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THE DEVELOPMENT OF THE CONSTRUCTION OF CITY BUSES IN TERMS OF REDUCING THE KERB WEIGHT OF THE VEHICLE

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Abstract

Modern city buses are made of various construction materials and the share of material groups has changed over the decades. By replacing heavy materials for structural elements or bus components with their lighter counterparts, the kerb weight of the bus can be reduced by up to several hundred kilograms. This article presents the issues of the development of city bus design in terms of passenger space comfort and bus structure in the context of reducing the vehicle's own weight since the 1970s. The main changes in vehicle design allowing for reducing the weight of structural elements of bodies and chassis as well as the main assemblies in city buses are presented as well as research on body types in terms of aerodynamics, safety and travel comfort. It has been shown that reducing the weight of the bus does not negatively affect its load capacity and the new bus designs are equipped with safety and comfort systems, including ABS (Anti-lock Braking System), ASR (Automatic Stability Regulation), ESP (Electronic Stability Program) and air conditioning in the passenger space. Thanks to modern light construction materials, we gain the opportunity to improve safety and comfort without losing the transport capabilities developed as a result of the development of city buses over the years.

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1. Introduction

Urban transport plays a significant role in shaping the topography of the city and its adjacent areas [14]. The development of urban and industrial areas depends on the development of transport infrastructure. Urban transport provides access to strategic places and service points such as schools, offices, public facilities and workplaces. Moreover, it plays a very important role for people who do not have their own means of transport and is provided using various buses known as city buses. The city bus is an essential public transport vehicle in everyday life [51]. Unfortunately, there are not only advantages of this type of transport as it is associated with nuisances for the natural environment and residents in the form of exhaust emissions [13, 26, 43], dust pollution [3, 52] and noise [40, 44, 53]. Currently, most urban agglomerations are struggling with capacity problems of communication routes [14, 34] and high traffic intensity [29, 31] leading to the phenomenon of transport congestion. A lot of attention has been devoted to this issue in the available literature, of which several works are worth mentioning [28, 35, 48]. Another threat from transport are road accidents, which, according to WHO, are one of the most significant causes of death among young people under forty years of age [25]. Fortunately, the number of road accidents occurring in urban areas and the resulting injuries are less tragic compared to those occurring on other roads. The main reasons for this state of affairs are speed limits in built-up areas and traffic congestion. In such conditions, there are more road collisions than serious accidents, but it also causes traffic problems for public transport vehicles. Another important factor in the transport sector is its energy intensity related to the consumption of fossil fuels or other available energy sources. The issue of energy consumption in transport has been an important issue since the fuel crisis in the nineteen-seventies, but recently this interest has increased significantly. Many works [32] are devoted to various aspects of reducing energy consumption by road vehicles, e.g. limiting the vehicle's own weight [51], determining routes and urban logistics [41, 50], adapting vehicle engines to alternative fuels [4, 8, 45] etc.

To counteract these negative effects, many technical solutions and improvements have been introduced in the design of vehicles, as well as restrictions, mostly legal, regarding road traffic. There are also various government incentives to change the means of transport to more ecological solutions, for example, in Romania [39]. Great progress has been made in the field of the active safety of vehicles, where many safety systems have been introduced, such as ABS or ESP [1, 36] and other driver support systems such as ACC (Adaptive Cruise Control) or parking assistance systems (these abbreviations are the names of Bosch systems and are necessarily called the same by other manufacturers). The design of vehicles has been changed, with a particular emphasis on passive safety systems. When it comes to the design of city buses, the requirements regarding passenger comfort in terms of getting on and off,

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taking up space, more seats, visibility, etc. have changed a lot [7, 38]. In the case of reducing emissions, the successively introduced exhaust toxicity standards and developments in the field of vehicle power units played an important role [4, 12, 37]. Studies on the optimisation of energy consumption by a bus powered by hydrogen fuel cells were presented by Małek et al. [33] and Stecuła et al. [42] and Yang et al. [51]. Many cities have decided to use trolleybuses in public transport as a pro-ecological solution [9, 30] and electric buses are increasingly being used [5]. A very important factor influencing fuel consumption and, therefore, exhaust emissions is reducing the vehicle's own weight without losing its short-term durability. In this case, advanced manufacturing methods [2] (especially additive techniques) and modern engineering materials [47, 51, 53] in the construction of vehicles have become very helpful.

This article presents issues related to the development of city bus design in terms of passenger space comfort and bus structure, with a particular emphasis on the possibility of reducing the vehicle's own weight. The main changes in vehicle design that enable reducing the weight of structural elements of bodies and chassis as well as the main assemblies in city buses are presented. The last part summarises the collected material and formulates conclusions for future research areas of city bus design.

2. Methodology

The study uses a comparative analysis of city buses over the last few decades, taking into account the following technical parameters of the vehicles:

- dimensions of the bus;
- kerb weight and load capacity;
- number of passengers;
- number of seats in the passenger space;
- number of doors;
- floor height;
- air conditioning of the passenger space.

Examples of the use of modern construction materials and manufacturing techniques to reduce the vehicle's own weight are presented. For this purpose, CAD (Computer-Aided Design) modelling and FEM (Finite Element Method) analysis were used for selected structural elements of the bus, in particular fragments of the supporting structure and chassis assembly locations.

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3. Bus division

City buses can be divided according to various technical criteria, e.g. floor height, type of drive and its location and type of body.

Due to the height of the bus floor, we can distinguish a bus:
- low-floor (entrance without steps, floor at the bottom of the body, up to 350 mm above road level);
- medium-floor (one entrance step, floor approximately 360–750 mm above the road level);
- high-floor (two or more entrance steps, floor level from 760 cm above the road level);
- high-deck (floor over 1 m above the road level, separate lower deck for luggage compartments, structure typical for long-distance and tourist buses);
- low-entry (partly low-floor – most often in the front part and high-floor in the rear part).

Depending on the type of drive, the following can be distinguished:
- compression ignition combustion engine;
- gas drive (CNG – compressed natural gas, LNG – liquefied natural gas);
- hybrid drive (series, parallel and mixed hybrid);
- electric drive (battery buses);
- with another drive source (hydrogen fuel, fuel cells).

Due to the location of the drive source, the following can be distinguished:
- front power source with power transmission to the central or rear axle;
- central power source with power transmission to the central or rear axle;
- rear power source with power transmission to the rear or central axle.

Depending on the type of drive used, the supporting structure of the bus may differ, because the drive unit and fuel tanks or batteries will be placed in the electric bus differently than in the case of a drive with an internal combustion engine using traditional fuel (diesel fuel). These requirements will be different for an electric bus or a bus powered by CNG or LNG gas fuel, as well as for hydrogen. An example of the design of a city bus equipped with fuel cells is shown in Figure 1.

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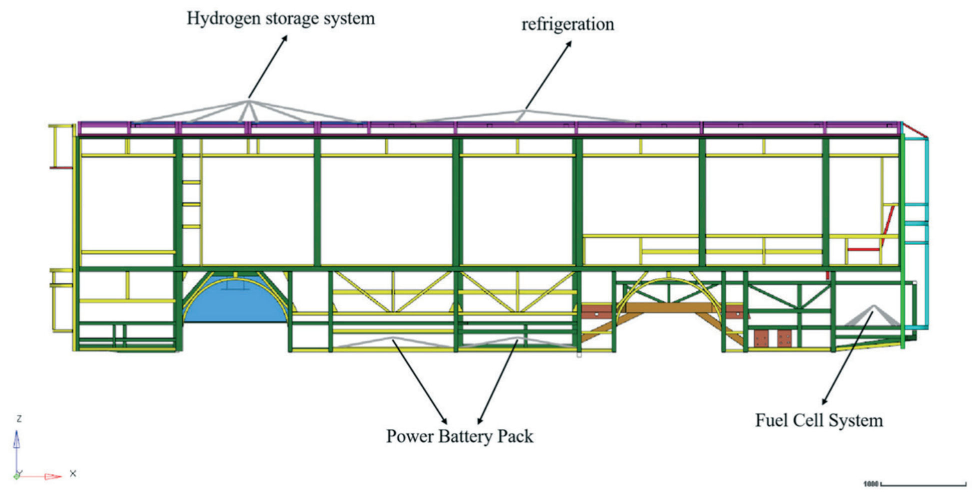

Fig. 1. Model of the body structure of a city bus with fuel cells [51]

The overall dimensions of the fuel cells city bus are: 10,500×2,500×3,390 (in mm), the wheelbase is 5,100 mm, and the bus power system weighs 1,384 kg. The individual elements of the power system weigh respectively: hydrogen storage system 480 kg, refrigeration 330 kg, power battery pack 400, and fuel cell system 174 kg.

In the case of a different power supply system (e.g. gas), the bus's supporting structure may be different due to the location of appropriate fuel tanks, for example on the roof of a city bus. It should be noted that buses are currently being designed, and this trend will also be developed in the future, in terms of an alternative drive source and not just an adaptation of the existing bus structure. This is a much more creative approach that ensures better passenger comfort and greater vehicle stability, which translates into safety in road transport.

4. Reducing the kerb weight of a city bus

The first bus designs were based on trucks, which had a positive impact on the development of urban bus transport but had numerous disadvantages. The main problem was the weight of the vehicle, high passenger deck and noise, which reduced travel comfort, as well as some problems with service, such as difficult access to the engine from inside the vehicle. Along with the development of city buses, attempts were made to eliminate these problems in the following decades thanks to a new design approach, development research and new construction materials. In the nineteen-forties, buses with a self-supporting body structure appeared (Chausson). In Poland, the first buses were built in the interwar period at the

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Ursus plant. Zawrat was a model produced under a license agreement from Saurer. Due to import restrictions at that time, emerging bus companies were forced to import large bus chassis from Western countries (e.g. Leyland) and build the bodies themselves. The structure consisted of a wooden frame with a tin roof. In Poland, bus production developed after 1945 in plants in Jelcz and Sanok. In the nineteen-sixties, structures were created that allowed for better visibility in city buses – skylights in the roof and then raising it to enlarge the windows. After 1970, there was a tendency in the design of city buses to lower the floor, which made it easier for people with limited mobility to board and accelerated the exchange of passengers at stops. An example of a self-supporting body with a frame structure is shown in Figure 2.

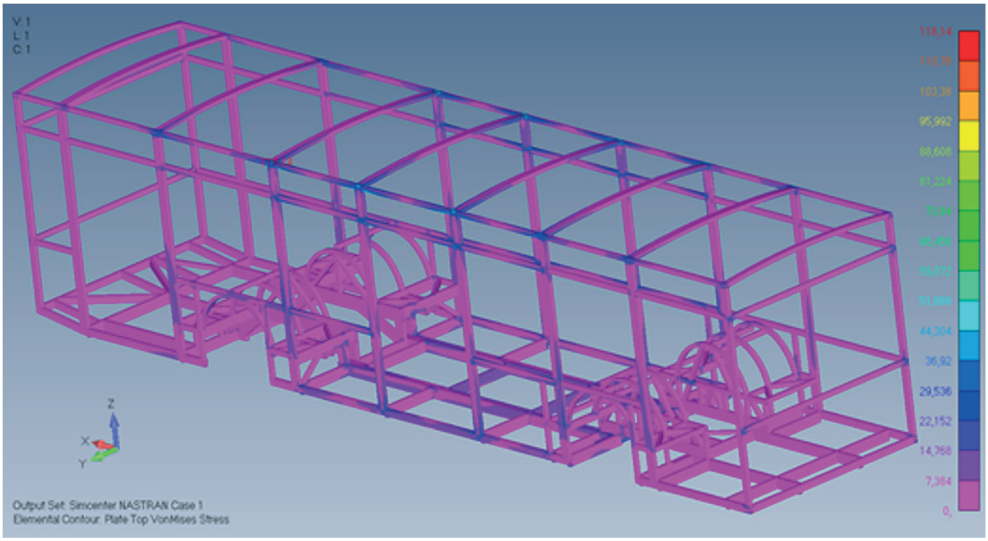

Fig. 2. An example of a self-supporting city bus body

Modern city buses are made of various construction materials, and the share of material groups has changed over the years due to the availability of materials and the popularisation of new options, such as composite materials. These changes were primarily caused by increasing the load capacity of vehicles and reducing their own weight, which translates directly into the energy consumption of vehicles. The vehicle's energy consumption is also significantly influenced by the weight distribution, which is indirectly dependent on the position of the engine and drive units [6], which also affects the vehicle's structure and passenger comfort.

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The mass share of individual material groups in the construction of an 11-ton city bus powered by a diesel engine is shown in the chart in Figure 3.

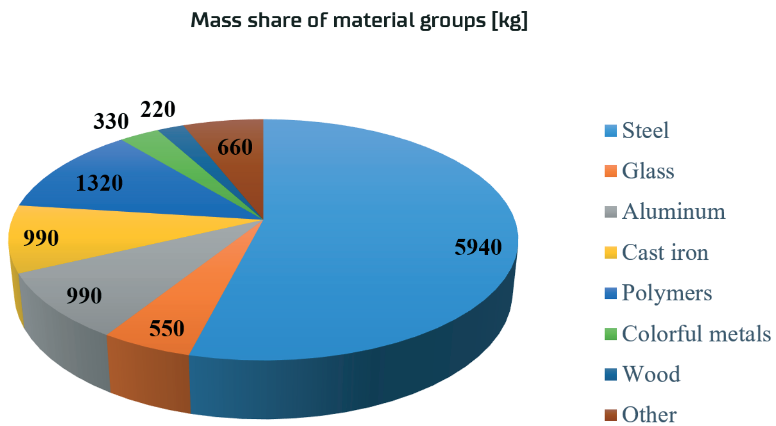

Fig. 3. Mass share of material groups for an example city bus with an unladen weight of 11 tons [10].

As can be seen from Figure 3, the largest mass share in the case of the city bus is steel, and a significant share of materials are polymers, aluminium, cast iron and glass. It should be noted that polymeric materials, including composites, account for an increasing share at the expense of wood, which is the least abundant. These changes have a positive impact on the vehicle's kerb weight.

Another important factor affecting energy consumption in buses is the structure of the body and aerodynamic properties of the bus. Research on new bus designs and body aerodynamics is presented in [11]. Four body structures were tested: Retro, Natural, Stone and Advanced (see the examples in Figure 4). The comparison results were then presented in five categories: aerodynamics, stability, comfort, safety and aesthetics, with each bus rated as low, medium or high. A summary of these results is presented in Table 1.

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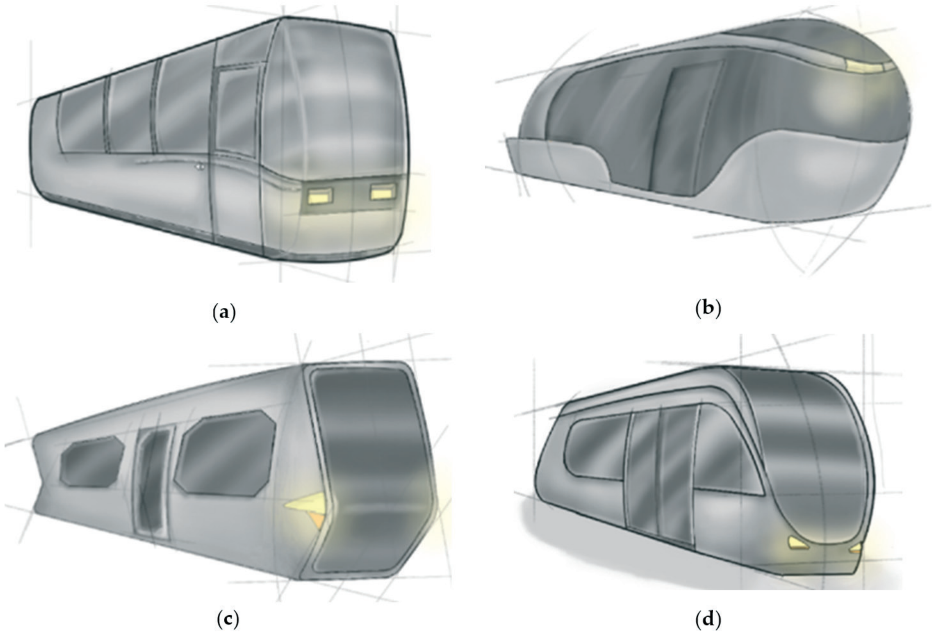

Fig. 4. Four body structures: (a) Retro; (b) Natural; (c) Stone; (d) Advanced [11]

Tab. 1. Comparison of four different bus body types [11]

Parameter	Retro	Natural	Stone	Advanced
Aerodynamics	Low	High	data	High
Stability	Medium	Medium	High	High
Comfort	High	Medium	Low	Medium
Safety	Medium	Medium	Medium	Medium
Aesthetics	Medium	High	Medium	High

Of these types, the Advanced type was rated the best, followed by the Natural type. In terms of comfort, however, the oldest body structure (Retro) is the best in this comparison, although in terms of aerodynamics it was rated the lowest. It is also worth adding that in the case of city buses, aerodynamics is not a key parameter and does not play such an important role as in the case of intercity or tourist buses. However, all types of tested bodies achieved the same level in the safety category. From this comparison, it can be concluded that the development of a bus body is quite a complex process requiring many compromises and evaluations of the assessed parameters.

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5. Comparative analysis of selected city bus designs

Over the last few decades, city buses have changed in line with advancing technologies and market expectations. Back in the nineteen-seventies, high-floor buses (e.g. Jelcz PR110, Ikarus 280) dominated in Eastern Europe due to material shortages and the use of truck components. However, the situation was changing and these structures began to be replaced in favour of partially low-floor and fully low-floor vehicles in subsequent decades.

Comparing bus designs over several decades, changes in the approach to the design of city buses can be noticed. Firstly, the frame borrowed from trucks was abandoned and new frame-type bus structures were designed. This approach resulted in lowering the floor first in the first part of the bus, and later designs began to be dominated by low-floor buses. These changes also allowed the introduction of new construction materials, and thus structural carbon steel is currently replaced with a stainless steel frame. Adhesive technologies are becoming increasingly popular, limiting welding operations to only those that are necessary. Bonding technologies also facilitate the connection of various materials with different properties, such as composite materials from which, for example, entire front panels are made. Thanks to this, it is possible to reduce technological operations and speed up the assembly of the body and its reinforcement. These changes result in a reduction in the kerb weight of city buses and an increase in their load capacity. This is reflected in the data presented in Table 2, which presents several types of twelve-metre and articulated city buses used on the Central and Eastern European market over the last fifty years.

Tab. 2. Selected technical data of compared city buses [15–24]

Parameter	Buses with a length of approx. 12 m				Articulated bus			
	Jelcz PR110	Sancity 12LF	Solaris Urbino 12	Mercedes-Benz Citaro O530	Jelcz 021	Ikarus 280.26	Mercedes-Benz O405GN2	Solaris Urbino 18 III
Years of production	1975–1992	From 2011	From 1999	From 1997	1967–1979	1973–2002	1994–2001	2006–2017
Length [mm]	12000	12000	12000	11950	15880	16500	17820	18000
Height [mm]	3040	2890	3040	2869	2900	3040	2933	2850
Width [mm]	2500	2550	2550	2550	2500	2500	2500	2550
Axles	2	2	2	2	3	3	3	3
Kerb weight [kg]	9275	10490	10800	10770	12000	12500	No data	17500
Gross weight [kg]	17280	18000	18000	19000	20980	22500	28000	28000
Number of passengers	110	105	104	106	136	160	159	157
Seats	1/36	1/40	1/43	1/31	1/42	1/35	1/46	1/51
Doors	3	3	3	2	3	4	3	4

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Tab. 2. Selected technical data of compared city buses [15–24]; cont.

Parameter	Buses with a length of approx. 12 m				Articulated bus			
	Jelcz PR110	Sancity 12LF	Solaris Urbino 12	Mercedes-Benz Citaro O530	Jelcz 021	Ikarus 280.26	Mercedes-Benz O405GN2	Solaris Urbino 18 III
Air conditioning	No	Option	Option	Option	No	No	Option	Option
Active safety	No	ABS, ASR, EBS	ABS, ASR, EBS, ESP	ABS, ASR, EBS, ESP	No	No	ABS	ABS, ASR, EBS
Kneeling	No	90 mm	70 mm	80 mm	No	No	No	80 mm

Analysing the data in Table 2, it is clear that in structures such as the Jelcz PR110 or Ikarus 280.26, the payload is significantly lower compared to the Sancity 12LF and Solaris Urbino 12 or the eighteen-metre Solaris Urbino 18 III. Interestingly, these vehicles achieve a similar maximum number of passengers, while the new bus models have more seats. This means that the comfort of passengers has significantly improved, and some new vehicles are equipped with passenger air conditioning systems as standard. In addition, new bus designs have a kneeling function, which greatly facilitates the replacement of passengers, depending on the model, the value is from 70 to 90 mm. Also noteworthy is the presence of active safety systems such as ABS, ASR or EBS (Electronic Braking System), and also ESP, which improves not only safety but also travel comfort. An interesting study on the reliability of these safety systems and their impact on safety in urban transport was presented by Rybicka et al. [38].

Analysing the data regarding the vehicle's own weight, we can notice that the lightest structure is the Jelcz PR110, but the differences between the other vehicles amount to approximately one and a half tons, and the difference in total weight is approximately 700 kg for the Sancity 12LF and Solaris Urbino 12 and as much as 1,700 kg for the Mercedes Citaro. In the case of new bus designs, we have more seats, an additional kneeling function, air conditioning and active safety systems. Therefore, there is a significant difference between the compared vehicles from the nineteen-seventies and new bus designs. These differences result mainly from technological changes [27, 49] and changes in the quantities in the material groups used. New bus designs use stainless steel, larger amounts of polymer materials and composites [46, 47] and aluminium alloys [36], which has a beneficial effect on reducing the weight of the body itself. In addition, new bus designs have much more glass compared to previous models, which is unfavourable due to the fact that the glass is relatively heavy, but has a positive effect on travel comfort. Despite this, modern structures are much more durable, lighter and can accommodate the same number of passengers in much more comfortable conditions.

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6. Conclusions

Currently, city bus structures are designed as a separate type of vehicle, not based on truck chassis, as was the case at the beginning of their development. We increasingly use stainless steel, composite materials, aluminium alloys and plastics for the bodies of city buses. Some elements are immediately treated as interior finishing, which has a positive effect on reducing the vehicle's own weight, this applies primarily to stainless steel and thermo-chemical-hardening plastics. Material changes have also been influenced by the development of modern manufacturing techniques, primarily additive technology. Thanks to this, we can make complex shapes that are much lighter but equally durable. The article has analysed selected designs of popular city buses with a length of approximately twelve metres and long articulated buses. Based on the available technical data, it was found that the currently used city buses are even several hundred kilograms lighter than their predecessors and have not worse transport capabilities, and often even larger ones, and the journey takes place in better conditions. It was found that modern city buses have more seats, larger glazing, are equipped with air conditioning of the passenger space and active safety systems: ABS, ASR, EBS and more and more often, ESP.

Based on the conducted literature stage and the authors' own research and experience, specific directions for future research regarding the construction of lightweight city bus bodies can be formulated, including:

- Research of selected structural nodes made using the additive technique;
- Development research of critical points of the structure (door mounting points, front and rear panels of the bus, anchoring points of the chassis and drive units);
- Energy consumption research depending on the drive system used.

7. Acknowledgement

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8. Nomenclature

ABS Anti-lock Braking System
ACC Adaptive Cruise Control
ASR Automatic Stability Regulation
CAD Computer-Aided Design
CNG Compressed Natural Gas

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EBS Electronic Braking System

ESP Electronic Stability Program

FEM Finite Element Method

LNG Liquefied Natural Gas

9. References

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