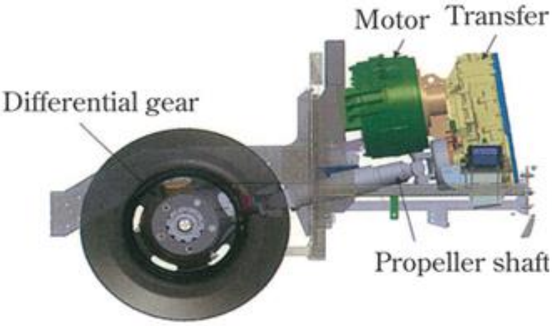


Figure 5 EM mounted on conventional type [15]

Figure 6 In wheel mounted electric motors [16]

An inverter is needed in an electric drive system to convert the DC energy from a battery to AC power to drive the motor. An inverter also acts as a motor controller and as a filter to isolate the battery from potential damage from stray currents. In extended–range electric vehicles that use range extender (a small IC engine with a generator that supplies energy for electric propulsion when the battery is empty) power electronics contain an inverter generator.

DC/DC converters are used to increase or decrease battery voltages to accommodate the voltage needs of motors and other vehicle systems. If the vehicle electric motor design requires higher voltage, such as an internal permanent magnet motor, it will require a boost DC/DC converter. If a component requires lower voltage, such as most vehicle systems, it will require a buck DC/DC converter that reduces the voltage to the 12V to 42V level 17].

Onboard vehicle chargers convert AC energy from the electrical grid to DC energy required to recharge batteries. Battery chargers for plug-in electric vehicles are currently based on proven, traditional, high-frequency charger circuits and can be located either on the vehicle or off board, as part of a DC fast charger.

A battery management system (BMS) is any electronic system that manages a rechargeable battery, monitoring its state, calculating secondary data, reporting that data, and controlling its environment.

Battery as a power source

Energy storage systems, usually batteries, are essential for electric drive vehicles. Batteries must have a high energy-storage capacity per unit weight and per unit cost. Because the battery is the most expensive component in most electric drive systems, reducing the cost of the battery is crucial to producing affordable electric drive vehicles.

The electrical energy storage units must be sized so that they store sufficient energy (kWh) and provide adequate peak power (kW) for the vehicle to have a specified acceleration performance and the capability to meet appropriate driving cycles. For those vehicle designs intended to have significant all-electric range, the energy storage unit must store sufficient energy to satisfy the range requirement in real-world driving. In addition, the energy storage unit must meet appropriate cycle and lifetime requirements. These requirements will vary significantly depending on the vehicle type (battery or fuel cell powered or hybrid electric).

There are many energy storage technology and battery chemistry and packaging options for electric drive vehicles. A number of different battery technologies exist at present. However, none of these battery technologies provide the energy density required for sufficient driving distance in pure electric mode.

Lithium ion (Li-Ion) battery chemistry represents the technology of choice for electric vehicles today and for the foreseeable future. All Lithium-ion technologies are based on the same principle: Lithium-ions are stored in the anode (or positively charged electrode), and transported during the discharge to the cathode (or negatively charged electrode) in an organic electrolyte. The most popular materials are graphite for the cathode, and a metal oxide for the anode, based on Nickel, Manganese and Cobalt. All of these materials have good Lithium insertion properties, allowing the large amount of energy storage [18]. Research on next generation lithium batteries will continue the development of electrode and electrolyte materials and chemistries in order to increase the life and energy density of the battery while reducing size and weight.

The original Li-Ion chemistries developed for consumer applications have proven too expensive for vehicle uses, given their large share of the total cost of the vehicle. This has spurred the development and deployment of alternative, cheaper Li-Ion chemistries with more suitable thermal characteristics better adapted to vehicle applications. These include lithium-iron-phosphate (LFP), lithium-manganese-oxide spinel (LMO), and nickel-cobalt-aluminium. To date, no dominant chemistry has emerged, but deployment for vehicle applications is still in its infancy and further experience will prove invaluable in improving performance and reducing costs [7].

The iron phosphate based systems are believed to be the safest and to have the lowest cost, but also have lower performance than other chemistries [19].

The relationship between power density and specific energy density is very important for the performance of the vehicle. Figure 7 show the specific power density relative to specific energy density for different electricity storage options [7].

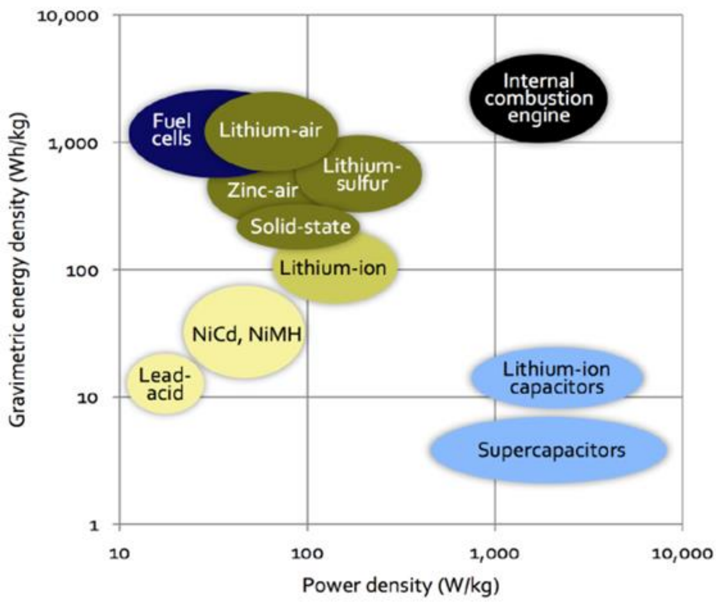


Figure 7 Energy density versus power density of different energy storage systems

The key parameters a vehicle designer must take into account when considering a battery are costs, the specific energy density of the battery, and the relationship with power charge and discharge. The specific energy density can be measured in two ways; either in terms of energy per unit mass (e.g. Wh/kg) or volume (e.g. Wh/litre) [7].

The estimate of battery pack costs for EVs in 2012 varies quite widely depending on the source of data, but is typically USD 500-800/kWh. The average battery cell costs are USD 400/kWh, but they vary widely depending on the scale of production. The build-up into battery packs adds 50-100% to the cell costs [7].

Battery performance degrades over time with the number of cycles (charge/discharge cycles) performed. Maximizing the number of cycles a battery can perform before it deteriorates to a point it needs replacement will significantly enhance the economics of PHEV and EVs. To maximize the life of a battery, the swing in the state-of-charge (SOC) is typically limited to 40-80%. Thus the effective cost of electricity available for driving is higher than the nameplate cost, as only 40-80% of the battery charge is made available. For instance, a battery pack that costs USD 500/kWh, but that charges and discharges over only 60% of its capacity would have an effective cost of USD 833/kWh [7].

The most promising chemistry materials to involve silicon, sulfur and air (oxygen) and another important development is research into nanotechnologies. These trends have been widely recognized and a recent presentation by Limotive researchers showed the following battery technology roadmap, Figure 8 [19].

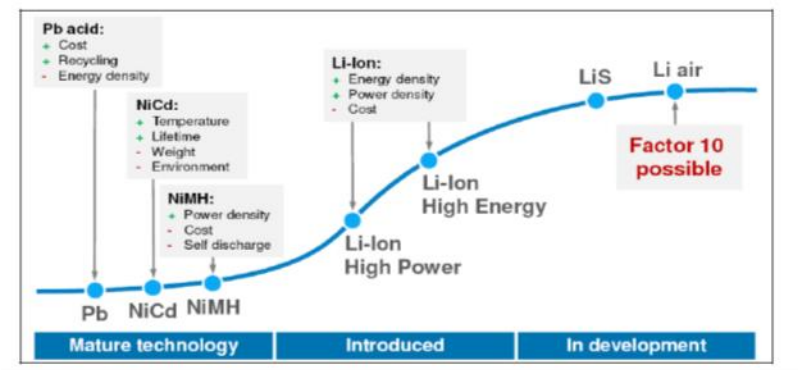


Figure 8 The battery technology roadmap

Silicon is an attractive anode material for lithium-ion batteries because it has about ten times the amount of energy that a conventional graphite-based anode can contain. It also has a specific energy of 1.550 Wh/kg – about four times the energy of a conventional graphite-based anode. Furthermore, silicon is the second most abundant element on the planet and has a well-developed industrial infrastructure, making it a cheap material to commercialize with a cost comparable to graphite per unit of weight [19].

The problem with silicon is that it is very brittle and when lithium-ions are transferred during charge and discharge cycles, the volume expands and contracts by 400% which can pulverize the silicon anodes after just the first cycle.

The lithium-sulfur systems have a theoretical specific energy of 2.600 Wh/kg which exceeds current generation lithium-ion batteries theoretical specific energy by about a factor of 5. Current cathode materials, such as those based on transition metal oxides and phosphates, are limited to an inherent theoretical capacity of 300 Ah/kg while the theoretical capacity of sulfur is 1.600 Ah/kg. Other benefits of sulfur are that it is abundant and low cost [19].

The lithium-air technology uses oxygen as a catalytic air cathode to oxidize a metal anode such as lithium or aluminum. Theoretically, with oxygen as essentially an unlimited cathode reactant source, the capacity of the battery is limited only by the lithium anode. Estimates of energy density vary from 2 to 10 times the energy capacity of current lithium-ion batteries.

Also, it could greatly reduce costs as lithium batteries currently use a cathode which is the most expensive component of lithium batteries. Lithium-air with a theoretical specific energy of 13.000 Wh/kg is one of the few, promising technologies that can potentially approach the energy density of a hydrocarbon fuel [19].

Battery manufacturers also indicated that each battery generation was likely to be in production for 4 to 5 years at least to recoup capital investments and R&D costs, so that 2011/2012 introduction of the first generation of vehicle lithium-ion batteries implies that the second-generation batteries could be commercialized in 2016/17 and third-generation batteries in the early 2020 time frame [19].

BATTERY CHARGING SYSTEMS

The battery electric and plug-in hybrid buses require top-up charging stations, but only at terminals or other locations where sufficient time (at least 5 minutes) is available within duty cycles for recharging. Without super-capacitors the vehicle batteries cannot be charged sufficiently rapidly to make charging during normal bus stop dwell times a practical proposition [20].

Most battery electric buses use “conductive charging”, which is also known as “direct wired contact” or “direct coupling”. This well tried and proven system has traditionally involved plugging a cable into a socket on the vehicle. However other variants are being created which involve physical contact with an overhead power supply - but only whilst the bus is stationary at a dedicated charging point.

In addition to “conductive charging” another way to charge the batteries (whilst they still remain in the bus) is via electromagnetic “inductive charging”. One of the problems with batteries is that they risk being damaged if charged too quickly. Fast charging will also shorten their service life.

The power electronics for charging the energy storage system could be on-board or off-board the vehicle. Improving the efficiency and cost of this component may be critical to the success of electrified transportation. Weight of on-board units is also important. On-board units take AC power from the grid and rectify it to DC power to charge the DC battery pack. Off-board units make this same conversion and deliver DC power to the vehicle [21].

Some buses, known as opportunity electric buses, are charged end route either at charge points throughout the bus circuit or at first and final stops. Others have their batteries recharged overnight and are therefore known as overnight electric buses [21].

With fast charging, it is possible to reduce the weight and size of the battery pack dramatically while simultaneously increasing the operating range. Instead of using a 300 or 400kWh battery pack, a 50 or 100kWh pack can be used instead. This has major benefits in reducing the bus weight, and providing more room inside the bus for passengers [22].

Some interesting systems for battery charging are:

<u>The IPT (Inductive Power Transfer) charging system:</u> The first ever field trials of a 12 - meter electric bus charged wirelessly by induction is currently underway in the Netherlands [23].

The charging technology IPT allows the electric bus to run reliably for 18 hours, covering some 288 kilometers a day, without the need to stop for prolonged periods or return to the depot to recharge. The project, which is currently in the final phase of vehicle testing, has come at just the right time, as stricter emissions standards are due to come into effect in the EU in 2014 [23].

Inductive Power Transfer is an energy transfer system for electric vehicles that works by magnetic resonance coupling. The system consists of two main components: a primary coil in the road, which is connected to the power grid via a converter, and pickup coils fitted in the road and underneath the bus. IPT is based on the principle of short but regular charging during operation. The battery is fully charged over night and then topped up as necessary and as possible over the course of the day at suitably equipped stops, usually by about 10-15%, when the bus stands still for longer at a station or at each end of the route. Conventional electric buses are almost exclusively recharged overnight by cable [23].

<u>The Opbrid Bůsbaar charging system</u>: In April 2014, during recent tests of Hybricon Bus Systems’ new Arctic Whisper (HAW) urban bus in Umeå, Sweden, the Opbrid Bůsbaar achieved ultrafast charging at 625 amps for 6 minutes. This paves the way for charging at 500 - 1000 kW or more to achieve 2-3 minute charges at the end stations of longer bus routes [24].

The Opbrid Bůsbaar is an overhead, pantograph-based fast-charging station for buses, Figure 9.

While fast charging of urban buses has already been shown to be a valuable way to achieve “infinite electric range” in bus systems by Hybricon, Proterra, Volvo, and others, bus operators want ever shorter charging times. If charging times can be reduced to just 2-3 minutes, then the operators do not have to add additional buses-and their associated costs-to a route [24].

The unit cost of a roof mounted pantograph charging station is around € 200,000, while the cost of manual plug-in charging station approximately £ 58,000 (€ 73.000) [20]. Manual equipment can charge the vehicle batteries to full capacity in less than 2 hours.

Bombardier’s PRIMOVE charging system: In February 2013, Bombardier has announced that it will be testing its electric bus technology on buses that are operating in Montréal [25]. Bombardier is currently also working on implementing its PRIMOVE system for electric buses in Mannheim and Berlin, Germany, and in Bruges, Belgium. In addition, tests with a dynamically charged truck were successfully completed in Mannheim in January 2014. Bombardier’s PRIMOVE charging technology is based on inductive energy transfer, Figure 10. It is installed entirely under the road surface and under the floor of the vehicles. The charging process begins as soon as the vehicle completely covers the charging segment.

Figure 9 The Opbrid Bůsbaar fast-charging station

According to information from Bombardier the costs for a PRIMOVE charging point amounts to approx. 125,000 €, but it is unlikely that this sum includes the costs for the installation or the costs for the feeding cables [26].

On the basis of the available information it is assessed that the costs for a complete charging point amounts to approx. 150,000 €. Thus, the inductive charging point would be about 50,000 € more expensive than the conventional charging point (no consideration at all of the feeding cables from the next rectifier substation to the charging point and no consideration of the costs for expansion of the rectifier substation itself).

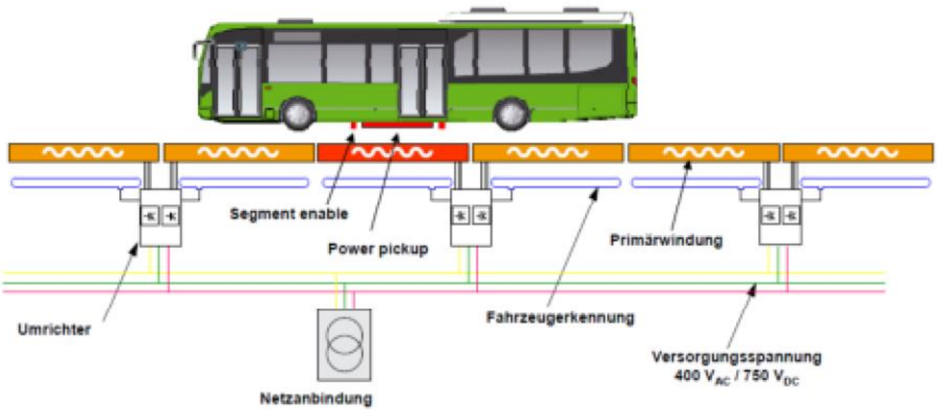


Figure 10 Charging point according to the PRIMOVE principle of Bombardier

The ABB flash charging system: European technology giant ABB (a global leader in power and automation technologies based in Zurich) has developed a new technology that will help power the world's first high-capacity flash charging electric bus system [27].

In 2013, ABB announced at the 60th congress of the International Association of Public Transport (UTIP) in Geneva that it is working together with the city's public transport company (TGP), the Office for the Promotion of Industries and Technologies (OPI), and the Geneva power utility SIG on the TOSA electric bus system pilot project [27].

The new boost charging technology will be deployed for the first time on a large capacity electric bus, carrying as many as 135 passengers. The bus will be charged directly at selected stops with a 15-second energy boost while the passengers enter and leave the bus, based on a new type of automatic flash-charging mechanism [27].

Onboard batteries can be charged in 15 seconds with a 400 kilowatt boost at selected stops. At the end of the bus line a 3 to 4 minute boost enables the full recharge of the batteries. Thanks to an innovative electrical drive system, energy from the roof-mounted charging equipment can be stored in compact batteries, along with the vehicle's braking energy, powering both the bus and its auxiliary services, such as interior lighting [27].

ELECTRIC BUS MARKET AND DEVELOPMENTS

This Section presents the state at the market of full electric buses and gives information on some of the buses already in routine exploitation and on some which are in different phases of development or trial/demonstration stages over the European market.

Electric bus market

Over the past few years governments around the world stimulate development and introduction in use of alternative fuel buses, including buses with electric drive trains, especially, hybrid and battery buses.

Hybrid buses have already captured significant market share in the United States. China has also been strong in this technology. Hybrid buses have begun increasingly to appear in Europe, albeit at a slower rate than in the United States or China [28].

Battery electric buses currently available are rigid vehicles 11 to 12m in length and no production of battery electric articulated bus is running. However, manufacturers published roadmaps for future product development to indicate that such vehicles are likely to become available in the near future and plans have been announced for the operation of 18m battery electric buses in Braunschweig, Germany and Barcelona, Spain commencing during 2014 [20].

China is the world leader in developing battery electric buses. The southern city of Shenzhen has the world's largest zero-carbon fleet of all-electric buses and taxis, and plans to have 6 000 electric buses in service by 2015. Shenzhen is also home to the world's largest manufacturer of electric buses, BYD (Build Your Dreams). The company has started to enter overseas electric bus markets. At the start of 2013 its vehicles received Whole Vehicle Type-Approval from the European Union, giving the company the green light to sell its buses to all EU member countries without further certification. The number of electric buses in countries other than China is limited but growing [29].

Sales of electric drive buses in Western Europe will experience steady growth (around a 20% CAGR- Compound annual growth rate), as the hybrid market begins to take off and there is continued interest in building the electric and fuel cell bus markets [29].

The Latin American market will be driven largely by uptake in Brazil, but other countries will also spur adoption, notably Uruguay which recently indicated it would purchase 500 battery electric buses [28].

The Africa/Middle East countries will see very little uptake due to the high cost of electric buses and infrastructure.

Some investigations [30] indicated that of all alternative technologies the largest growth in the future would have the electric drive systems (about 41,5%), the largest growth being that of the hybrid systems (69,7%) and the fully electric with batteries somewhat lower (45,5%), Figure 11.

The US-based market research and consulting firm Pike Research forecast in August 2012 that the global market for all electric drive buses including hybrid, battery electric, and fuel cell buses will grow steadily over the next six years, with a CAGR of 26,4% from 2012 to 2018 [29].

According to Pike, the largest sales volumes will come in Asia Pacific, with more than 15 000 e-buses being sold in that region in 2018 – 75% of the world total. China will account for the majority of global e-bus sales, Pike predict. They believe that growth in the e-bus market will accelerate strongly in Eastern Europe and Latin America, the latter driven largely by Brazil [29].

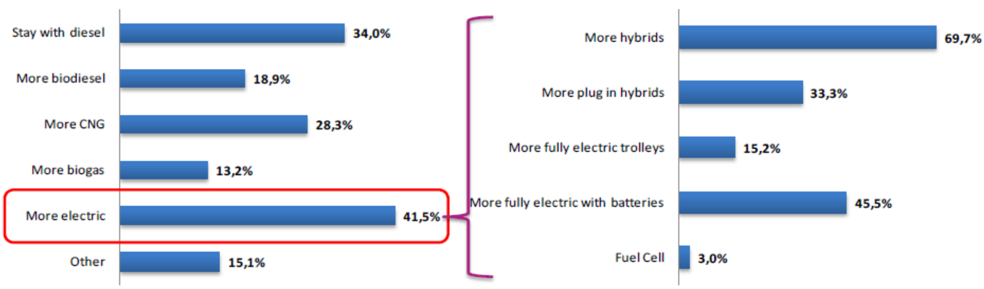


Figure 11 Future plans for propulsion technology change

The report by the research and consultancy firm IDTechEx forecast that the market for electric buses and taxis will rise 8.7 times from 2012 to 2022, of which the largest part will be buses. China will become by far the largest market for both electric buses and electric taxis [29].

Electric buses in regular service

BYD electric bus: BYD Co., Ltd based in Shenzhen, China is a globally leading-edge provider of green energy technologies that specializes in the IT, automotive and new energy fields. Today, BYD is the fastest-growing Chinese auto company and a global pioneer in the field of new energy vehicles including pure electric models. BYD Europe is the marketing and distribution arm of BYD Co., Ltd.

Build Your-Dream (BYD) hybrid buses were showcased during the 2008 Beijing Olympics and have been selected as the sole eBUS provider for the 2011 International Universiade Games held in Shenzhen, China. The 12-meter long BYD electric bus, Figure 12, is made from carbon steel chassis and aluminium bodies. The top speed is 70km/h. At the core of the eBUS technology is BYD's in-wheel motor drive system and the Iron Phosphate battery technology.

Figure 12 BYD electric bus

The wheel-hub permanent magnet synchronous AC motors are water-cooled and installed in the rear drive axle together with regenerative braking technologies. Compared with a normal motor, the rear drive axle system in the BYD eBUS has no gear box, no transmission shaft, and no differential mechanism. The power from the motor is directly transmitted to the wheels, so that significant improvements are achieved in transmission efficiency and reductions in noise and vibration. In addition, the bus weight can be cut by 300kg, and interior space is greatly saved [31].

Each of the wheel-hub motors has a maximum power output of 90kW and produces maximum torque of 350 Nm. Rotation speed is 0~7500 rpm. Power comes from the 600Ah, 324kWh BYD Fe (Lithium Iron Phosphate) batteries. On board the batteries are located in three banks, one each over the two front wheel arches and the third at the rear on the roof.

In theory the batteries give the buses a range of between 200-250km a day. The plan is to keep developing the bus range in every way. One of the targets they have set themselves is to reduce the weight of the e-bus by around 700kg to a figure of 13.100kg. They claim that those on the e-bus are good for over 4.000 cycles from fully charged to discharged and back to fully charged which at one charge a day equates to just under 11 years. Each of the battery packs contains 168 cells, each cell weighing 6kg, giving a total of 1.008kg. The weight of the three traction battery packs together is therefore 3.024kg [31].

Building buses since 2003, they have tested the e-bus in European cities including: Paris, Bremen, Bonn, Madrid, Barcelona, Salzburg, Warsaw, Amsterdam, Brussels, Budapest, Copenhagen and London. BYD presently has sold and deployed over 1,000 operating electric buses in China and throughout Europe and Latin America [32]. Already BYD has over 4,000 bus orders for 2014, most of them admittedly in China [31]

BYD has gained official permission to sell its electric buses in all European Union member states without the need for individual national approval. A Whole Vehicle Type

Approval (W.V.T.A) has been obtained from the European Commission, which is compulsory for vehicles for sale within the E.U. The W.V.T.A. encompasses 25 tests and sets the standards for vehicle and safety performance. In order to achieve the certification, a bus must conform to European directives for the transportation sector [33].

According to the data from exploitation of 220 BYD electric buses [34] in Shenzhen, China who have achieved 27 million kilometers by the end of May 2014, the significant savings compared to the same diesel bus are as follows:

- BYD e-bus has achieved energy savings valued approximately €7.425.600 and
- Reduced CO2 tailpipe emissions by about 28.390 tons.

Optare's battery-powered Versa: Optare's battery-powered Versa is the UK's first commercial full-size battery bus, Figure 13, which started on 1. April 2011. At 11.1 meters long, the buses seat 38 (23 of them including three tip-ups with step-free access) and have a total carrying capacity of 59. Maximum range is 75-95 miles (120-153km), depending on the terrain, on one overnight charge [35].

Battery-powered Versa buses are planned to be in service at peak times, providing a capacity increase on the 12-minute interval service. The buses can either be rapid charged, using a special charger, or slow charged. A return journey is around 5 miles (8 km).

The fast charging station was made in Holland and is capable of taking the Versa EV's batteries to full capacity in less than 2 hours compared to the standard 6 to 8 hours of a normal charger, thus potentially doubling the vehicle's daily range.

When first ordered, it was envisaged the Versa EVs would utilize a Siemens drive system and summation gearbox with 90kW of power and 320Nm of torque, power being drawn from 48 lithium ion batteries arranged in two banks of 24. However, that was changed to the Enova Systems P120 motor with a summation gearbox, working in conjunction with 56 Valance lithium ion/magnesium phosphate battery packs to deliver a more powerful 120kW with 650Nm of torque [35].

Figure 13 Optare's battery-powered Versa

The 56 batteries are split into two packs of 28, and are covered by a five-year warranty. Equalization and conditioning is managed by on-board computers during recharge. Already the replacement cost of the battery packs has fallen from £75.000 to £56.000 (€94.500 to 70.560), and is likely to come down further.

e-Busz: Netherlands' company e-Traction (European integrator of low-floor fleet buses), delivered in the year 2010 the first of two e-Busz electric drive buses (with extended range) to Rotterdam's public transportation authority [36]. The e-Busz, Figure 14, is a VDL Bus & Coach Citea CLF bus converted with the third generation of the e-Traction system. The RET (Rotterdam Electric Tram) tested two buses in 2012 on its route between Station Zuidplein and Rotterdam Central [37].

e-Traction specializes in development of TheWheel as a direct-drive in-wheel motor system with integrated power electronics and fluid cooling. TheWheel SM500/3 is designed to deliver very high torque at low revolution and 240kW power [38]. The vehicles with TheWheel save up to 40% traction energy and are 50% more fuel efficient compared to the standard diesel equipped bus.

The e-Buzs is a "battery dominant" hybrid bus or E-REV (Extended Range Electric Vehicle). This means that it has the ability to run on battery only 107 kWh (allowing 80km range or about 4 hour zero emission drive) with the diesel generator turned completely off. The diesel unit (30kW) can be replaced and, importantly, the bus returned to revenue service in roughly one hour [38].

Figure 14 e-Busz electric powered bus

After nearly 3 years of operational experience e-Buzs has achieved [39]:

- Consumption reduction by 25% to 50%,
- Engine noise int./ext. below 67dB/73dB,
- Regenerative braking in urban cycles saves about 25% of energy (potential 40%),
- Direct drive of e-Traction/ZA makes 0.9 kWh/km feed to wheel energy use feasible, other tested systems need 10-15% more and
- Total energy cost varies between 0.2 and 0.5 €/km, to earn back batteries as much as possible full electric driving is mandatory.

Electric buses in trials and demonstrations

Trials are usually conducted on a small scale and on less crucial routes and they have the benefit of encouraging innovation and help to mainstream newly developed technologies. They also help manufacturers establish whether improvements need to be made, in order for their vehicles to perform optimally in real life conditions [2].

Demonstrations are used to test whether a technology could take over from a normal 'in service' vehicle, after the technology has been successfully trialed. Using demonstration buses before purchasing allows the transport operator to test the passenger acceptance, real world performance and practicalities of the vehicle before any significant investment is made into a fleet, including any infrastructure requirements [2].

Below are given typical examples of electric buses that are in trials and demonstrations across Europe.

Caetano Bus (Cobus 2500 EL): In 2011, the City of Vila Nova de Gaia (Portugal) started commercial testing of a full electric 25 seat (total capacity 67) Caetano Bus (Cobus 2500 EL), Figure 15. The bus can also be adapted for use on urban areas due to its smaller dimensions - 2.55 m width and 9 - 12 m length. It has an aluminum body (CO-BOLT system) assembled on a modular chassis. The front module contains the 150kW UQM

Power Phase 150 permanent magnet synchronous electric motor fed by seven lithium ion batteries with a total capacity of 150 kWh, allowing a range of approximately 120 - 160 km [40].

Recharging the batteries of the bus from 10% to 90% SOC (state of charge) took less than 3 hours. After the positive experience in the testing period in Gaia, as well as in the German cities of Offenbach and Wiesbaden, the Cobus EL 2500 is now certified to run on regular roads and ready for market and series production [2].

Figure 15 Cobus 2500 EL full electric bus

Hybricon Arctic Whisper city bus (HAW 12 LE): In 2011, the City of Umeå in Sweden tested fully electric buses on standard routes, with very good results [2]. A 12-metre Hybricon Arctic Whisper city bus (HAW 12 LE), Figure 16, featuring the in-wheel hub drive ZAwheel, produced by the German electric motor manufacturer Ziehl-Abegg. The operating time is 18 hours a day [41]. Due to the fact that there is a pure wind and hydro plant power in Umea, buses can run fully on clean energy, well-to-wheel.

The bus uses LTO (lithium–titanate battery) batteries that can be charged for 1 hour drive in 6 minutes. Hybricon Bus Systems AB provides the city with the whole system, including charging stations. The City of Umea has a startup plan for up to ten 12m buses and 20 articulated 18m buses [42].

Figure 16 Hybricon Arctic Whisper electric bus

The buses have been ordered in two different sizes: three 18-metre vehicles, each with four drive motors (HAW 18 LE 4WD), and five 12-metre vehicles, each with two drive motors (HAW 12 LE). Delivery is due to start in autumn 2014 with the 12-metre buses. In spring 2015, there will be nine fully electric city buses circulating in Umea. The vehicles will be charged with 650 kW each at three ultra-fast charging stations. The batteries have a power output of at least 50kWh, depending on the route. They will be recharged for three to five minutes per hour, enabling non-stop electrical operation (24/7) [41].

Each city bus will have a small range extender on board, which can run on biodiesel or ethanol and recharge the battery via a generator. This means that each electric bus can still be operated even in the event of a power cut. As the range extenders are part of a modular system, it will be simple to switch to a fuel cell in five years time [41].

Solaris Urbino 12 electric bus: A Solaris battery bus was also chosen by the Swedish city of Västerås, which ordered the Solaris Urbino 12 electric with conventional plug connection. Its 160 kWh battery will be divided into four packs. Two of them, 40 kWh each, will be placed on the roof, while the remaining two will be installed at the rear of the vehicle. Thanks to this solution, axle loads will be evenly distributed and three additional seats will be added on the rear bench. The bus will additionally be equipped with a heater powered by two gas cylinders installed on the roof. The gas heater will extend the range of the bus, since it will not use the energy stored in the battery to heat the interior. It will improve the vehicle's efficiency, especially during Swedish cold winters. The bus will be also equipped with a 25 kW electric heater [43].

In the spring of 2014, Solaris delivered two Solaris Urbino 12 electric with conventional plug connections to Düsseldorf, Figure 17. They are fitted with 210 kWh batteries. Both vehicles can be also equipped with an automatic system for conductive fast charging mounted on the roof at a later date. According to a stimulation prepared by Solaris's engineers, there will be one 200 kW battery charger on the route. Buses will use it during their daily service. The charging time will be adapted to the timetable and will take only a few minutes. The charging cable will be fitted into a special arm allowing easy and comfortable use. Thanks to this solution, the charging process is as simple as fueling a bus. Two additional 32 kW battery chargers located at the depot will be used at night. All parameters were adapted to supply the amount of energy required to complete the service, even in case of unexpected obstacles preventing a bus from arriving at a charging point on time [43].

Figure 17 Solaris Urbino 12 electric bus in Germany

The German city of Braunschweig chose the Solaris Urbino 12 electric with contactless inductive charging. The system allows a bus to be charged automatically at bus stops thanks to induction coils fitted under the road surface. The whole process is fast and efficient. In 2014, Solaris will deliver four more inductively charged electric buses to Braunschweig, this time 18-metre versions. These Solaris Urbino 18 electric will be the first articulated electric buses produced by Solaris. Their purchase is part of the EMIL project for "e-mobility through inductive charging", whose aim is to increase the number of inductively charged electric buses. The first five Solaris buses are only the beginning of this project [43].

Siemens/Rampini electric bus: The first 8m electric bus (eBus) for the Austrian capital city of Vienna, Figure 18, supplied by Siemens and Rampini, has been brought into service by "Wiener Linien", the municipal public transport company. The buses recharge at their end stations by hooking up to the overhead lines of the Viennese tram using an extendable pantograph, an arm on the roof [44].

With this recharging technique, it is possible to install a smaller battery system (nine lithium iron phosphate batteries with a total capacity of 96 kWh instead of the 180 kWh electric buses usually need). Buses have a top speed of 62 km/h and a range of up to 150 km without recharging (the distance decreases to 120 km in winter when the heating system consumes about 7 kW more energy) [45].

Each electric bus cost is €400.000, double the cost of a comparable diesel bus. Prices are likely to drop as production rises, however. In addition, the additional charging infrastructure costs included a charging point at each end stations (each costing €90.000), and charging point at the bus depot (€320.000) [45].

In 2013, Bremen's public transport company (BSAG) tested an 8m electric bus from the manufacturer Siemens/Rampini, which it borrowed from the City of Vienna. The bus does not generate direct or indirect CO_2 emissions, because it is charged in Bremen with electricity from renewable sources. Bremen is also undertaking a trial with three small battery electric buses, which are charged overnight from the grid at the depot and a 12m battery electric bus will also soon be trialed [2].

Figure 18 Siemens/Rampini electric bus

EMOSS e-bus: In 2012, the first ever public-service field trials of an electric bus charged wirelessly by induction are currently underway in the Netherlands [47]. EMOSS e-bus 12 meter is unparalleled seating capacity, full low floor, zero emission, and quiet electric bus based on the Volvo 7700 range, Figure 19. Top speed is 85 km/h, occupancy 86 passengers. Available with AC and DC, conductive or inductive fast charge, the versatile configuration gives Public Transport Operators a wide range of deployment possibilities [46].

Figure 19 EMOSS e-bus

Hybrid and Electric drive train supplier EMOSS provided the electric drive train and integrated wireless charging system to the vehicle system. Benefits of this full electric “charging on route” concept is a downsized battery pack, resulting in lower weight- and cost balance and ability to operate on regular bus routes.

In addition to overnight plug - in charging (7 hours), opportunity charging will allow the electric bus to run reliably for 18 hours, covering some 288 kilometers a day, without the need to stop for prolonged periods. Opportunity charging means that the electric bus invisibly receives a top-up charge by a 120 kW wireless inductive charging system within the space of a few minutes (4-7 min) while at a bus stop. The battery is Lithium-Ion Polymer, 128 - 300 kWh energy. Electric motor has power 240 kW, torque 960 Nm, direct drive transmission, and operating voltage 700V [47].

SOR BN 12 electric bus: SOR BN 10.5, a low-floor city electric bus, is a double-axle three-door electric bus of 10.370 mm in length designed for public transport for shorter distances (120 km) in city traffic and maximum speed 80 km/h [48] is in service since 11th February 2014, Figure 20. The SOR-Cegelec, which is now being tested in Prague, has already been in full operational use in Ostrava for several years. The city has four vehicles of an older design [49].

The body of the bus comes from the SOR BN 12 city bus, the rear overhang was shortened and the low-floor section remained unchanged. The bus seating capacity is 85 passengers, out of which 19 seats, with other 6 folding seats. A brand new six-terminal electric motor, TAM 1049 Pragoimex, of the nominal output of 120 kW, was developed to drive this electric bus.

The traction battery is composed of 180 cells, 300 Ah, 1.700 kg. Each cell is monitored independently as for overcharging, undercharging, and temperature. In case of a temperature increase, the whole box is cooled. By contrast, for extreme frosts, there is an option to install a heating system into the battery box [48].

The traction battery may be charged in 8 hours by means of "slow" charging (32A), including balancing of cells (necessary once a day). While charging, it is possible to set preheating of the bus interior so that it can be heated at the moment of the departure. Moreover, it is possible to charge by means of "fast-charging" of up to 250A - the charging time is reduced proportionally to the current to about 1 hour [49].

Figure 20 SOR BN 12 electric bus

Skoda Perun electric bus: In 2013, Skoda has begun developments of two basic types of battery-powered electric bus Skoda Perun (Pure Electric RUNner), Figure 21. Both are twelve-meter low-floor buses with a power output of 160kW and battery of 221 kWh, whose design makes use of the latest technological trends and modern solutions. The first type of Skoda electric bus will have a range of about 150 kilometers and its charging will take place at the depot during the night, when the vehicle is not in operation. The production of the second type of bus, with an average range of about 30 km, is planned for 2014. The vehicle will be designed so that the battery can be recharged quickly - in a matter of minutes - at the terminals and bus stops [50].

The battery is charged by a roof-mounted pantograph charging station during the daytime and by a portable charger with COMBO CCS standard during the night time. The vehicle batteries can be recharged up to 100 % of their capacity in 50 minutes during the day, while the night-time charging up, inclusive of balancing of the cells, takes several hours. The vehicle has a capacity of more than 80 passengers and its maximum speed is 70 km/h [50].

Figure 21 Skoda Perun electric bus

VDL Citea Electric bus: The first electric bus of VDL Bus & Coach, the VDL Citea Electric, is introduced during the UITP Mobility & City Transport in Geneva (May 2013). This is a fully electric bus is the Citea SLF Low Floor with a length of 12 meters, Figure 22 [51]. The ability to choose from various electric drives and battery packages ensures that the most ideal and optimal combination can be selected for every deployment area, without consequences for accessibility, interior layout, or comfort.

When selecting options for the Citea Electric, one can choose from various electric drive systems: a large battery charged via a plug-in connection; a relatively small battery charged with various quick-charging methods, such as induction, trolley, or plug-in; and a medium battery charged with a diesel generator (Range-extender vehicle (REV)).

In late May 2014, the first Finnish VDL Citea Electric will be delivered to Veolia Transport Finland. The bus is equipped with Ziehl-Abegg wheel hub motors. These motors are located in the rear wheels of the Citea. A Valence battery pack is installed as energy storage medium [52].

Figure 22 VDL Citea Electric bus

BYD electric bus: In 2012, Movia, the largest public transport company in Denmark, and BYD Europe B.V., have announced the introduction of the first full-size pure electric city buses to enter service in Copenhagen, Figure 23, which has set itself an ambitious goal, in terms of sustainable mobility, to become the world's first zero-emission capital by 2025 [53].

Figure 23 BYD electric bus in Copenhagen

The two electric buses provided by BYD will operate on trial service on different passenger-carrying routes with different loads in Copenhagen for two years. The project is being carried out in cooperation with the Municipality of Copenhagen, DONG Energy, City-Trafik, and Arriva. The company objective is that by 2015, 85% of the municipality's own vehicles should be electric, hydrogen or hybrid powered [41].

In 2013, London has begun trials of two BYD pure electric buses operating on two central London routes, the first in the UK capital to be serviced by fully electric, emissions free buses, Figure 24, [41].

Six further electric buses are set to be introduced into the TfL fleet in early 2014. In addition to the electric buses, London will be running 1.700 hybrid buses by 2016 - covering a fifth of its fleet [54].

Figure 24 BYD electric bus in London

The trial in Ankara is only the latest in a series of European trials of the BYD electric city bus. More than 25 major cities have evaluated the bus in revenue service. Results have been impressive across many different duty cycles showing that the bus is capable of up to 24-hour route-service on a single battery charge (usually completed in 3-5 hours off-peak), unlike the competition that requires in route charging every couple of hours. When compared to a conventional diesel or natural gas fueled buses, the BYD electric bus has demonstrated a dramatic reduction (from 80 - 90%) in operating and maintenance costs [55].

At the beginning of April 2014 the city of Belgrade took a BYD electric bus E-12, Figure 25, to its streets to test whether it lived up to its 'silent and efficient reputation'. This is the first time the model has been tested in the region and this initial trial - run proved it to be a real contender [56].

Figure 25 BYD electric bus in Belgrade

Over a three day period, the E-12 was tested on bus-routes No.26 and No.41, which run through the city of Belgrade, in addition to a suburban route. City Line No26 is known to have the most difficult exploitation conditions in Belgrade (low speeds, multiple traffic lights, large passenger – flow, and steep topography).

On the last Bus Committee, which was held in Copenhagen on 22 May 2014, under the patronage of UITP, some data on the BYD buses involved in several European trial tests were presented [57]. The results are summarized in Table 3.

Table 3 Some results on trials of BYD electric buses

No.	City	Units	Period	Average Range (km)	Energy (kWh/km)
1	LONDON[1)]	2	January 2014	257	1,07
2	MILAN	2	March 2014	237	1,16
3	COPENHAGEN[2)]	2	January 2014	197	1,40
4	BARCELONA	1	November 2013	190	1,44
5	BELGRADE	1	April 2014	212	1,30

[1)] Potential saving of up to 75% in fuel cost, 50% reduction in CO_2 per passenger journey;
[2)] Noise problem – Insulation needed to reduce from 74 to 69 dB.

ZeEUS project: On January 23 the Zero Emission Urban Bus System (ZeEUS) project has been launched in Brussels [58]. The project, with a 42-month duration, involving 40 European partners coordinated by the UITP will focus on showing the economic, operational, environmental, and social viability of electric buses as a real alternative for mobility in urban environments based on various innovative technological solutions in eight European cities: Barcelona, London, Glasgow, Stockholm, Münster, Rome, Pilsen, Bonn, and one city in Italy [59].

Leading manufacturers in bus electrification (ALEXANDER DENNIS; IRIZAR; SKODA; SOLARIS; VDL; VOLVO), Figure 26, will participate with plug-in hybrids or full electric buses using different charging infrastructure and strategies [30].

Figure 26 Leading manufacturers will participate in ZeEUS project

ELECTRIC BUS COSTS, EMISSIONS, AND ENERGY EFFICIENCY

Electric bus costs and tailpipe emissions

Battery electric buses are still not widely commercially available so precise figures for procurement cannot be given. However, there are literature data on prices of these buses. These data are of informative character and they are usually presented concurrently with prices of other busses having different drive trains.

E.g., Table 4 presents data on prices of buses 12m long [61], whereas Table 5 contains data on prices of buses 18m long (articulated buses) [20]. The source data on articulated buses in British pounds have been converted to Euros (1£ = 1.26 €). At the same time, the tables contain information concerning maturity of each technology for its application to the buses, based on the level of its present day development.

Table 4 Capital cost of 12m buses

Bus Type (12m length)	**Capital cost (€)**	**Technology maturity**
Diesel EV	225.000	Mature
Diesel Euro VI	240.000	Mature
Diesel-Hybrid EEV	300.000	Mature
Battery bus (opportunity charging)	**500.000**	**Mature**
Battery bus (overnight charging)	**400.000**	**Mature**

Table 5 *Capital cost of 18m buses*

Bus Type (18m length)	**Capital cost (£)**	**Capital cost (€)**	**Technology maturity**
Diesel	280.000	350.500	Mature

Diesel hybrid	420.000	525.800	Mature
Plug-in Hybrid	470.000	588.400	Incremental development
Battery electric	**500.000-550.000**	**625.900- 688.500**	**No 18m vehicle**
Fuel Cell Hybrid	600.000/	751.100	Unproven

Some reports [2] estimate cost of €5000 more than that of traditional diesel buses for maintenance plus around €100,000 extra for infrastructure. The City of Vila Nova de Gaia, for example, paid around €500,000 to purchase the Cobus 2500EL.

Prices of battery buses are influenced not only by the high cost of the batteries, but also by the need for their replacement during the lifetime of the bus. The batteries may need to be replaced at some point, probably after 8-12 years of use. Costs and risks related to batteries could be spread and/or minimized by leasing the batteries separately. Although initial investments will be high, BEVs provide the benefit of savings in fuel costs and potentially less maintenance requirements, as there are fewer moving parts [2].

E.g. the current cost of a complete replacement battery pack for the Optare Versa EV battery electric bus is £56,000 (€70,560); it is therefore considered that the additional cost of a larger battery for plug-in hybrid will be no more than £15,000 to £20,000 (€ 18,900 to € 25,200) [20].

Full electric buses produce no tailpipe emission, which means no local pollutants. Embedded emissions including carbon, nitrogen and sulphur oxides, depend on the proportion and type of fossil fuels used to generate electricity for the national grid [2].

Emissions savings from battery electric buses are dependent on how the electricity is generated. The grid mix across Europe varies and the emissions savings will be almost 100% if renewable sources of electricity are used. It has been estimated that even with CO2 eq intensive electricity generation the savings will be at least 30% [2].

Full electric buses are less flexible as they will be designed to run on a specific route according to recharging regime. With some systems, delays on busy lines could cause problems due to the charging regime. Recharging could be an issue for smaller fleets or longer bus lines, but there are many other parameters that may influence this. Battery electric buses are suitable for operating in urban areas with stop/start operation [2].

LCA (LIFE CYCLE ANALYSIS) FOR DIFFERENT BUS TECHNOLOGIES

The implementation of alternative technologies in the transport sector is aimed at increasing the efficiency of the vehicle itself but also the vehicle environmental impact. One important tool to evaluate a vehicle utilization impact, including the energy used, is the life cycle analysis (LCA) methodology.

In the literature there are data on concurrent emissions of buses driven by different alternative fuels and drive trains obtained on the basis of numerous studies. One such study, the results are presented in [20], has been carried out in 2013 includes data on emissions of CO2 of buses including battery electric buses.

The study [20] considers CO2 benefits in terms of both well-to-wheel and tank-to-wheel emissions.

- The well-to-wheel (WTW) CO2 emissions of a particular activity captures the CO2 emitted during fuel/electricity production, distribution, and vehicle use;

• Tank-to-wheel (TTW), or tailpipe, CO2 emissions refer to CO2 emissions directly from the vehicle as a result of combustion of fuel.

The report includes a comparison of potential WTW and TTW CO2 emissions relative to the diesel bus baseline for all of the drive train technologies and alternative fuels relevant to the buses under consideration. This is summarized in Figure 27.

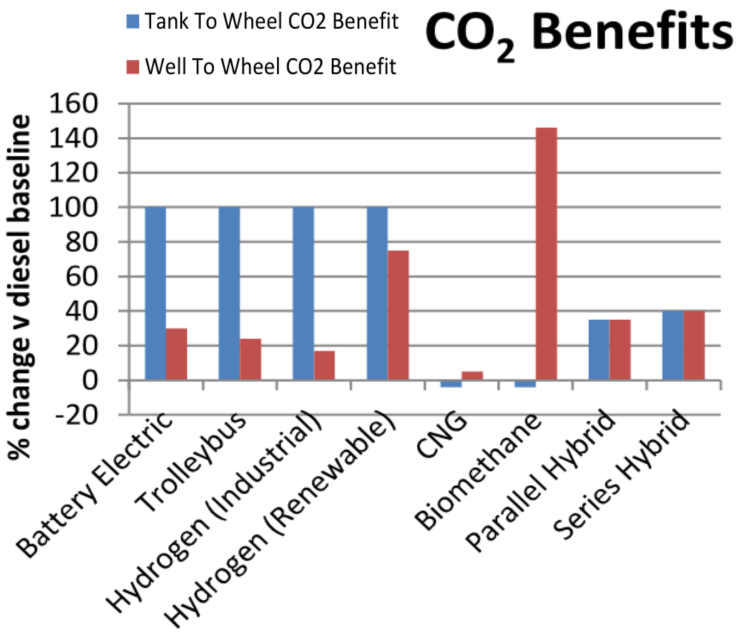


Figure 27 Comparison of alternative fuels vs. diesel baseline

The key points from this comparison are [20]:

- Battery electric, trolleybus, and fuel cell buses can deliver a 100% reduction in TTW CO2 relative to the diesel baseline, but WTW benefits vary significantly with the fuel type and energy pathway.
- The potential WTW CO2 benefits for the battery electric and trolleybus depend on electricity production methods. The reductions of 24% for trolleybus and 30% for battery electric are based on the UK grid mix (164 g CO2 eq/MJ).
- The higher potential reduction in WTW CO2 for battery electric relative to trolleybus is not explained, but is presumed to derive from assumed higher energy efficiency for the battery electric vehicle.
- The WTW CO2 benefits for a hydrogen powered fuel cell bus are lower than the electrically powered buses unless the hydrogen fuel is formed through the electrolysis of water powered by renewable electricity.
- The use of fossil CNG offers only marginal reductions in WTW CO2 emissions relative to a diesel bus and may generate an increase in TTW CO2 emissions.
- The use of biomethane has the greatest potential to deliver a reduction in WTW CO2 emissions relative to diesel bus. The 146% reduction assumes the use of biomethane produced by anaerobic digestion in a dedicated plant, using animal/agricultural waste as a feedstock.

- The potential CO2 benefits of hybrid buses are derived from a reduction in diesel fuel consumption and thus the WTW and TTW reductions are the same?
- Series hybrid technology is considered to offer greater potential for regenerative braking than parallel hybrid technology.

Energy Efficiency of different buses

Table 6 presents the results of the desk research undertaken into the relative energy conversion efficiency of different buses. In order to present data for all vehicles, the figures presented come from a range of sources and thus may not represent directly comparable vehicles or operating conditions [20].

The energy consumption of vehicle heating, ventilation and air conditioning (HVAC) systems can represent a significant proportion of the total vehicle energy consumption and thus data for vehicles operating in warm or cold climates will not be comparable with that for vehicles operating in more temperate conditions requiring less use of HVAC systems.

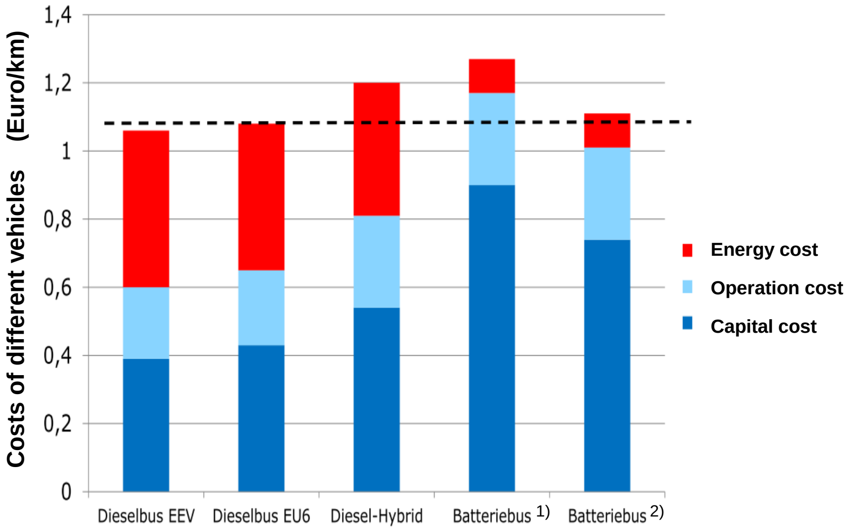
For comparison purposes data have been presented in a common unit of kWh per 100km distance travelled. Table 6 compares the energy efficiency of 12m rigid buses and 18m articulated buses. Battery electric buses are significantly more energy efficient than the hybrid electric buses, which are in turn almost twice as efficient as the buses powered by internal combustion engines. CNG buses are the least energy efficient of all the vehicles and less efficient than a conventional diesel bus which is included for comparison.

Table 6 Energy Efficiency Comparison for 12m and 18 m buses

Bus	**Energy Efficiency (kWh/100km)**	
	12 m bus	**18 m bus**
Fuel Cell Hybrid	269	504
Diesel Hybrid	283-380	523
Plug-in Hybrid	260	No data
Battery Electric	**119-140**	**No data**
Compressed Natural Gas (CNG)	655	735
Diesel	500	624

The general picture of 18m buses is similar to that for the 12m buses, battery electric buses being the most efficient, followed by the hybrids with the fuel cell hybrid performing marginally better than the diesel hybrid, and CNG again being the least energy efficient compared to the electric buses and less efficient than a conventional diesel articulated bus. There are no data for the plug-in hybrid and battery electric buses in this table as there is no production 18m articulated buses. In summary, the best performing buses in terms of energy efficiency are the battery electric powered buses.

Certain analyses of bus costs per 1km of the road, which have taken into account their capital cost, operation cost, and energy cost, are shown in Fig. 28 [60]. The major noticeable differences between compared buses are in the capital cost and energy cost. Despite high capital costs of battery electric buses, their total costs per unit of covered road are acceptable compared to other buses. The current expansion of their development is increasingly motivated by their good energy and ecologic characteristics compared to other drive train technologies.



1) The batteries are recharged overnight, including replacement of batteries

2) The batteries are recharged overnight

Figure 28 Costs of buses with different technologies

CONCLUSIONS

A significant part in the future reduction of consumption of fossil fuels and of the corresponding reduction of emissions of harmful gases will be played by the electric propulsion systems and alternative fuels.

Electrification of buses is considered as major strategy for reducing dependence on oil and greenhouse gases, and meeting the aggressive fuel economy standards. However, there are many barriers to electric buses market expansion. The limitations that relate to battery technology include: limited electric drive range and long recharge time.

Energy storage systems, usually batteries, are essential for electric drive buses. Batteries must have a high energy-storage capacity per unit weight and per unit cost. Because the battery is the most expensive component in most electric drive systems, reducing the cost of the battery is crucial to producing affordable electric drive buses.

Despite the significant number of barriers, some factors could facilitate the transition of EVs to the mass market. These factors include the effect of zero tailpipe emissions, incentives and low running costs, as well as innovations in the supporting infrastructure.

Current development of the battery technologies and other electric drive system components resulted in some solutions of buses that are in use at regular exploitation.

The analysed state of the development and market of full electric buses, including presentation of the current projects, trials, and demonstrations, show that their growth has been intensified over the past several years and that, irrespective of the existing barriers, their greater commercialization should be expected in the immediate future.

The presented solutions of full electric buses are aimed at confirming the application of electrical energy as an alternative fuel of vehicles in general, specifically of buses, in order to stimulate operators to innovate the exiting fleets by the solutions of this type.

In the future, electric buses will continue further development through the improvement of battery technology, increasing their life and capacity, optimizing electric drive components, and improve the system for recharging the battery.

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MVM *Editorial Board*
University of Kragujevac
Faculty of Engineering
Sestre Janjić 6, 34000 Kragujevac, Serbia
Tel.: +381/34/335990; Fax: + 381/34/333192
www.mvm.fink.rs