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Cost/Performance Analysis of Battery Pack placed in Spare Tire Area for Extending the Range of Hybrid, and Electric Vehicles

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Research Article

Abstract

Electric vehicle sales are increasing rapidly beyond expectations offering many advantages over vehicles with internal combustion engines. The hybrid electric vehicles are often considered a transition between the two due to added advantages of both models. Out of hybrid models, plugin hybrid vehicles have more resemblance to the fully electric vehicles because of the electric range and lower cost per mile. This paper investigates placing a battery pack in the spare tire location to extend the range of any type of electric vehicle. Cost and extended range calculations are performed based on two top selling vehicles that use 16”, 17” and 18” size tires. The volumes of spare tires are calculated and battery packs built with various lithium battery dimensions and chemistries are fit into the calculated area. Results for combinations are demonstrated with battery pack capacity, cost and range. When compared with other chemistries, battery packs built with Li-Ion cells provided more range for the calculated spare tire volume. In addition, results indicate that a sufficient electric range could be achieved for daily driving using the battery pack placed in the spare tire location. Obtained results provide insights on the feasibility of installing battery packs in the spare tire location using various battery chemistries.

Keywords: Battery pack location in hybrid vehicles; Hybrid vehicle conversion; Plugin hybrid vehicle batteries; Spare tire location

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1. Introduction

Technological advances are introduced every single day to our lives. In the transportation industry one of the most forefront of these advances are electric vehicles (EV). There are numerous advantages of electric vehicles that attract potential car buyers such as the opportunity to charge using renewable energy, cost per mile, cost of maintenance, faster acceleration, quieter rides, and tax credits. These advantages lead to an inevitable rise of electric vehicles in various parts of the world. The number of EVs in the world rose from less than half a million in 2013 to more than 11.5 million in 2020 [1]. Every day more and more people start using electric vehicles and this turnout is reflected in the statistics.

There are also some disadvantages of electric vehicles that inhibit their sales. Among them are short driving ranges, lack of widely available charging stations, long charge times, decreasing battery life, and the initial cost of purchase. Some of these are being enhanced by companies through the establishment of faster charging stations and the addition of longer lasting more durable battery cells. In addition, countries provide incentives for drivers to switch from internal combustion engine (ICE) vehicles to EVs. However, these improvements do not fully satisfy drivers and many drivers are reluctant to drive an electric vehicle as they wait for better conditions that will favor electric vehicles.

To a lot of drivers, a hybrid vehicle is an ideal transitional vehicle that consists of an internal combustion engine and an electric motor. The vehicle can transition between the two depending on certain conditions such as state of charge, instant power needs, and cruising speed. A hybrid vehicle suits to circumstances where range is the primary issue. A hybrid vehicle can use an electric motor at low speeds and switch to an internal combustion engine at higher speeds. This paper investigates placing a battery pack in the spare tire location to extend the range of any type of electric vehicle. There are two main types of hybrid vehicles. One of them is the hybrid electric vehicle (HEV) that cannot be charged through an external power source. An HEV holds a small battery pack generally less than 2 kWh which corresponds to around 10 kilometers/6 miles (assuming an average consumption of 19.3 kWh/100 km. This consumption is calculated by taking the average consumption of 121 electric vehicles [2]). Toyota has been the pioneer in hybrid vehicles. These vehicles typically use Nickel Metal Hydride (NiMH) battery chemistry.

The other type of hybrid is the plug-in hybrid vehicle (PHEV) that allows users to charge using household power or public charging stations. A PHEV has a relatively higher battery capacity, which is generally higher than 5 kWh and less than 20 kWh, depending on the make and model. Since plugin hybrid vehicles have higher battery capacity, they also provide more electric powered range generally around 30-60 kilometers/20-40 miles. In addition, PHEV models can use both electric motor and internal combustion engine simultaneously leading to higher performance and quicker acceleration. Due to its many advantages, almost all PHEV models use lithium battery chemistry. There are studies that have researched various battery chemistries for EVs especially lithium batteries [3–6]. One study compares the final state of charge of a battery pack with various battery types and lithium-based batteries lead four other chemistries studied [4].

In order to accelerate the conversion of vehicles with ICE to PHEV, a hybrid to plugin hybrid conversion has been a topic studied in research activities [7–10]. For instance, in a 2007 study, the Illinois Institute of Technology acquired a Ford Escape Hybrid from the City of Chicago to be used as a test platform for this concept. An article has been published about the results of the conversion [11]. Another project was carried out in 2012 by two researchers from the University of Louisville and Western Kentucky University. In this study, a Toyota Prius, which is a hybrid vehicle, was converted into a plugin hybrid vehicle. In studies [12,13] an electric vehicle conversion is applied to internal combustion engine vehicles; however, battery pack placement is not articulated. In research [14] mechanical design and placement options are studied. This study found that high voltage components should be placed outside the passenger compartment due to safety issues.

In the study [15], various battery configurations are studied and comfort levels are compared. Rigid and flexible connections of battery packs are investigated in [16]. In another study battery pack at various heights inside a commercial van is investigated [17].

To extend the range driven by electric, some companies offered a conversion kit to hybrid owners. Conversion kits include a lithium battery pack and other required electronics, such as Battery Management Systems (BMS); this is located in the trunk of the vehicle. This extra battery pack makes the trunk smaller. From the above studies, it can be inferred that various works are conducted converting a vehicle to hybrid or extending the electric range. However, there is a gap in literature studies about utilizing spare tire locations for extending electric range. This paper investigates placing a battery pack in the spare tire location to extend the range of any type of electric vehicle. The main contributions of this work can be summarized as:

•Various battery pack configurations utilizing spare tire locations are investigated.

•Approximate extended ranges acquired by relative configurations are provided.

•Insights on the feasibility of conversions are presented.

• Provide the number of cells that can be used for mass distribution in electric vehicles.

2. Materials and Method

Most sedans and SUVs use 16”, 17” and 18” tires and have a spare tire area in the trunk. The volume of this area can be calculated and the approximate size of a battery pack can be determined. Similar to Liquefied petroleum gas (LPG) conversion kits, where LPG tanks are shaped as round tanks that can fit in the spare tire’s location as shown in Figure 1, the battery pack can be shaped as a round spare tire. Using this space to place a battery pack will eliminate the use of a spare tire; however, this can be overcome by a tire repair kit, which comes as a standard in many brand new cars.

Fig. 1. An LPG tank that fits in the spare tire location (18)

For model year 2021, Toyota RAV4 and Toyota Camry are among the top selling vehicles in the U.S. (19). Therefore, tire sizes for these vehicles are considered for this work. Tire sizes for Toyota RAV4 are 225/65R17, 225/60/18, and 235/55/19. For Toyota Camry, tire sizes are 205/65/16, 215/55/17, and 235/45/18. Considering the spare tire storage area will have a volume of a tire, Eq. (1) and (2) are used to calculate the volume required for a battery pack.

$$V = A \ x \ h \qquad (1)$$

where V stands for volume, A for base area, and h for height.

$$A = \pi \ x \ r^2 \qquad (2)$$

where r is the radius.

Table 1 shows the spare tire volume calculations for six different tire sizes. Tire size of 235/55/19 offers the largest area for a potential battery pack providing 101319 cm^3.

Table 1. Spare tire volumes for various tire sizes

Model	Tire Size	Radius (cm)	Area (cm^2)	Volume (cm^3)
Camry	205/65/16	33.645	3554	72866
Camry	215/55/17	33.415	3506	75379
Camry	235/45/18	33.435	3510	82490
RAV4	225/65/17	36.215	4118	92659
RAV4	225/60/18	36.360	4151	93403
RAV4	235/55/19	37.055	4311	101319

Table 2. Battery specifications of two major electric vehicle manufacturers

	Make 1	Make 2
Battery Capacity (kWh)	42.2	78
Useable Capacity (kWh)	37.9	73.5
Length (mm)	160	218
Width (mm)	90	150
Height (mm)	18	15
Volume (m^3)	0.2592	0.4905
Weight (kg)	275	479
kWh per (1 m^3)	162.81	159.02

Table 2 presents battery specifications of two major electric vehicle manufacturers. Based on data in Table 2, it can be assumed that battery packs are manufactured with approximately 160 kWh per 1 m^3 capacity to volume ratio.

As far as forms, 18650 (18 mm diameter, 65 mm height) cylindrical Lithium-Ion (Li-Ion) battery, introduced in 1994, is one of the most available and cost effective lithium batteries in the world. This is partly due to 18650 cells being used in laptop batteries, therefore supply in this form is more common than others. Relatively newer 21700 (21mm diameter, 70mm height) cylindrical Li-Ion batteries provide higher discharge capacities and energy by 51% compared to 18650 cells. In addition, 21700 cells can have approximately 6% higher specific energy and energy density [6] Similarly, 22650 and 26650 cylindrical batteries are introduced to the market. On the hand, there are prismatic lithium cells that are enclosed in aluminum or steel casing. Prismatic cells can be manufactured in larger casing and provide more opportunity for cost reduction [20].

Lithium batteries come in various chemistries as well as forms. Li-Ion, Lithium Iron Phosphate ($LiFePO_4$), Lithium Titanate (LTO) (grouped based on nominal voltages) are widely available battery chemistries in the electric vehicle market.

In this paper Li-Ion, $LiFePO_4$, LTO battery chemistries are investigated in one or more of 18650, 21700, 22650, 22650 and prismatic dimensions. Dimensions are chosen from the commonly sold battery dimensions on the market. Researched combinations of battery chemistry and dimensions can be found in Table 4.

26650 battery has a diameter of 26 mm and height of 65 mm. Similarly, 22650 battery has a diameter of 22 mm and height of 65 mm. Volume of a single 18650 cell is shown in Table 3.

Table 3. kWh per m^3 calculations

Width (mm)	18
Height (mm)	65
Radius (cm)	0.9
Area (cm^2)	2.543
Height (cm)	6.5
Volume (cm^3)	16.53
Volume (m^3)	0.00001653
Weight (gr)	43-50

18650 battery has a height of 65 mm and spare tire location for 16" has a height of 205 mm. Therefore, three layers of batteries can be mounted in the spare tire location. First, the number of batteries on each layer needs to be calculated. A fitting tool is used similar to the reference [21] for finding the maximum number of 18650 cells in a given area. Figure 2 shows a sample image by the tool fitting 18650 cells (smaller circles with 18mm diameter) into 631.9 mm (larger circle with diameter of 16" wheel). There are 958 batteries on this image.

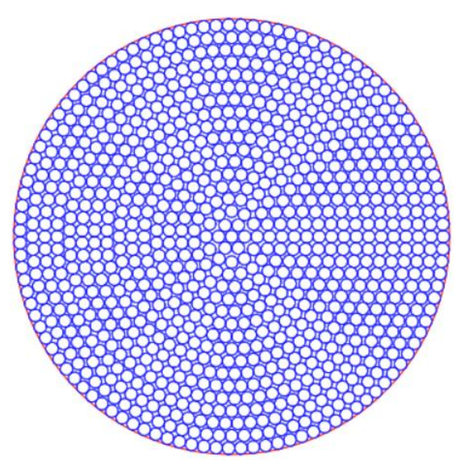

Fig. 2. An example of fitting 18mm diameter cells into 631.9 mm (diameter of 16" wheel): 958 batteries on each layer

Table 4. kWh per m^3 calculations

	Dimension 1	Dimension 2	Dimension 3 (width x height x depth)
Li-Ion	18650 (10.8 Wh)	21700 (18.5 Wh)	Prismatic (8.1 Wh) (34 x 49 x 11 mm)
$LiFePO_4$	18650 (1.1Wh)	26650 (8 Wh)	Prismatic (64 Wh) (71 x 178 x 28 mm)
LTO	18650 (3.12 Wh)	22650 (4.8 Wh)	Prismatic (75.9 Wh) (130 x 205 x 20 mm)

Table 5. Calculations showing the number of 18650 cells that can fit in spare tire location

Configuration number	Tire Dimensions	Volume (m^3)	Number of 18650 cells (Theory)	Number of 18650 cells (Calculated)	Calculated capacity (kWh)	Range (km / miles)
1	205/65/16	0.0729	3976	3264	35.25	176/109
2	215/55/17	0.0754	4560	3219	34.77	173/108
3	235/45/18	0.0825	4990	3219	34.77	173/108
4	225/65/17	0.0927	5606	3780	40.82	204/126
5	225/60/18	0.0934	5651	3810	41.15	205/127
6	235/55/19	0.1013	6129	3960	42.77	213/132

Table 6. Recalculated capacity with 160 kWh/1m^3

Configuration number	Calculated capacity (kWh)	Recalculated capacity, re ducing to 160 kWh/m^3 (k Wh)	Percentage left after losing capacity in casing and the rmal management (%)
1	35.25	11.7	33
2	34.77	12.1	35
3	34.77	13.2	38
4	40.82	14.8	36
5	41.15	14.9	36
6	42.77	16.2	38

Figure 3. presents a 3D drawing of 18650 cells placed in three layers into the spare tire location.

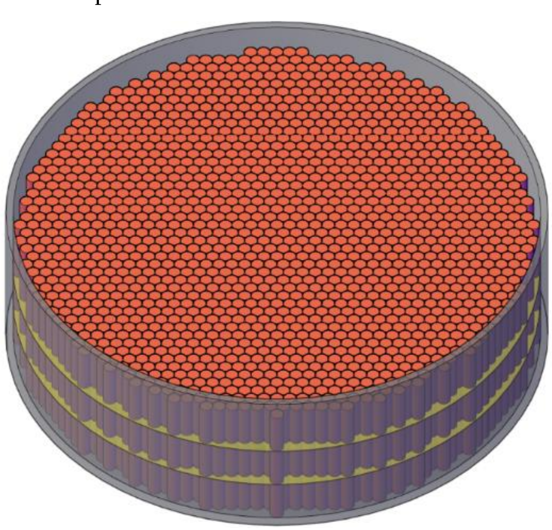

Fig. 3. Cells placed in three layers into the spare tire location

Similar procedure is performed for 21700, 22650, and 26650 cylindrical batteries. Figure 4 shows fitting prismatic cells into 225/60/18 spare tire location.

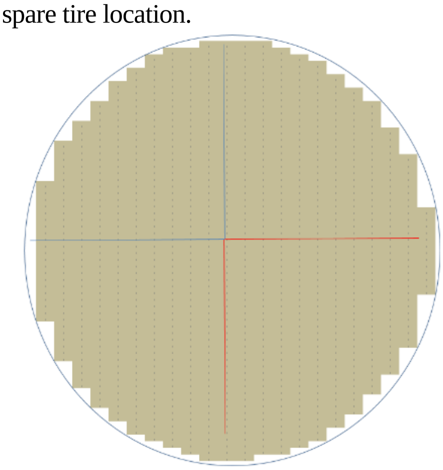

Fig. 4. An example of fitting 11 x 34 mm prismatic Li-Ion cells into 72.72cm (diameter of 225/60/18 tire): 1078 batteries on each layer of total four layers

For simplicity of this paper, details of calculations and figures are shown only for 18650 cylindrical batteries. For the rest of the batteries, results are shown in Tables 5-6.

Extended ranges are calculated based on an average consumption of 19.3 kWh /100 km as mentioned in the introduction section.

Due to different energy density/volume ratios of batteries used by various vehicle manufacturers listed in Table 2, an average of 36% is assumed for percentage left after losing capacity in casing and thermal management using values in Table 6.

For calculating approximate cost of all battery chemistries, Li-Ion battery price of $137 for the year 2020 is used [22]. The price given is an approximate cost of battery excluding labor. It should be noted that general trend in Lithium battery costs is declining. As more manufacturers join in the supply chain, lithium battery prices could be even lower in the coming years.

3. Calculation Results

Approximate cost and extended ranges were calculated for each of the battery pack built with respective cells. Table 7 shows the results for extended range acquired with a battery pack built with Li-Ion cells in 18650 form.

Table 7. Approximate cost and extended ranges using 18650 Li-Ion cells with 10.8 Wh capacity per cell

Conf. number	Calculated capacity (kWh)	Recalculated Capacity (kWh)	Approx. Cost ($)	Range (km/miles)
1	35.25	12.7	1739	66/41
2	34.77	12.5	1715	65/41
3	34.77	12.5	1715	65/41
4	40.82	14.7	2013	76/48
5	41.15	14.8	2029	77/48
6	42.77	15.4	2109	80/50

According to the Table 7, 16” tire can provide 12.7 kWh of energy delivering extended range of 65 km or 40 miles. As the tire size increase, battery capacity increase reaching a maximum range of 80 km or 50 miles. Table 8 presents the results for a battery pack built with 21700 Li-Ion cells.

Table 8. Approximate cost and extended ranges using 21700 Li-Ion cells with 18.5 Wh capacity per cell.

Conf. number	Calculated capacity (kWh)	Recalculated Capacity (kWh)	Approx. Cost ($)	Range (km/miles)
1	29.49	10.6	1454	55/34
2	43.57	15.7	2149	81/51
3	43.68	15.7	2154	81/51
4	51.34	18.5	2532	96/60
5	51.73	18.6	2551	96/60
6	53.72	19.3	2650	100/63

According to the Table 8, spare tire location for 235/55/19 tire can provide 19.3 kWh delivering the longest extended range of 100 km or 63 miles. Table 9 presents results for battery pack built with prismatic Li-Ion cells.

Table 9. Approximate cost and extended ranges using Prismatic Li-Ion cells with 8.1 Wh capacity per cell.

Conf. number	Calculated capacity (kWh)	Recalculated Capacity (kWh)	Approx. Cost ($)	Range (km/miles)
1	29.87	10.8	1473	56/35
2	28.97	10.4	1429	54/34
3	29.16	10.5	1438	54/34
4	34.73	12.5	1713	65/41
5	34.93	12.6	1723	65/41
6	36.35	13.1	1793	68/43

Tables 10 through 12 provide calculation results for $LiFePO_4$ cells. According to Table 10, range acquired by $LiFePO_4$ cells is relatively short. This is attributed to the capacity of a single $LiFePO_4$ cell.

Table 10. Approximate cost and extended ranges using 18650 $LiFePO_4$ cells with 1.1 Wh capacity per cell.

Conf. number	Calculated capacity (kWh)	Recalculated Capacity (kWh)	Approx. Cost ($)	Range (km/miles)
1	3.59	1.3	177	7/4
2	3.54	1.3	175	7/4
3	3.54	1.3	175	7/4
4	4.16	1.5	205	8/5
5	4.19	1.5	207	8/5
6	4.36	1.6	215	8/5

Table 11. Approximate cost and extended ranges using 26650 LiFePO4 cells with 8 Wh capacity per cell.

Conf. number	Calculated capacity (kWh)	Recalculated Capacity (kWh)	Approx. Cost ($)	Range (km/miles)
1	12.43	4.5	613	23/14
2	12.26	4.4	605	23/14
3	12.29	4.4	606	23/14
4	14.42	5.2	711	27/17
5	14.52	5.2	716	27/17
6	15.12	5.4	746	28/18

Table 12. Approximate cost and extended ranges using Prismatic LiFePO4 cells with 64 Wh capacity per cell.

Conf. number	Calculated capacity (kWh)	Recalculated Capacity (kWh)	Approx. Cost ($)	Range (km/miles)
1	9.86	3.5	486	18/11
2	9.47	3.4	467	18/11
3	9.54	3.4	470	18/11
4	11.26	4.1	556	21/13
5	11.46	4.1	565	21/13
6	11.90	4.3	587	22/14

Tables 13-15 present results for various dimensions of LTO for various tire sizes.

Table 13. Approximate cost and extended ranges using 18650 LTO cells with 3.12 Wh capacity per cell.

Conf. number	Calculated capacity (kWh)	Recalculated Capacity (kWh)	Approx. Cost ($)	Range (km/miles)
1	10.18	3.7	502	19/12
2	10.04	3.6	495	19/12
3	10.04	3.6	495	19/12
4	11.79	4.2	582	22/14
5	11.89	4.3	586	22/14
6	12.36	4.4	609	23/14

Table 14. Approximate cost and extended ranges using 22650 LTO cells with 4.8 Wh capacity per cell.

Conf. number	Calculated capacity (kWh)	Recalculated Capacity (kWh)	Approx. Cost ($)	Range (km/miles)
1	10.45	3.8	516	20/13
2	10.30	3.7	508	19/12
3	10.32	3.7	509	19/12
4	12.11	4.4	597	23/14
5	12.23	4.4	603	23/14
6	12.69	4.6	626	24/15

Table 15. Approximate cost and extended ranges using Prismatic LTO cells with 75.9 Wh capacity per cell.

Conf. number	Calculated capacity (kWh)	Recalculated Capacity (kWh)	Approx. Cost ($)	Range (km/miles)
1	8.20	3.0	404	16/10
2	8.05	2.9	397	15/9
3	8.12	2.9	401	15/9
4	9.56	3.4	472	18/11
5	9.64	3.5	475	18/11
6	9.87	3.6	487	19/12

4. Discussion

Results indicate that battery dimensions and chemistries play an important role in the extended range provided by the battery pack. For instance, Li-Ion cells provide better range than $LiFePO_4$ and LTO cells. It is observed that the energy density of the cells greatly affects the resulting battery pack. Moreover, cylindrical-shaped cells, such as 18650 and 21700 present a placement with less space between cells. Since the spare tire location is round by nature, more round cells can fit into it, yielding to a higher battery capacity. Prismatic cells did not perform well due to the limited number of cells that fit into the proposed location. On the other hand, when electric vehicles are designed, areas such as beneath the rear seats or the floorboard under the passenger compartment are widely used. These locations are more spacious than the spare tire location making it easier to fit various cell dimensions in those spaces while meeting space requirements. In addition, battery pack mass distribution and center of gravity could be better adjusted. However, in this study, a spare tire location is investigated and a major, costly modification to the vehicle body is avoided.

Investigated $LiFePO_4$ 18650 cells have low energy capacity. Therefore, the resulting range is comparatively shorter. LTO cells are relatively new and capacity offerings are limited. Therefore, with the dimensions tested in this study, this chemistry did not perform well. According to calculation results, most driving range is acquired with 235/55/19 tire size. This yields to a battery pack capacity of 53.72 kWh before integrating power electronics. When thermal management and other supplementary hardware are installed, a capacity of 19.3 kWh is achieved. This configuration costs nearly 2650 US dollars providing 100 kilometers or 63 miles. U.S. drivers travel 29.2 miles (47 km) daily [23]. All 18 possible battery packs built with Li-Ion cell combinations provide more range than the average trip mentioned in the study.

Results show that a vehicle with a 19” spare tire is capable of holding a 19.3 kWh battery (with 21700 Li-Ion) in the spare tire area, providing an extended range of 100 kilometers/63 miles which is adequate for an average daily commute. Depending on the design limits, an 18.8 kWh battery can be charged in 6-8 hours using a 230 V socket, and in 13-16 hours using a 110 V socket. When compared to a gas-powered vehicles, EVs are cheaper to maintain and cost per mile is less. Assuming an equal distribution, 16000 km/10000 miles a year is approximately 44 km/27 miles a day, which can be driven by electric power of a plugin hybrid with any of the battery configurations in Tables 7, 8 and 9. Substituting travel by electric range instead of distance traveled by ICE vehicles will eventually result in remarkable reductions in CO_2 emissions.

5. Conclusion

In this study, the potential use of spare tire locations of various sizes for battery pack placement is investigated. Tire sizes of the two most commonly sold vehicles in the U.S. are selected for cost and range calculations. Battery packs that fit into the spare tire locations are demonstrated through various lithium battery dimensions and chemistries. Approximate extended ranges acquired by relative configurations are calculated. According to the calculations, the following conclusions are drawn:

- The energy density of the cells greatly affects the resulting battery pack.
- Battery packs built with Li-Ion cells provided more extended range than $LiFePO_4$ and LTO cells for the calculated spare tire location dimensions and battery cell form combinations.
- The cylindrical cells provided higher capacities than prismatic cells for the majority of the combinations in the study.
- A sufficient extended range could be achieved for daily commutes using the spare tire location for a battery pack.

This work provides insights on the feasibility of installing battery packs in the spare tire location using various battery chemistries. In addition, battery packs can be used for balanced weight distribution. Converting a hybrid vehicle to a plugin hybrid vehicle is a transition to a more sustainable future to realize the environmental and cost benefits of electric vehicles. This work includes only a certain number of battery configurations. Batteries are constantly improving, and so are the efficiency, and related numerical values. This study presents possible battery pack configurations into a spare tire's location, which makes the spare tire unavailable for the car. However, the lack of a spare tire can be mitigated by a tire repair kit which comes as a standard in many new cars. In addition, roadside assistance is accessible in many parts of the world. Future work can be an actual implementation of the suggested method on a test vehicle and acquire data from the research.

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Conflict of Interest Statement

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

CRediT Author Statement

Mustafa Nurmuhammed: Writing-original draft, Validation, Data curation,
Teoman Karadağ: Conceptualization, Supervision, Formal analysis

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