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Mechanical Evaluation of Road Durability Test in Battery Electric Buses

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Abstract

Electric vehicles contribute significantly to energy consumption and emissions of greenhouse gases, as well as being silent and highly sustainable in terms of usage. Public transportation vehicles, such as buses, play a significant role in transportation, reducing fuel consumption for society as a whole and resolving traffic congestion. It raises the impact values of concepts such as electricity and a bus when these two phenomena are combined under one roof. To ensure long-term serviceability, electric vehicles must be capable of operating under similar conditions as conventional vehicles. In order to ensure that the vehicles are ready for use, they undergo several stages of testing simulating actual operating conditions. Following the completion of the test process, if the vehicle meets the predetermined criteria, the test process is considered complete, and the vehicle is approved for use. In this study, two different battery electric bus models were subjected to road endurance tests, critical parts were determined, and product reliability was ensured by product development studies. For this purpose, technical specifications of vehicles were shared, road durability test area and several road conditions were evaluated, qualification criterias were specified, loading conditions were assessed, mechanical evaluation stages were explained and finally, critical parts of vehicles were shared. By this study, parts required periodic maintenance were revealed, fundamental information has been obtained to ensure standardization in bus road durability tests, ensuring adequate vehicle safety has been facilitated.

Keywords: Electric bus, Road durability test, Critical component detection, Vehicle design, Maintenance

Research Article

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1. Introduction

The serious increase in the world population both triggers the search for new sources of energy and also provides the development of energy saving methods. One of these savings methods is public transportation. Public transportation vehicles are vehicles that move on a certain route and enable people to change their position in an order. These vehicles not only benefit the social traffic order, but also bring energy savings. In the literature, it is stated that public transportation vehicles have a positive effect on issues such as traffic problems, fuel savings, human health, environmental concerns, economic contribution and reliability [1]. In order to encourage public transportation, the German government has announced a system where all bus, train and tram services can be used with a low, fixed and single monthly ticket [2]. According to the official statement of the Dutch government [3], vehicles such as buses, trams, subways, taxis, trains can be listed among public transportation vehicles. Among these vehicles, buses are an important type of vehicle that we use frequently in daily life. The fact that the movement constraint is less compared to the rail systems and that it does not cause any disruption in the traffic in terms of length allows the buses to be considered as a preferable vehicle.

The increase in the number of electric vehicles in the first quarter of the 21st century undoubtedly reveals the fact that the awareness of carbon emissions and clean energy has also increased. In the study of Wu and Chen, worldwide electric vehicle sales are seen as 17.000 units in 2010, 774.400 units in 2016 and 3.244.000 units in 2020 [4]. According to the data shared by the International Energy Agency, the number of electric vehicles sold in 2021 is 3 times the number of sales in 2018 [5]. The serious increase in sales volumes suggests that the society is keeping up with this technological transformation and that the transformation will increasingly continue. The transition to electricity in vehicle drive is not limited to passenger vehicles whose sales amounts are specified, but also takes place in commercial vehicles. Considering the usage habits of fossil fuel engines, relatively high-volume engines are used in vehicles such as buses and trucks, and the fuel consumption in these vehicles is also high. Giving electrification priority to vehicles with high fuel consumption in terms of carbon emissions will give more positive results. Switching to the electric version in buses among public transportation vehicles will reduce one of the branches of high fuel consumption and carbon emissions [6]. Moreover, due to large engine displacement, a solution to the noise problem will be found and passenger comfort will be increased. In addition to its technical possibilities, authorities also support electrification in buses. According to Environmental Protection Agency's statement [7] between 2022 and 2026, there will be an electric conversion to school buses in some regions in the USA.

When electric vehicles are examined structurally, they show a great deal of systematic similarity to the existing internal combustion engine versions. Basically, the fact that the drive center is an electric motor and the use of a fixed ratio transmission as a transmission element reveals the structural difference of electric vehicles. However, instead of the fuel tank as an energy source, there is a battery, which is still under development. With the variety of drive system layouts, electric vehicles can move without the need for a mechanical differential, resulting in a lighter structure. Considering the chassis, body design and interior trim, the differences compared to conventional vehicles have been revealed in detail by Işılak [8]. After all these differences, the low number of parts that make relative movements in contact in electric vehicles reduces the friction and wear rate throughout the vehicle. As a result, the need for maintenance is reduced to very low levels.

Moving and active systems get inoperable due to the deformation that occurs over time depending on the period of use and usage conditions. In order to restore the functionality of a part that belongs to the system from a technical point of view, periodic maintenance is required. Since vehicles are also moving systems, they need maintenance according to the structural features of the parts they have. According to the expression of Çırak [9], the aims of maintenance are to eliminate the functional discontinuity caused by malfunctions, to ensure the sustainability of the production plans, and to increase the systematic service time. At the same time, he also shared the time-varying graphs of the frequency of failures in mechanical, electrical, and software systems. In the graphs of the frequency of failures in 3 different groups, it is seen that the mechanical systems have an increasing character according to time, the electrical systems have a fixed value and the software systems have a decreasing character over time. Fault characters of different systems are visualized in figure 1. As can be seen from the image, it is seen that the mechanical system elements have a higher importance in terms of the service life of the product compared to the other elements in terms of damage and maintenance. Therefore, in this study, the test result was evaluated mechanically.

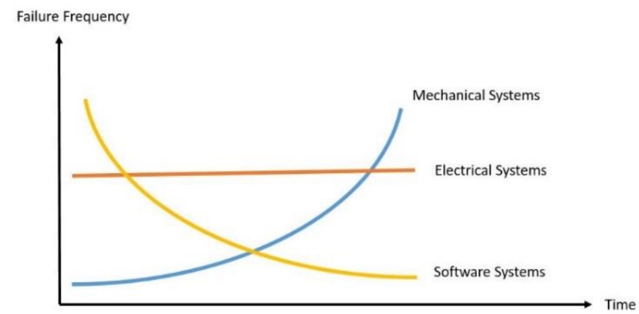


Fig. 1. Failure frequencies of mechanical, electrical, and software systems [9]

In vehicle design processes, there are various types of driving cycles around the world in order to verify the design and determine the consumption values. When looking at the general cycles, Şentürk's study [10] mentions NEDC, FTP-75 and 10-15 Mode cycles and it is seen that there are New York, Manhattan, Orange County, Braunschweig driving cycles for buses. Apart from these cycles, real-time tests are also carried out in order to obtain the situation against real physical conditions in order to increase the design accuracy. Real-time tests enable the design to face unpredictable conditions. As a result of the tests performed, the accuracy rate of the numerical studies is determined and the reliability rate is increased. The conditions of the route where the test will be carried out should be determined in a way that best reflects the realistic conditions in which the designed vehicle will be used. Önçağ et al. [11] obtained real usage data of the fleet consisting of 20 electric buses in the city of Izmir between April 2017 and December 2019 in the city. 27 urban lines were selected for the route where the vehicles were tested, and the lines have a high passenger density and have a maximum average slope of 5%. Gül [12] stated that the bus test route shared between the two centers is 7.5 km with 14 stops, and 6.3 km with 10 stops on the return line. This route has no slope in general, asphalt pavement, and there are 10 traffic lights on the turn line.

Durability test is a technique used to determine the endurance performance of a system against several impacts and driving under different load conditions in a certain period of time. The most common of these can be stated as road durability, shaker method, and numerical analyses (e.g. Finite element analysis). Numerical analyses give reliable clues for future predictions and are effective in taking precautions. In order to determine NVH (noise, vibration, harshness) conditions in road durability, test rigs that save time and cost and allow more sensitive data can be preferred. The effects in real road conditions can be simulated with these mechanisms, which also allow for more detailed examination during the test. In these mechanisms, which have electrical and software support systems, the brackets fixed to the vehicle with electrical, hydraulic or pneumatic drive systems can be transmitted to the drive vehicle body, which the vehicle is exposed to by the road while driving. Apart from the drive systems of the vehicles, vibration and acoustic examinations on the chassis and other auxiliary systems can be carried out and the product condition review can be completed. An example visual of the mentioned test setup is shared in figure 2.

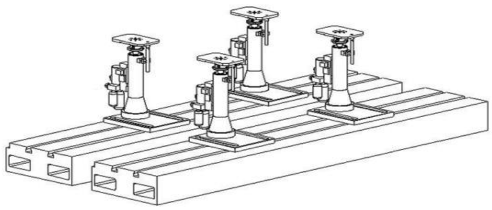


Fig. 2. Shaker bench figure [13]

In this study, it was aimed to determine the parts that are mechanically damaged parts during the road durability test in battery electric buses and to improve the reliability of the vehicle with repair studies. The road durability test results in the vehicles starting to drive at full capacity charge, advancing on the specified route, and taking the vehicle for detailed inspection at the end of the targeted range. The study was carried out with the aim of obtaining the reactions of electric vehicles in real usage conditions, and the obtained results reveal the components that should be considered in the electric vehicle design, taking into account the road conditions, and provide guidance to manufacturers (suppliers), designers and maintenance processes on the basis of electric vehicles.

2. Methodology

In this section, the technical specifications of the tested vehicles are shared. It is explained that road durability test is applied to two separate battery electric buses, approximately 12 m and 8 m long, determining possible problems and making improvement studies. The routes and stages of the road durability test are expressed together with their percentages. During and after the test, evaluation regions are specified according to the units. The working flow is shown in figure 3.

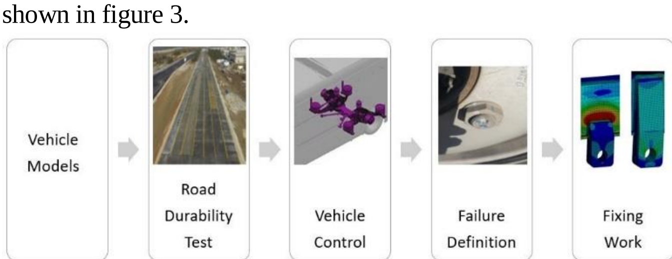


Fig. 3. Stages of the study

2.1 Vehicle Models

The technical data of the vehicle models subjected to the test can be seen in table 1. Both vehicles are low-floor city buses belonging to the M3 category. Basically, although both vehicle models are similar, they differ from each other in terms of length and weight.

Table 1. Battery electric bus models and technical properties

Model Name	Vehicle – 1	Vehicle – 2
Maximum Power	250 kw	230 kw
Range	400 – 500 km	300 – 400 km
Maximum Velocity	80 km/h	70 km/h
Gross Vehicle Weight	18,5 – 21 ton	11 – 12 ton
Total Length	10 – 12 m	8 – 9 m

2.2 Road Durability Test

In vehicle design processes, vehicle leveling tests are applied to verify the design and reveal a reliable product. These tests generally include slope, acceleration, braking, heating-ventilation, cold starting, center of gravity control and vibration. In addition to these, road durability tests are applied in order to dynamically determine the reactions of the vehicles to the road conditions they may expose in real use and to take the necessary precautions. The vehicle, which was put to the test in the road durability test, completes the tour by advancing in stages on the route determined in accordance with the determined speed profile with all the basic equipment attached to the vehicle. The chosen route can be circular or rectangular. In order to test the real conditions, the test route's asphalt, secondary road and broken dirt road, as well as rainy, rainless and mixed conditions in terms of weather conditions are also included in the test process. The test vehicle's completion of the 100.000 km distance in a 4-month period without any damage (this period of time can be longer depending on problems) or error that will prevent the operation, except for special requirements, and the verification of the remedial applications for the problems that occur, at a distance of 25.000 km, shows that the test has been completed successfully. This is the shortened and scaled version of 1.000.000 km road durability test. The road conditions are shown in figure 4, a sample route from the test is shown in figure 5, and distribution of road conditions on the route is shown in figure 6.

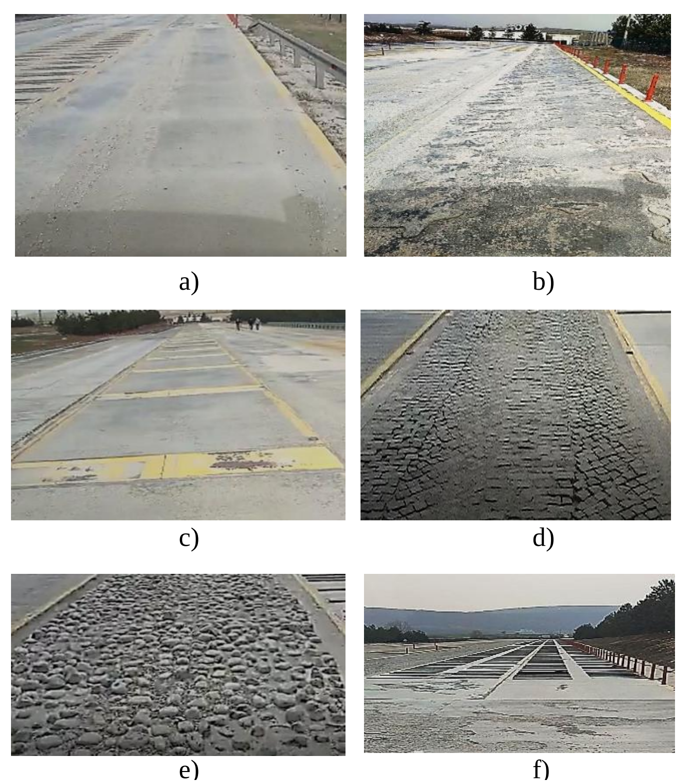


Fig. 4. Road durability conditions:
a) Irregular Wavy Way, b) Irregular Bumpy Way,
c) Regular Metal Pot-holed Way, d) Cobblestone Pavement Way,
e) Boulder Way, f) Regular Asymmetric, Metal Pot-holed, and Protruding Way

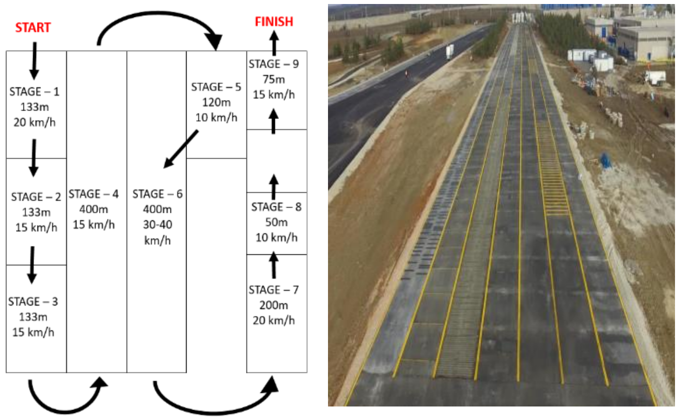


Fig. 5. Test Route (left) Illustration (right)

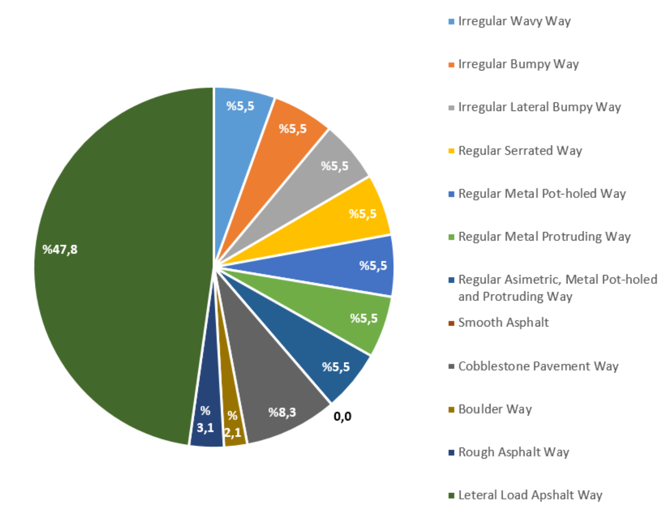


Fig. 6. Distribution of test route conditions

During the test process, vehicle controls are carried out daily before and throughout the test. In this process, the test and necessary improvement work are completed by following the 6 stages shared below. This study includes the first 3 stages of the test stages.

Road durability test stages:

- Road test
- Reporting of problems
- Resolving the problem
- Communicating the problem to responsible
- Follow-up of the solution process
- Examination

Road durability test is a process that aims obtain the reactions of vehicle toward real working conditions. Vehicles can be exposed to the same road conditions with different weights. Considering the same road situation, according to Newton's 2nd law of motion, even the smallest acceleration value will create a big effect with high weight. This big effect can also create different situations such as vibration on the vehicle. Therefore, the condition of the vehicle under different payloads should also be considered. The loading rates of the vehicles during the test can be seen in figure 7 and real-time illustrations can be seen in figure 8.

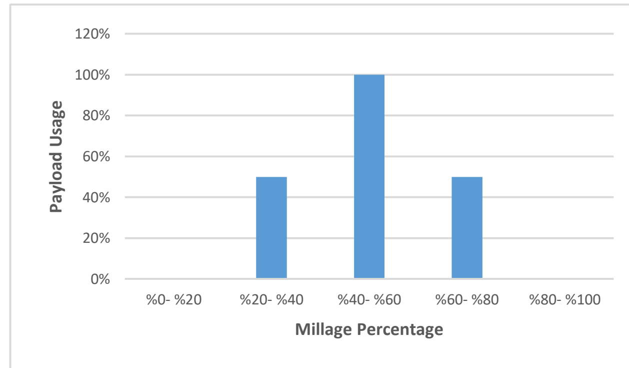


Fig. 7. Load distribution on test process

Fig. 8. Load applied vehicle illustrations

The examinations and evaluations to be made during the test process vary according to the type of problem and the subject it is related to. In the road durability test, the examinations to be made on the vehicle are distributed according to the personnel of the relevant department and their competence. Otherwise, examination and evaluation with sufficient accuracy will not be possible. In the mechanical evaluation of the tests, Body, Chassis and Powertrain departments were included in the examination phase, respectively. Inspection regions according to the sections are given in table 2.

Table 2. Mechanical control responsibilities of departments

Body	Chassis	Powertrain
Visual body control while the vehicle is on the lift	Steering connection	Drive axle connection fracture and wear control
Seat connections	shock absorber connections	Drive axle interconnection control
Rear axle connections	Leaf spring connections	Drive axle motor connection fracture and wear control
Rear axle carrier profile	Suspension sounds	Motor connection brackets bolt control
Front axle area		Motor connection brackets fracture control
Rear anti-roll bar		Body connection brackets bolt control
Distance between front axle profile and ground		Elastic wedges wear
Battery connections		Motor wedge connection bolt control
		Motor sound, noise, performance control

As seen in table 2, divisions participate in the mechanical observation of the test vehicles on 3 different main subjects. Since electric vehicles have fewer moving parts, control needed parts are more restricted. Body section pays attention to components that are connected to frame of the vehicle. Chassis section has also same attitude however this section observes dynamic parts when body section stays on the static parts. Powertrain section join to test process on drive parts of vehicle such as e-motor, differential, and transmission.

Here are some of the specific parts examined during testing:

- Air compressor mounting bracket and wedge
- Steering mechanism
- Steering – frame assembly brackets
- Drive axle anti-roll bar right and left brackets
- Drive axle upper and lower control arms
- Front axle upper and lower control arms
- Dashboard assembly bolts
- Door mechanism

Table 3. Damage assessment of Vehicle – 1

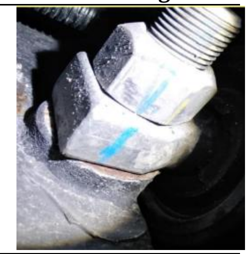
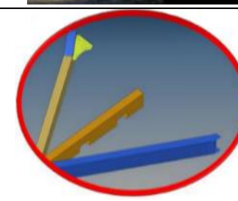
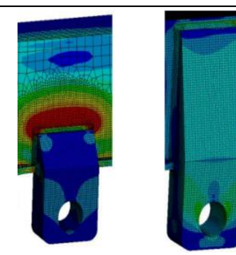
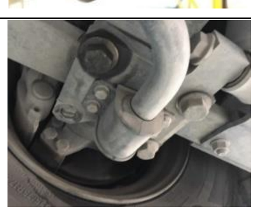
Damage	Fixing work	Related Figure
Excessive flexing of the rear axle connection bracket	Damage was prevented, loss of torque and high deflection were eliminated by using a solid designed connecting bracket.	
Corrosion and crack formation in the weld area of the rear axle body joint	Brackets were added to the support bars for load homogenization and increasing rigidity.	
Deformation occurred due to casting gaps in the body connection bushing of the rear axle.	The problem was eliminated by creating solid part from billet with the machining method.	
Fracture of the anti-roll bar bracket	Shear stress was reduced by increasing the bracket contact area.	

Table 4. Damage assessment of Vehicle – 2

Damage	Fixing work	Related Figure
Deformation in battery–body connections	A support rod was added to the battery connection. The fatigue strength of the bolt and weld zones in the connection is also taken into account.	 
Torque loss was occurred on front axle left wheel bolts	The friction value on the contact surfaces h as been taken into ac count for safety in dy namic operation. Bolt sizes and contact surf ace roughness were e valuated. Bolt boot v alue increased.	
Torque loss and noise problem were occurred in steering rod bolts	The rigidity of the region has been increased by adding welded parts.	
Deformation and noise problem were occurred in the shock absorber connection bearing	The decrease in the energy absorption ability of the bush was evaluated depending on the material and operating conditions, depending on the usage time. The bushing was changed.	
Bolt breakage was occurred in the leaf spring	The bolt tightening m ethod has been chang ed and a more stable system has been obtai ned against dynamic operating conditions.	
Tearing and crushing were occurred in the drive shaft (cardan) interconnectio n wedge seal	Part was replaced with a seal with higher fatigue and sealing life.	
Torque loss Was occurred in a bolt on dashboard connection points	Tightening torque of chassis connecting bolts increased from 16 Nm to 25 Nm.	
Sound problem around differential	The increase in the gap caused by the deformation between the contacting parts caused the sound problem. The problem was solved in the middle with assembly control and suspension element replacement.	
Sound problem from leaf springs	Due to eccentricity, the leaf spring bush deforms over time. The sound problem has been eliminated by replacing the suspension element and leaf spring.	

3. Conclusions

In this study, the mechanical problems that emerged at the end of the road durability test on battery electric buses were determined and product development studies were conducted. Fully equipped prototype vehicles were subjected to the road durability test, whose route and method were shared, targeting predetermined success criteria. Following the test process was completed, the vehicles were observed by authorized personnel in a suitable environment and mechanically damaged areas were determined. As a result of the mechanical examination, problems such as loss of torque in the connecting bolts, corrosion and damage to the welds, increased rigidity in the anti-vibration parts have occurred. These problems were eliminated with design and production method changes and product reliability has been increased. In light of the situations obtained in the study and considering the dynamic operating conditions in battery electric buses, results that guide preventive maintenance plans depending on usage conditions have been reached. Moreover, these results have also guided new designs and engineering-based repair works that have increased vehicle mechanical reliability.

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Conflict of Interest Statement

The authors declare that there is no conflict of interest in the study.

CRediT Author Statement

Efe Savran: Conceptualization, Methodology, Writing and editing. **Burcu Yıldırım Kılınç:** Data collection, Methodology, Writing and editing. **Umut Çandır:** Industrial supervision, Proof reading. **Fatih Karpat:** Academic supervision, Proof reading

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