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Study of Electric Vehicle Range Loss Associated with Replacement Tires

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Buildings and Transportation Science Division

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1. INTRODUCTION

The FuelEconomy.Gov website has become a trusted source for consumers to find information pertaining to fuel economy and fuel-efficient vehicles. As electric vehicles are an increasingly important part of the light-duty fleet in the U.S., there is a need to expand the website content that is targeted to electric vehicle (EV) owners.

This report addresses a concern about which several anecdotal reports have come to the attention of the website support staff. Specifically, some EV owners have observed a sudden, noticeable decrease in their all-electric range when they replace the tires that came with their vehicle when it was new. This change has reportedly led some owners to take their vehicles to the dealership service department out of concern that something had gone wrong with the vehicle.

1.1 VEHICLE DRIVING LOSSES

All vehicles need to overcome energy losses during driving. Many consumers are familiar with the concept of aerodynamic losses but may not be as familiar with other losses that the vehicle experiences. In general, losses can be grouped and measured according to their dependence on vehicle speed. During the process of vehicle emissions and fuel economy certification, these losses are measured by conducting what is known as a coast-down test. The coast-down test involves driving a vehicle at highway speeds on a test track under controlled conditions, then allowing the vehicle to coast to a low speed without the use of braking (whether by friction brake or the use of regenerative braking on EVs). The driving losses that the vehicle experiences are responsible for slowing the vehicle as it coasts to a lower speed. Data are collected during this test that allow measurement of these losses. [1] The losses are grouped according to their relationship with vehicle speed. Some losses are constant regardless of vehicle speed, some are proportional to speed, and some are proportional to the square of speed. These losses are characterized by three coefficients, F0, F1, and F2, which are also sometimes referred to as A, B, and C coefficients. Figure 1 shows an example of the effects of these losses for a 2022 Hyundai Ioniq 5 battery electric vehicle (BEV). The bottom blue bar shows the effect of losses that are constant at all vehicle speeds (F0). Losses that increase in proportion to the vehicle speed (F1) are shown by the orange bars, and the topmost gray bar shows the losses that increase in proportion to the square of vehicle speed (F2). The units of the losses are newton-meters per meter traveled (Nm/m). Readers may recognize Nm as a unit of torque; it is also equivalent to a unit of energy, the Joule (J). Thus, the unit of Nm/m expresses a loss of energy per unit of distance travelled by the vehicle. At 20 MPH, the F0 losses account for 69% of the total driving losses of the Ioniq 5. Because the F1 and F2 losses increase as speed increases, the F0 losses account for only about 15% of the total losses at 80 MPH. The result of this trend is that changes in the F0 losses are more significant in terms of energy use at low speeds more typical of city or urban driving than at higher speeds typical of highway driving. For example, if the F0 losses increase 10%, it results in the total driving losses for the Ioniq 5 at 20 MPH increasing by 5%. At 80 MPH the same 10% increase in the F0 term increases the total driving losses by only 1.1%.

The interaction of a vehicle's tires with the roadway results in driving losses. There are several effects that come into play. These effects include, for example, deformation of the tire side-walls as the tire departs from roundness to a nearly flat surface at the tire/road interface and deformation of the tread blocks resulting from acceleration, deceleration, and cornering forces. Although some of these effects have a dependence on driving speed, the overall tire loss is usually considered to be independent of vehicle speed. [2] [3] It is therefore a part of the F0 term losses.

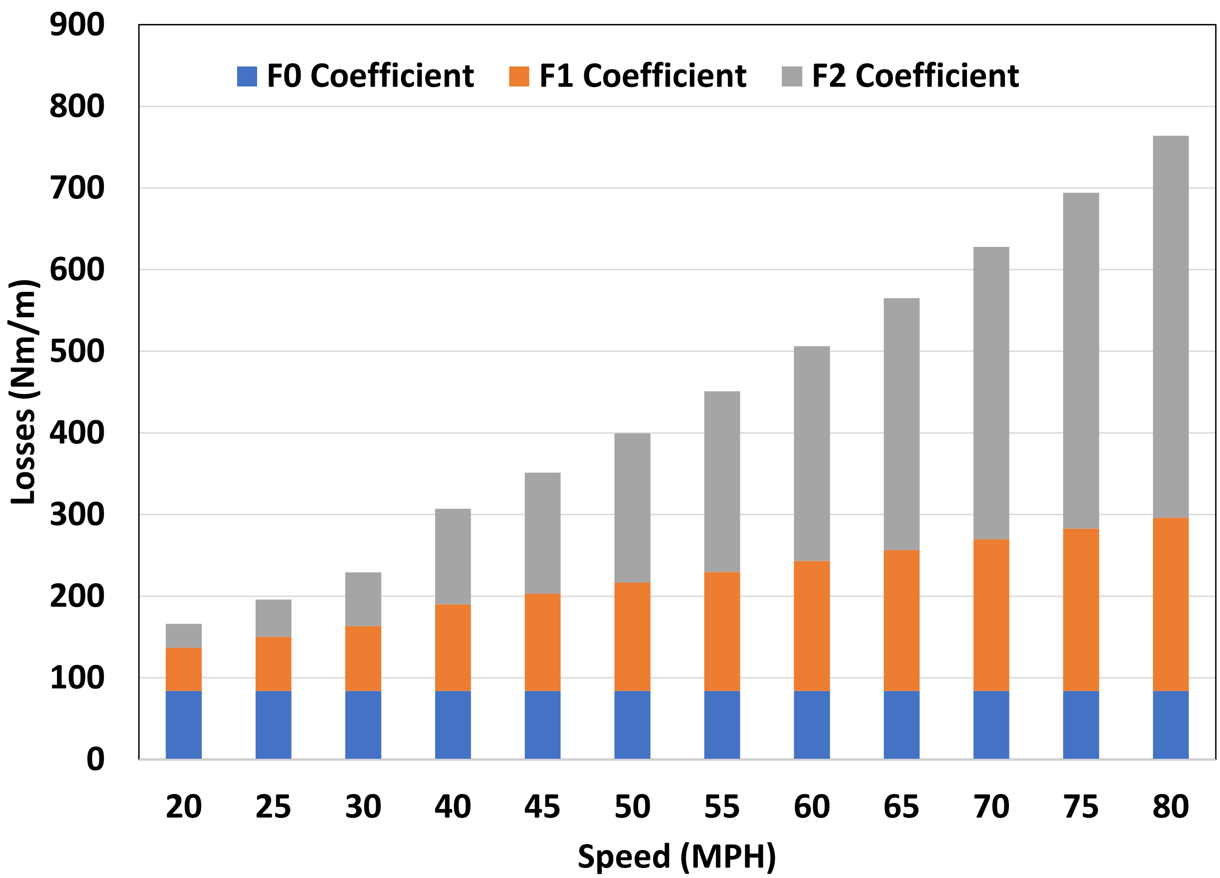

Figure 1. Driving losses versus speed for a 2022 Hyundai Ioniq 5 broken down by F0, F1, and F2 loss terms.

1.2 TIRE ROLLING FRICTION METRICS

As discussed in section 1.1, vehicle driving losses including those attributable to the tires are measured using a coast-down of a vehicle on a test track. Tire friction metrics are measured using a different test of the tire itself. This test uses a tire mounted on a laboratory test apparatus. The apparatus applies a force to the tire to simulate the weight of a vehicle and measures the friction losses as the tire interacts with a roller that simulates the road. There are several similar standardized tire friction tests that offer different tradeoffs in terms of results. [4] [5] [6] The test that is being adopted in regulatory standards for tire efficiency in the United States and Europe is the ISO 28580. [4] Rolling resistance is defined in ISO 28580 as the loss of energy per unit of distance travelled. This definition is consistent with R0 determined from vehicle coast-down testing as discussed in section 1.1. All tires incur greater rolling losses as the vehicle weight increases, so it is useful to define a metric for a tire's rolling losses that is independent of vehicle weight; the rolling resistance coefficient, C_R, is defined as the ratio of the rolling resistance to the load on the tire. [4]

1.2.1 Range of C_R Variability in New Tires

Tires exhibit different C_R values because of differences in their design and construction. For example, tires designed primarily for efficiency (low rolling losses) have different construction than tires designed primarily for high performance applications, and so forth. Differences in construction such as the stiffness and height of the sidewall, compounding of the rubber, tread pattern design, and others cause differences in C_R. [3]

The California Energy Commission (CEC) conducted tire tests to support development of a tire efficiency regulatory framework. [7] The CEC report characterized tires as belonging to one of three groups: OEM tires, efficient tires, and replacement tires. OEM (original equipment manufacturer) tires are those that are original equipment on new cars purchased from the manufacturer. Efficient tires are those that are designated as efficient by the tire manufacturer. Importantly, this designation is not currently supported by an objective performance test in the US. Replacement tires are those that are available for purchase by consumers to replace their OEM tires when needed. The CEC test program found that the average C_R values for OEM tires were lower than those of either efficient tires or replacement tires, as shown in Figure 2. The units of C_R are newtons per kilonewton (N/kN). These units express the tire rolling loss (in Newtons) for every thousand Newtons of vehicle weight.

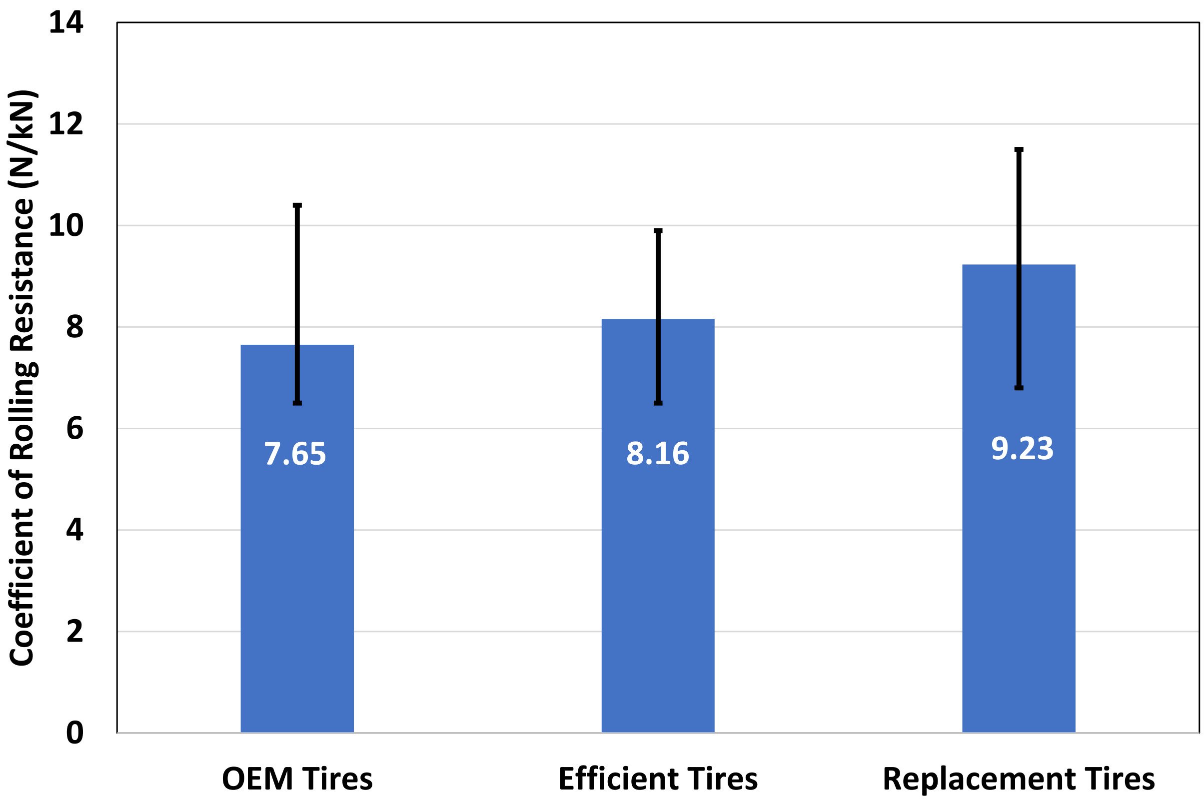

Figure 2. Average C_R values as reported by the CEC. Range bars are the approximate range from maximum to minimum within each category.

The CEC results showed that although it is possible that a consumer could select an efficient or replacement tire that is as efficient as the OEM tire for their car, there is a higher likelihood that replacement tires, whether or not marketed as efficient, will be less efficient than their OEM tires. There is not currently a consistent and objective tire efficiency rating system in the U.S. to support consumers in a decision about which replacement tires to select.

The U.S. National Research Council (NRC) also examined available data on tire rolling resistance. [8] Data on 36 tire models tested by the EPA in 1982-1983 provided coefficients of rolling resistance ranging from 9.8 N/kN to 11.3 N/kN. Data provided to the National Highway Transportation Safety Agency (NHTSA) by Michelin reported the C_R for 9 OEM and 37 replacement tires from several manufacturers. The 9 OEM tires had an average C_R of 9.1 N/kN, falling within a range of 8.3 to 10.5 N/kN. The replacement tire C_R values ranged from 8.7 to 14.3 N/kN and averaged 11.2 N/kN. These results agree with the CEC study in finding that OEM tires generally have a lower C_R than replacement tires. The CEC results show that replacement tires have a 20.7% higher C_R than OEM tires on average. The Michelin data show this difference to be 23%.

1.2.2 Tire Wear Effects on Rolling Resistance

Since deformation of the tread under load is a contributor to rolling losses, it is not surprising that these losses change as the tread is worn by the roadway. For this report, the term "worn" means that tires have worn to the point where they should be replaced. An analysis of the C_R and tread depth of new tires showed that a 22% decrease in tread depth would produce a reduction in C_R of approximately 10%. [8] A study conducted in 1980 concluded that C_R declines by an average of about 20% over the tread life. [2] Tread life is typically tens of thousands of miles; since the average consumer drives about 12,000 miles per year, tires do not normally need to be replaced more often than every two to three years. Gradual increases in BEV range resulting from the slow decline of C_R over an extended period are not likely to be noticeable to most consumers.

2. VEHICLE DRIVING LOSS MODELING

Estimating the driving losses that a vehicle will encounter at steady speeds on flat, straight roadways is straightforward. In this case, the driving conditions are similar enough to the driving conditions specified for vehicle coast down tests to allow the F0, F1, and F2 coefficients discussed previously to be used to describe the vehicle losses. However, conditions that depart significantly from the coast down conditions can also impact vehicle losses. These conditions could include, for example, unusually rough roadway surface, foul or extreme weather conditions, tires with incorrect pressurization, and more.

The coefficients that describe vehicle driving losses are available to the public from the EPA website. Data for BEVs from model year 2022 were used for this study. [9] Calculation of the vehicle driving losses using the F0, F1, and F2 coefficients was conducted according to equation 1. In this equation S represents the vehicle speed in miles per hour (MPH) and L_D represents the total driving loss at a given speed.

$$L_D = F0 + (F1 * S) + (F2 * S^2) \qquad \textit{Equation 1}$$

A previous study used these coefficients and other publicly accessible data to estimate the range of model year 2022 BEVs when they are driven at a range of steady speeds, such as would be the case during extended highway driving. This methodology is described in detail in a paper published through SAE International. [10] The estimated range results of the previous study are being used to support the current investigation of the impacts of replacement tires on BEV range.

2.1 APPARENT C_R OF MODEL YEAR 2022 BEVS

Records submitted to the Environmental Protection Agency (EPA) do not always list the specific tires provided by the manufacturer for new cars. Thus, it is impractical to match the C_R from tests conducted on tires to the R0 coefficient determined during coast down tests for emissions and fuel economy certification. With the simplifying assumptions that the entirety of the F0 losses result from tire friction and that the equivalent test weight is a reasonable surrogate for curb weight, C_R can be estimated based on publicly available information. For the purposes of this study, C_R estimated in this way is termed the apparent C_R to distinguish it from the result of an ISO 28580 rolling resistance measurement. This calculation is shown in equation 2. In this equation, C_{RA} is the apparent C_R measured in N/kN, the loss coefficient F0 is measured in N, and the equivalent test weight is measured in kg.

$$C_{RA} = \frac{F_0}{(ETW * 9.81)} * \frac{1000}{4} \qquad \textit{Equation 2}$$

C_{RA} results for model year 2022 BEVs are shown in Figure 3. The minimum, maximum, and median values were produced by the Hyundai Ioniq 5, the Tesla Model 3 Performance AWD, and the Nissan Leaf, respectively. Two other individual vehicles of interest were selected: the Ford F150 Lightning Platinum 4WD and the Chevrolet Bolt EV.

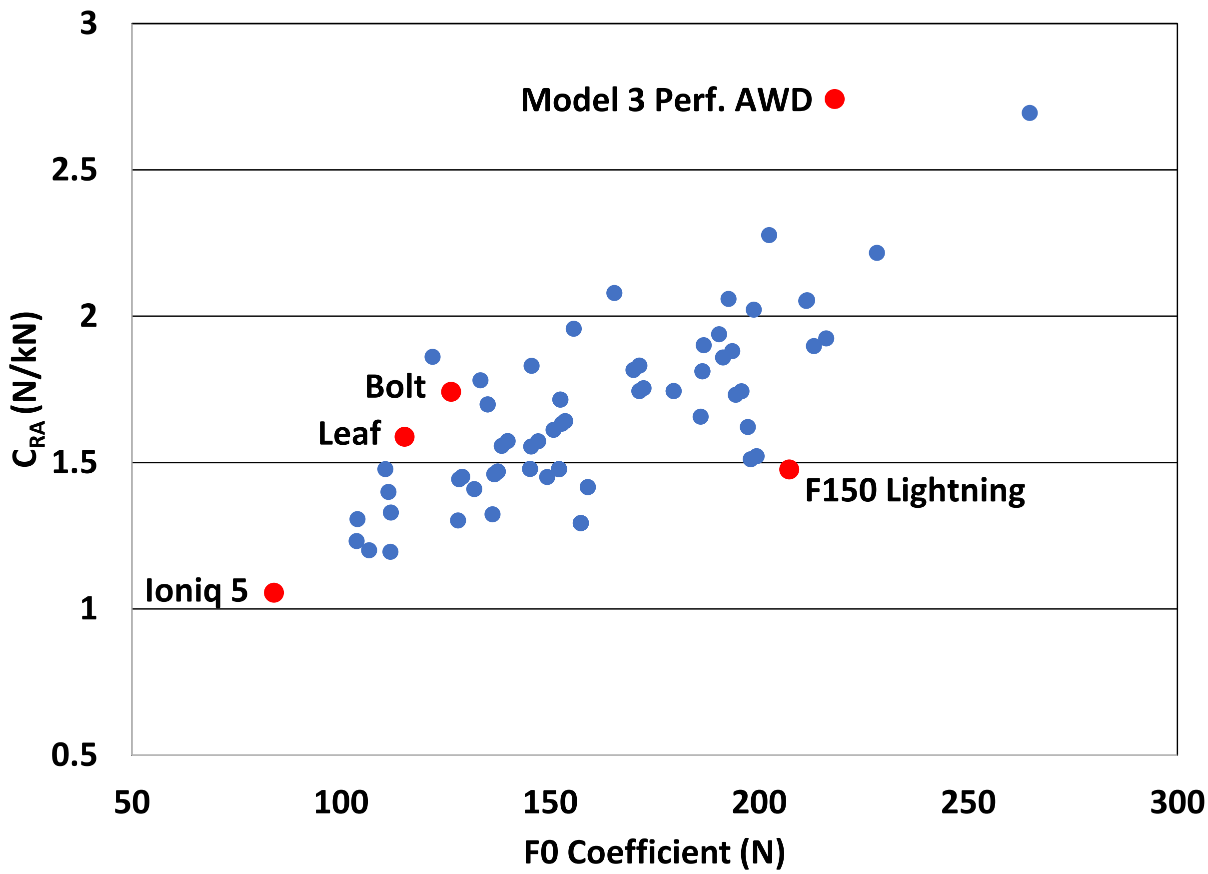

Figure 3. Apparent C_R versus F0 coefficient for model year 2022 BEVs.

The results show that C_{RA} varies from just over 1 N/kN up to nearly 3 N/kN. These values are substantially lower than the C_R results reported in tire friction studies discussed previously. This discrepancy is likely caused by a combination of factors, of which the most likely is a difference in test conditions between the vehicle coast-down test and the tire friction test. Tire friction is strongly dependent on test conditions, and the two tests were not intended to generate tire friction values that are comparable to one another. A second factor is that automotive manufacturers may use design strategies that result in tire operation at a lower fraction of their rated maximum load. Doing so may enhance ride quality, increase safety margin for underinflated tires, increase cargo carrying capacity, and so on. This design direction would tend to reduce the magnitude of C_{RA} compared to C_R values measured using the tire friction test. Finally, the assumption that all F0 losses are from tire friction likely causes C_{RA} to tend towards overstating the tire friction contribution to driving losses.

2.1.1 Adjusting C_{RA} to reflect Worn Tires and Replacement Tires

As discussed previously, studies have shown that worn tires have a lower C_R than when they were new; similarly, replacement tires can have a significantly higher C_R than OEM tires. C_{RA} values were adjusted to represent worn tires by multiplying them by 0.8. Replacement tire C_{RA} was estimated by multiplying by 1.2. These multipliers reflect the fact that worn tires have a C_R of approximately 80% of when they were new; replacement tires can have a C_R 20% higher than OEM tires. Once new values for C_{RA} were obtained, they were used to calculate a new value of F0 using the same relationship expressed in equation 2. The new F0 values, in turn, were used to calculate the driving losses for each MY2022 BEV. The methodology used in a previous publication was then used to estimate the driving range at steady speeds typical of extended highway driving. [10]

3. RESULTS

Using the F0 coefficients calculated for worn and replacement tires as well as the original F0 coefficients for model year 2022 BEVs, a comparison was conducted to examine the potential impact of tire friction changes on range.

3.1 CHANGE IN RANGE WITH WORN TIRES

The decrease in tire friction as tires wear causes a gradual increase in BEV range compared to their range when the original equipment tires were new. Figure 4 shows the potential change in range as this evolution occurs. The bars represent the spread of values from minimum to maximum at steady speeds from 20-80 MPH. The spread in values of range gain at a given speed is a result of the difference in importance of tire friction to total vehicle losses among the various vehicles. Low speeds are included for completeness, though extended steady speed driving more typically occurs at highway speeds greater than 50 MPH. Results are included for 48 MPH; this speed is the average speed of the highway fuel economy test that is used in both Corporate Average Fuel Economy certification and for the fuel economy value that is included on the window sticker of new vehicles. While the highway fuel economy test is not a steady-speed test, the 48 MPH result may be a useful indicator of how much impact could be observed for non-steady driving at the lowest highway speeds.

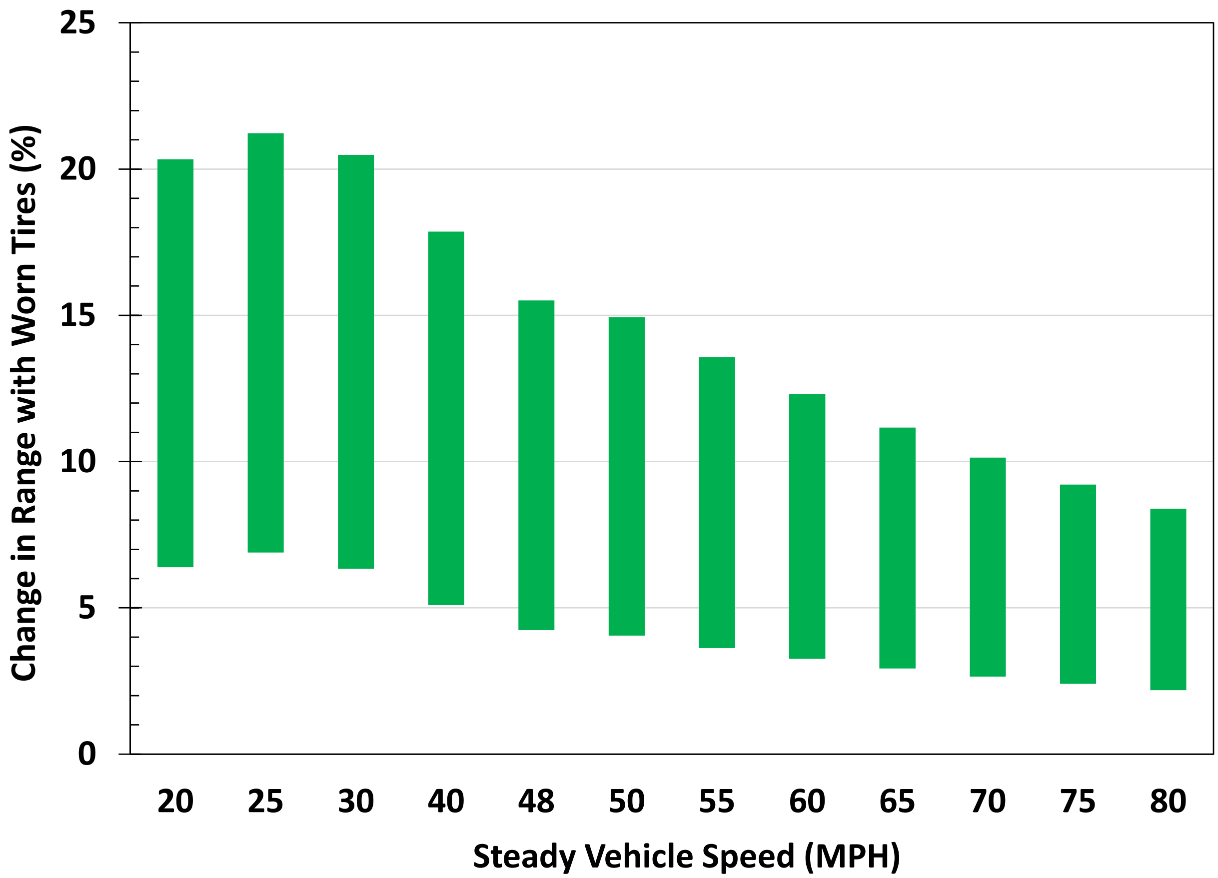

Figure 4. Potential change in estimated driving range at steady speeds with worn tires compared to the original tires in new condition. Positive values indicate an increase in range.

The decreasing importance of tire friction to total vehicle driving losses as speed increases causes its impact on range to decrease at high speeds typical of extended highway driving. At 50 MPH, for example, BEVs from the 2022 model year are expected to gain between 4 and 15% in range as their original tires wear. At 80 MPH, this difference decreases to 2-6%. This change could also be described as gaining 2-6 miles of range for every 100 miles of range the new car had when driven at 80 MPH. Since tire wear usually occurs over a period of a few years, this change is likely small and gradual enough that most BEV drivers would not notice the increase.

3.2 CHANGE IN RANGE WITH TIRE REPLACEMENT

In contrast to the gradual gain in range that BEV drivers experience with tire wear, replacement of the original tires on the vehicle causes a sudden change that is much more likely to be observed. Discussion of this change is clarified by examining it in two steps. Figure 5 shows the sudden change in range that could occur when worn original tires are replaced with tires having the same friction characteristics as the original equipment tires. This outcome is possible for some consumers since not all replacement tires will have greater friction than the tires originally installed on the vehicle by the manufacturer. The bars again represent the spread in values for individual BEVs from model year 2022 from minimum to maximum at each speed.

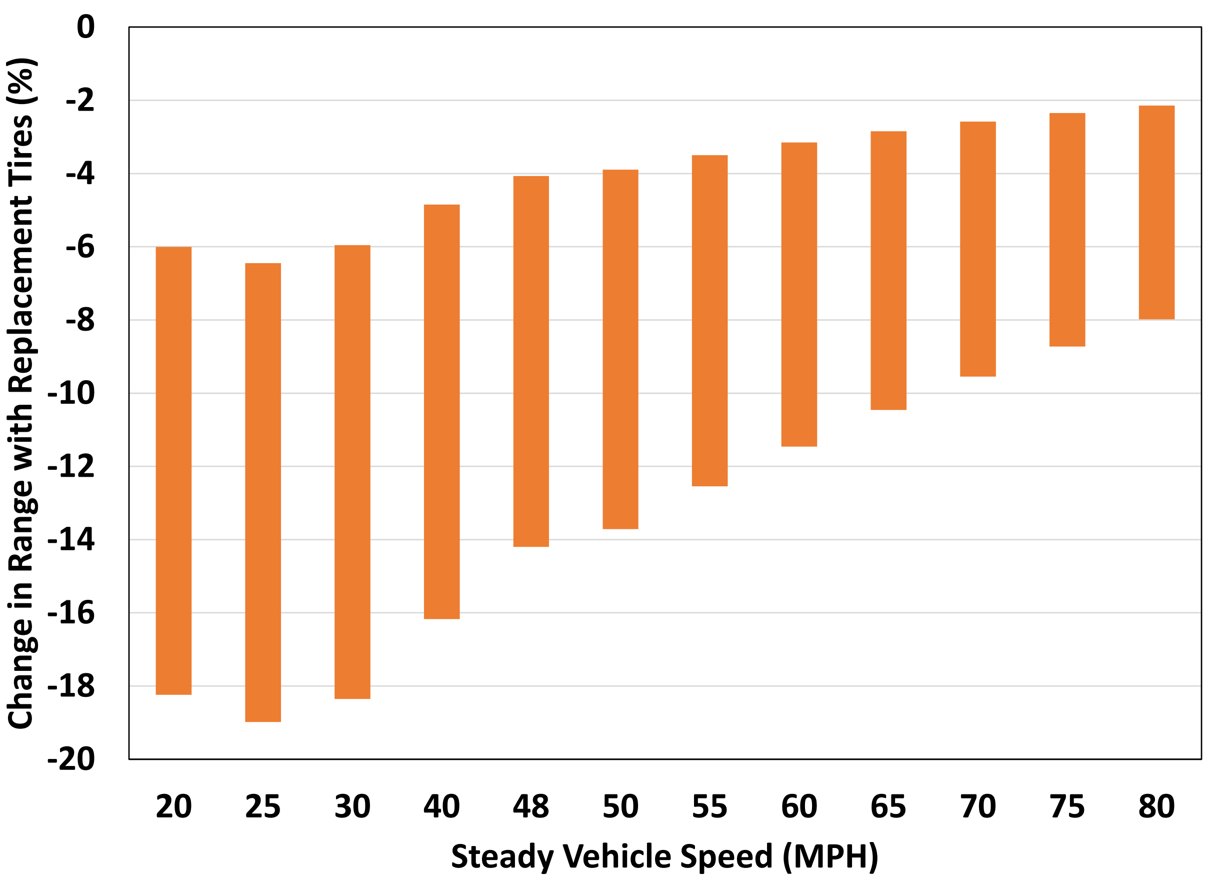

Figure 5. Potential change in estimated range at steady speed when worn tires are replaced with tires having the same friction characteristics as the original equipment tires. Negative values indicate a decrease in range.

At steady speeds greater than 50 MPH, replacement of the worn original tires can cause a decrease in range of about 2-14%. Even though the replacement tires do not have worse friction characteristics than the original equipment tires did when they were new, it is more likely that BEV drivers could observe this change given that it occurs in the space of a day to perhaps a week, rather than over a period of a few years.

Figure 6 shows the potential change in range if the replacement tires have 20% higher friction than the original tires, as is possible based on the results of the California study discussed previously. The increased friction of the replacement tires compared to the original tires when they were new causes range loss to increase. At speeds greater than 50 MPH, the range loss with higher friction replacement tires is about 5-25%.

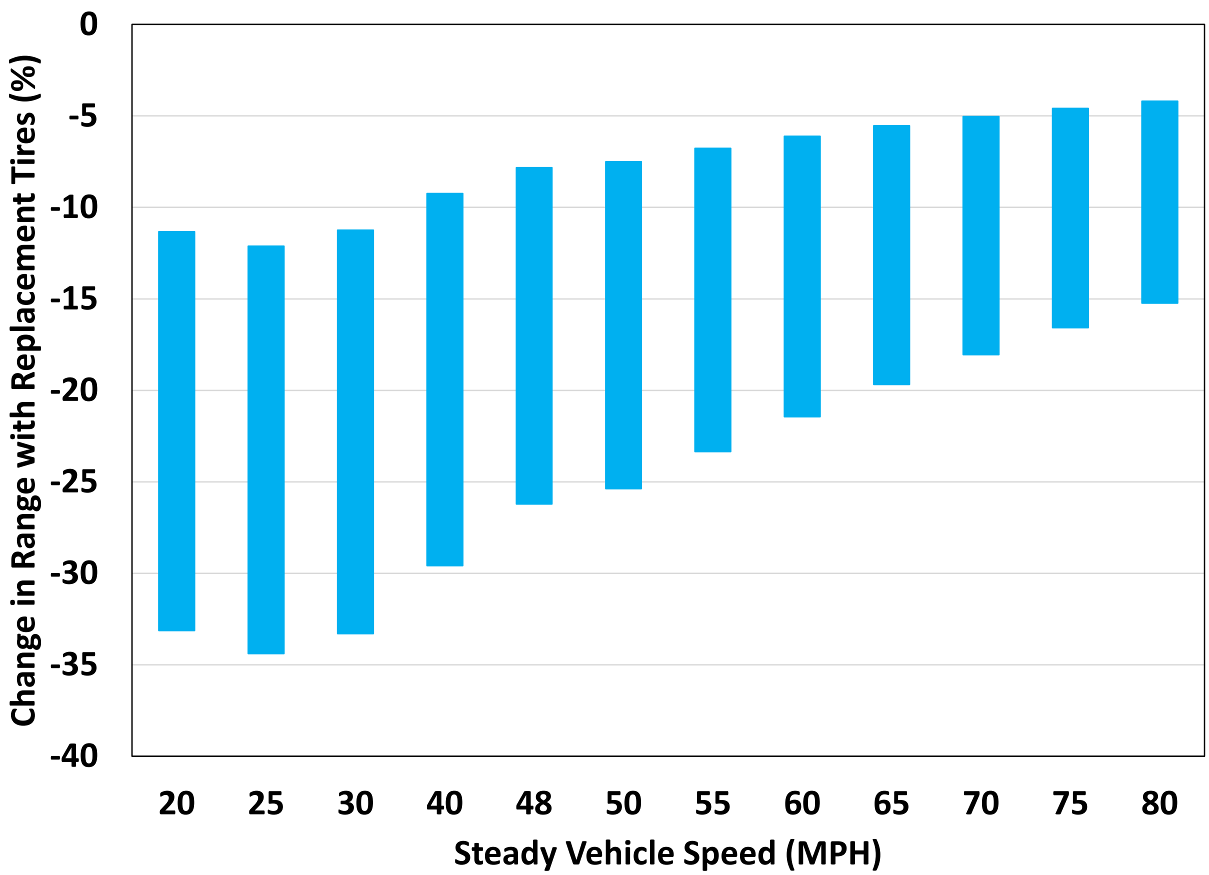

Figure 6. Change in driving range when worn original tires are replaced with tires having 20% higher friction than the original tires. Negative values indicate a loss in range.

3.3 INDIVIDUAL EXAMPLES

While the previous sections have discussed the impact of replacement tires on the range of the model year 2022 BEVs, it is also useful to examine a few of the individual vehicles. The minimum, maximum, and median values of C_{RA} were produced by the Hyundai Ioniq 5, the Tesla Model 3 Performance AWD, and the Nissan Leaf, respectively. Two other individual vehicles of interest were selected: the Ford F150 Lightning Platinum 4WD and the Chevrolet Bolt EV. Figure 7 shows the estimated range for these 5 vehicles when driven at a steady 65 MPH. Orange bars show the estimated range with the original equipment tires when new; green bars show the range with worn tires, and blue bars show the range with replacement tires having 20% greater friction than the original tires. The C_{RA} values for the original equipment tires in new condition are shown for each vehicle.

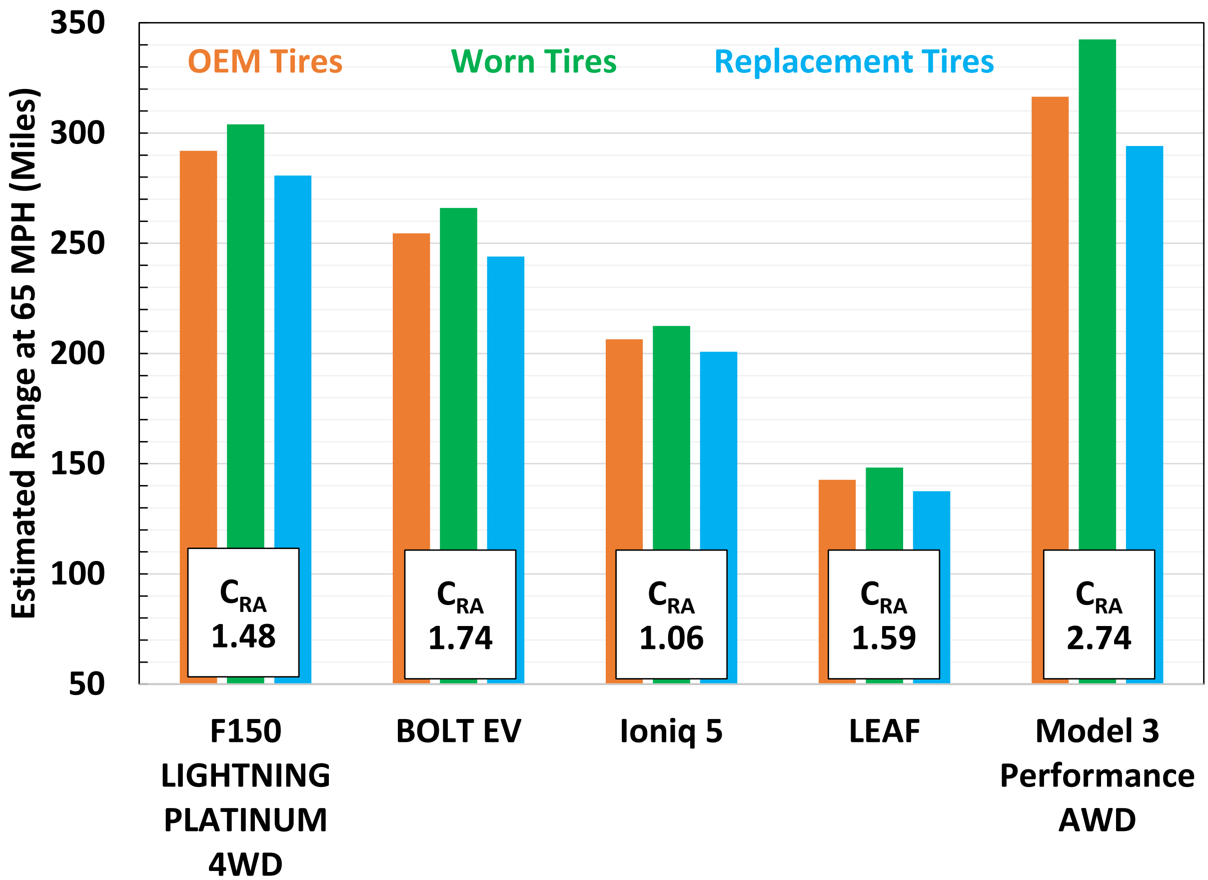

Figure 7. Estimated range at 65 MPH for 5 individual vehicles showing the impact of worn and replacement tires. The C_{RA} values of the original equipment tires in new condition are shown for each vehicle.

The F150 Lightning Platinum 4WD is estimated to have a range of about 290 miles at 65 MPH when using its original equipment tires in new condition. Tire wear results in an increase of range to just over 300 miles. When the worn tires are replaced, estimated range will drop to between 290 miles and 280 miles, depending on whether the replacement tires have the same or higher friction compared to the original tires. Similar trends are observed for the other vehicles as well. The Ioniq 5 has the lowest C_{RA} value for its original tires; the Model 3 Performance AWD has the highest C_{RA} value. It is perhaps more likely that replacement tires for the Ioniq 5 would have higher friction than the original tires. Conversely, the Model 3 original tires already have a high C_{RA}, and so it may be more likely that replacement tires would not have substantially higher friction than the original tires.

4. CONCLUSIONS

- Differences in tire friction become a smaller fraction of vehicle losses as speed increases, causing their effect on driving range at highway speeds to be less significant than at lower speeds.
- Gradual wear of original equipment tires on BEVs likely leads to an increase in driving range at steady highway speeds of 4-15% depending on the vehicle model, installed tires, and driving speed. This gradual change over an extended period of time may not be noticeable to most drivers.
- Replacement of original equipment tires with new tires having the same friction characteristics as the original tires likely leads to a loss in driving range of 2-14% depending on the vehicle model, installed tires, and driving speed. This loss is more likely to be observable by drivers because of its sudden onset.
- Replacement of original equipment tires with new tires having increased friction characteristics compared to the original tires likely leads to a loss in driving range of 5-25% depending on the vehicle model, installed tires, and driving speed. Losses greater than 15% are almost certainly observable by the driver owing to the magnitude and suddenness of the change.

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