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EFFECT OF PAYLOAD ON DRIVING RANGE OF BATTERY ELECTRIC TRUCK

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ABSTRACT

As the automotive industry continues to invest in electric vehicles and supporting infrastructure, consumers now have a significant selection of battery electric vehicle (BEV) models with more options on the way. As battery electric pickup trucks and SUVs become more common, it is important to consider the potential impacts of real-world use cases on range and efficiency.

AAA conducted primary research to understand the impact of payload on driving range and efficiency metrics for the 2022 Ford F-150 Lightning. Coastdown and dynamometer testing were performed in accordance with SAE International[1] standards J2263 and J1634 for unloaded and loaded test conditions. For the loaded test condition, 1,400 pounds of ballasts were added to serve as a surrogate payload.

Research Questions:

1. How does road load force for the loaded test condition compare to the unloaded condition?
2. How are driving range and efficiency affected by the added payload?

Key Findings:

1. For the unloaded test condition, the AAA-derived road load curve prescribes an average of 5.6 percent more applied force than the road load curve used for EPA certification over a speed range of 5 to 80 mph. For the loaded test condition (1,400 pounds added), the AAA-derived road load curve prescribes an average of 33.1 percent more applied force over a speed range of 5 to 80 mph.
2. For the unloaded condition, AAA found the test vehicle to have an efficiency of 62 MPGe (1.84 kWh/mi). This is 6.1 percent less than the EPA estimated efficiency of 66 MPGe (1.96 kWh/mi). In the loaded condition (1,400 pounds added), the test vehicle was found to have an efficiency of 47 MPGe (1.39 kWh/mi), a 24.2 percent decrease from the unloaded condition.

   The EPA estimated driving range for the test vehicle is 300 miles. In the unloaded test condition, AAA found the driving range to be 278 miles (7.3 percent less). In the loaded condition (1,400 pounds added), AAA found the range to be 210 miles, a 24.5 percent reduction compared to the unloaded test condition and a 30.0 percent reduction compared to the EPA estimate.

[1] Society of Automotive Engineers

GLOSSARY

Battery Electric Vehicle (BEV): A vehicle propelled by electric motors powered solely by energy stored in a battery pack. This is in contrast to hybrid electric vehicles, which also have a combustion engine supplying some portion of its energy or propulsion.

Coastdown: Refers to the procedure used to measure road force as a function of vehicle speed in which the vehicle is brought to a starting speed of 77.7 mph and allowed to coast until its speed is below 9.3 mph, according to SAE J2263.

Dynamometer: A device used to measure rotational power. In this text, refers to the two-axle chassis dynamometer used to simulate road forces while performing prescribed drive cycles.

HFEDS: Highway Fuel Economy Driving Schedule defined in 40 CFR § 600. It is used to represent vehicle highway driving for dynamometer testing. It is also referred to as the Highway Fuel Economy Test (HFET).

Miles Per Gallon Equivalent (MPGe): A unit used by the EPA to compare efficiency of alternative fuel vehicles (like battery electric vehicles) to traditional internal combustion vehicles. It represents the distance traveled per 33.7 kWh of energy consumed (the energy potential of one gallon of gasoline).

Phase Scaling Factor: In the context of SAE J1634 “BEV Energy Consumption and Range Test Procedure,” determines the contribution of each driving phase in calculation of total energy consumption.

Road Load Force: The force acting on a vehicle moving along a road surface in opposition to the direction of its velocity, which has the effect of slowing the vehicle. This force is the sum of various factors including (but not limited to) aerodynamic drag, road surface friction, and mechanical friction the vehicle’s moving parts.

Road Load Curve: The equation that describes road load force as a function of vehicle speed.

UDDS: Urban Dynamometer Driving Schedule defined in 40 CFR § 86. It is used to represent vehicle city driving for dynamometer testing.

CONTENTS

I. INTRODUCTION

Battery electric vehicles (BEVs) are continuing to increase in popularity as the automotive industry pledges significant investments towards greater vehicle selection, battery technology, and charging infrastructure. Sales of new electric vehicles grew by 65 percent and accounted for 6 percent of total new vehicle registrations in 2022, despite a decline in total new vehicle sales for the first time since 2011. Cox Automotive suggests that EV sales will exceed one million annual sales for the first time in 2023, spurred by fresh products and financial incentives from the Federal Government [1].

Besides the environmental benefits that accrue throughout a BEV's lifespan, these vehicles generally offer competent driving dynamics, robust acceleration, and require less maintenance than traditional internal combustion engine (ICE) platforms. According to an April 2021 study conducted by Argonne National Laboratory, scheduled light-duty vehicle maintenance costs for BEVs are $0.064 per mile when accounting for increased tire wear relative to ICE vehicles, on average. For ICE vehicles, the equivalent maintenance cost is $0.101 per mile, on average [2]. This is equivalent to a 37 percent reduction in maintenance costs when replacing an ICE vehicle with a comparable BEV.

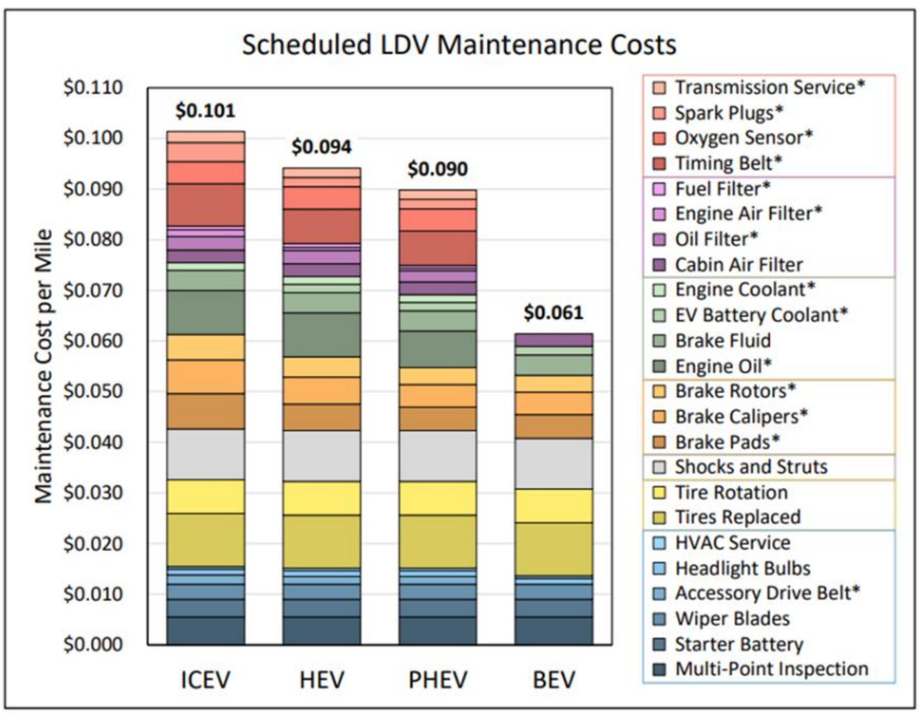

Figure 1: Breakdown of scheduled average maintenance costs. Asterisks refer to maintenance items specific to ICE platforms.
Image Source: U.S Department of Energy.

BEVs have made significant progress over the past several years and are continuing to improve in terms of battery capacity, safety, and recharge time. To realize comprehensive electrification and sustainability of the transportation sector, a sustained mobilization of resources and collaboration across a multitude of stakeholders including but not limited to automakers, suppliers, research organizations, academia, and government is essential. Additionally, energy, mining, and recycling sectors are closely intertwined with the overall ecosystem around transportation electrification.

In conjunction, rapidly improving the nationwide charging infrastructure is a priority of both the Federal Government and the automotive industry. However, the current availability of reliable electric vehicle chargers is significantly behind established refueling infrastructure, especially in more rural areas throughout the United States. As a result, many consumers still have concerns about driving range and recharging time, especially for longer trips.

It is imperative that consumers have access to realistic range and efficiency estimates for a variety of real-world driving conditions. With the release of several BEV pickup trucks, SUVs, and commercial cargo vans (with more arriving in the near future), information about the effect of increased payload on range and efficiency should be available to allow potential customers to assess if a prospective BEV meets requirements of their specific use cases.

II. BACKGROUND

Crossovers, SUVs, and pickup trucks have long been extremely popular vehicle segments in the United States. As the selection of BEVs in these segments continue to increase over the next several model years, it is anticipated that current sales trends will continue to be reflected within BEV models. Besides reflected market share trends, it is likely that the widespread availability of popular vehicle types will significantly increase total BEV market share at a rapid pace. A 2022 AAA survey found that 25 percent of consumers say they are likely to purchase a fully-electric vehicle for their next vehicle [3].

Figure 2: Selection of BEV crossovers and pickup trucks will substantially increase in the near future. Image Source: AAA.

Despite government and industry initiatives to hasten the adoption of BEVs as well as increasing public interest, consumers must feel comfortable knowing their BEV purchase will not require lifestyle sacrifices that wouldn't be encountered by owning a traditional ICE vehicle. While driving range and charging convenience are usually given the most attention, the effect individual use cases (such as towing and hauling) have on driving range and efficiency must be considered.

Currently, all driving range and efficiency estimates certified by the Environmental Protection Agency (EPA) are specific to baseline conditions that prescribe an equivalent test weight specification for the vehicle subconfiguration including the driver and test equipment. It is acknowledged that fuel economy estimates for ICE vehicles only account for baseline conditions as well. Additionally, the driving range and fuel economy of these vehicles are certainly influenced by specific use cases including towing and hauling. While magnitudes of range and efficiency losses may be similar between ICE and BEV vehicles, the current disadvantages of increased recharge time (even for fast chargers) and scarcity (depending on region) for charging BEVs compared to refueling ICE vehicles warrants additional consideration.

A. BEV Driving Range

The driving range of a BEV is primarily determined by two factors, the capacity of its fully-charged battery pack and the efficiency of its electric powertrain. External factors will influence powertrain efficiency to varying degrees.

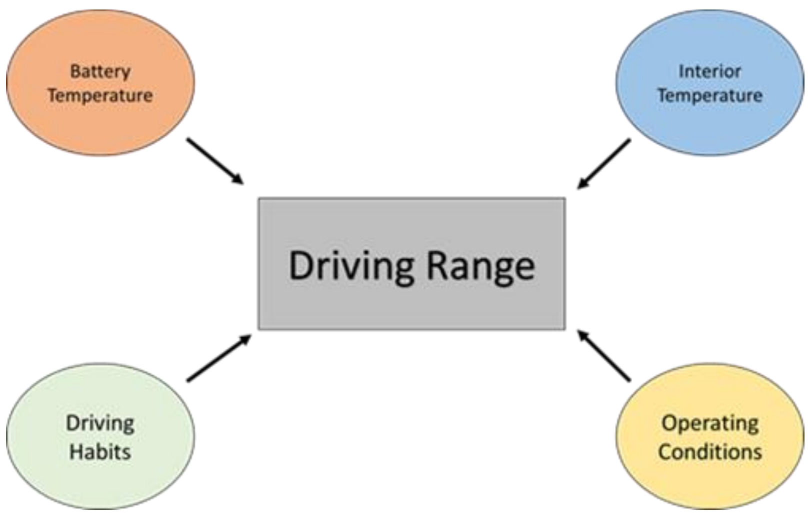

Figure 3: External factors contributing to observed driving range. Image Source: AAA.

- <u>*Battery temperature*</u>: For most efficient operation, an EV's battery pack has an optimal temperature range. This temperature range will vary somewhat depending on specific battery chemistry; in most cases, temperatures of 60°F to 80°F are ideal. Depending on the vehicle, operating conditions, and ambient air temperature, some of the available battery capacity may be required to heat or cool the battery. Pre-conditioning can be used to bring the battery to optimum temperature while the vehicle is on charge, eliminating this added load once removed from charge.
- <u>*Interior temperature*</u>: People prefer to keep the interior of their vehicles within a comfortable temperature range as well. With a BEV, this means drawing significant amounts of battery power to operate air conditioning or heating systems—with an accompanying reduction in driving range. The interiors of many BEVs can be "pre-conditioned" like the battery, using grid power to bring the interior to a comfortable temperature before the car is removed from charge.
- <u>*Driving habits*</u>: In any car, ICE or BEV, the faster and more aggressively it's driven, the quicker the vehicle's energy supply will become depleted. With BEVs, moderate acceleration and speed will provide maximum operating range. Additionally, BEVs can capture some of the vehicle's momentum and convert it back to electrical energy for the battery pack when slowing or stopping through

regenerative braking. Setting the level of regenerative braking to higher settings and braking moderately will maximize driving range and consequently increase the lifespan of brake rotors.

- _Operating conditions_: BEVs typically get better "mileage" in stop-and-go city driving than they do in sustained open highway operation, due to frequent use of regenerative braking. Additionally, the higher speeds of highway driving result in increased wind resistance, reducing efficiency. Terrain also has an effect. For example, a BEV will have a much shorter range climbing a mountain than it will driving down the other side. Additionally, increased weight will increase the load on the powertrain and decrease efficiency. For towing, the aerodynamics of the towed object is another major influence on efficiency and driving range.

B. BEV Battery Technology

Continuing innovation in battery design and underlying chemistries is necessary for the next generation of BEVs. Current Li-ion batteries for BEVs typically contain a graphite anode, a liquid carbonate electrolyte with a dissolved salt such as lithium hexafluorophosphate ($LiPF_6$), and a cathode composed of a layered oxide such as lithium cobalt oxide ($LiCoO_2$) or a spinel such as lithium manganese oxide ($LiMn_2O_4$). This general design is commonly utilized for BEVs because of its high energy density and proven reliability. However, chemistries beyond conventional Li-ion will need to be optimized for BEV traction batteries to address challenges including but not limited to battery pack mass, maximum charge/discharge rate, production cost/complexity, material scarcity, and recycling of spent battery packs. Of particular concern is the extensive use of expensive and rare transition metals such as cobalt, nickel, and manganese in battery cathode materials. Their use presents long-term sustainability concerns as their extraction, separation, and recycling are energy-intensive and environmentally damaging.

There are many research initiatives underway including the improvement of current battery design as well as promising new battery chemistries such as lithium-sulfur, lithium-air, and sodium-ion. Additionally, the eventual commercialization of solid-state electrolytes could significantly address current challenges pertaining to energy density, lifespan, battery pack mass, and flammability of battery contents when ruptured or otherwise compromised.

III. VEHICLE SELECTION & PAYLOAD DETERMINATION

A. Test Vehicle Selection

This work focuses on light-duty pickup trucks for personal use as well as use as road service vehicles in the AAA network. After examining the market for available half-ton BEV pickup trucks, the 2022 Ford F-150 Lightning was selected for testing.

B. Payload Determination

The purpose of this study is to compare the driving range of BEV pickup trucks, in both unloaded and loaded conditions, in order to better understand their usefulness for road service and personal use when loaded. Eight AAA clubs were surveyed about their typical vehicle types, uses, and payload in their fleets.

Survey results for half-ton pickup trucks showed an average estimate of approximately 1,200 pounds of equipment, not including vehicle modifications such as specialized framing, toolboxes, and equipment trays. An additional 200 pounds was added to the estimate to account for unreported modifications without exceeding the gross vehicle weight rating of the test vehicle. The weight to be added to the test vehicle in the loaded condition was selected as 1,400 pounds, bringing the total vehicle weight to 8,440 pounds (compared to a GVWR of 8,550 pounds).

IV.TEST EQUIPMENT AND RESOURCES

A. Coastdown Testing

Coastdown testing and road load coefficient derivation was performed by a certified third-party test facility (ISO 14001, ISO 9001, ISO 17025).

1) Equipment: Below is a list of major test equipment used to complete the coastdown tests according to SAE J2263 procedure. A full list of equipment is provided in the Appendix.

- **GPS Data Acquisition System**: A data acquisition unit (HBK eDAQXR-lite) with GPS receiver was used record vehicle position and speed.
- **Anemometer**: An electromechanical anemometer (Young 05103 Wind Monitor) was used to collect wind speed and direction during testing. It was mounted on a boom 2 meters in front of the vehicle at the approximate midpoint of the vehicle’s frontal cross section.
- **Ballasts**: Sand bag ballasts were placed in the bed, passenger seat, and rear seat of the vehicle to obtain the designated vehicle weight for the loaded condition. The unloaded test condition was performed without ballasts.

2) Test Facility: Testing was conducted on a 7.5-mile oval test track with a 180-degree turn at each end. Each turn has a travel distance of 1.75 miles. Two straight sections connect the turns and are each 2.0 miles in length and have a constant slope from north to south of 0.25 percent. Average elevation of the track is 1,086 feet above sea level.

Coastdown testing occurred on the west-side straight section with the track closed to other traffic to avoid interference. Weather conditions were measured by a weather station located near the mid-point of the section on which testing was conducted. Weather data is available in the Appendix.

B. Dynamometer Testing

The Automobile Club of Southern California performed all dynamometer testing at their Automotive Research Center (ARC) located in Los Angeles, California.

1) Data Logging Equipment:

- **Ampere-Hour Meter:** A Hioki power analyzer (model number PW3390) was used to measure all current leaving and entering the traction battery pack at a sampling frequency of 20 Hertz (Hz). The power analyzer was also utilized to measure AC recharge energy (kWh) for each vehicle and evaluated loading condition.
- **OBD-II Scan Tool:** Laptop-based OBD-II scan tool was used to capture traction battery voltage from vehicle network data as specified by SAE J1634 Part 4.6.b.

2) Dynamometer: ARC utilizes a pair of AVL 48-inch diameter electric chassis dynamometers in order to test front-, rear- and all-wheel drive vehicles. The front dynamometer is rated for 150 kW, while the rear dynamometer is rated for 220 kW. The dynamometer is used to simulate the same tractive forces that a vehicle encounters when it is driven in naturalistic environments.

The dynamometer is located inside of a temperature and humidity-controlled environmental chamber. The operating range of the chamber is between 20°F and 95°F. All testing was performed on this chassis dynamometer at 75ºF as specified by SAE J1634.

V. INQUIRY #1: HOW DOES ROAD LOAD FORCE FOR THE LOADED TEST CONDITION COMPARE TO THE UNLOADED TEST CONDITION?

A. Objective

Perform vehicle coastdowns according to SAE J2263 to measure road load in unloaded and loaded conditions and determine road load coefficients for use in dynamometer drive cycle testing.

B. Methodology

Testing was performed according to SAE J2263 MAY2020 “Road Load Measurement Using Onboard Anemometry and Coastdown Techniques” by a certified third-party test facility (ISO 14001, ISO 9001, ISO 17025).

1) Vehicle Preparation: Immediately prior to entering the test track, with the test vehicle cold, the vehicle’s tire pressures were set to manufacturer specification (42 psi for all) and the vehicle was weighed with the driver, instrumentation, and ballasts (for the loaded test condition). The vehicle was driven for 30 minutes at 50 mph (80 kph) around the test track to reach the prescribed operating conditions. For the loaded condition, ballasting was added to the truck bed and cabin in a manner to proportionally decrease the ride height at each corner relative to the unloaded condition.

2) Coastdown Procedure: Coastdowns were performed at low wind speeds, meeting the prescribed requirements. A weather station located near the midpoint of the section of test track used for testing recorded average and maximum wind speed, wind direction, temperature, humidity, and barometric pressure during each run.

Pairs of coastdowns were performed in alternating directions along one straight section of the test track. For each run, the vehicle was accelerated to approximately 77.7 mph (125 kph), the transmission was shifted into neutral, and the vehicle was allowed to coast to a speed below 9.3 mph (15 kph). Data elements specified by SAE J2263 were recorded continuously throughout at a rate of 10 Hz. This procedure was continued until five runs in both directions had been performed meeting all specified requirements. Once coastdowns were completed, the vehicle was weighed with driver and test equipment still in place.

3) Data Analysis: Test data was analyzed using software provided with the SAE J2263 Recommended Practice. A zero file was created by averaging wind angle from calibration run data. A two-point scaling method was performed on the anemometer during setup. Calibration files for the SAE J2263 software were created from post-test calibration runs. The SAE J2263 software generated weather-corrected coastdown coefficients for each run, combined the runs into pairs, and performed statistical analysis. The final results are the average of the test runs performed.

C. Test Results

Vehicle condition information and coastdown data and coefficients were provided by a certified third-party testing facility and are presented herein as received.

1) Vehicle Condition:

Make	Ford	
Model	F150 Lightning (EV)	
Year	2022	
V.I.N.	1FT6W1EV5NWG02903	
Starting Mileage (mi)	2389.4	
Frontal Area (ft2)	34.22	
Tire Make, Tire Pressure (psi), Tire Size	General - 42 Fr / 42 Rr – 275/50R22	
Curb Weight (lbs)	6820	
Test 1 Weight (lbs)	7040	
Test 2 Weight (lbs)	8440	
Tire Tread Depth (in)	FL: 10/32	FR: 10/32
	RL: 10/32	RR: 10/32
Suspension Height at Curb Weight (in) (Ground to fender lip)	FL: 37.375	FR: 37.625
	RL: 40.375	RR: 40.500
Suspension Height at ETW Weight (in)	FL: 36.375	FR: 36.500
	RL: 39.375	RR: 39.250

Figure 4: Test vehicle information and condition at start of coastdowns. Image Source: AAA.

2) Road Load Coefficients: The road load coefficients presented in this section are the result of the SAE J2263 coastdown procedure and are used to describe resistive forces on the vehicle. The coefficients are used in the following equation to describe road load as a function of vehicle speed and are used during the dynamometer drive cycles to replicate real world deceleration due to road force.

$$F = F_0 + F_1 V + F_2 V^2$$

Figure 5: Corrected road load force equation as a function of velocity as described in SAE J2263.

The table shown in Figure 6 presents the road load coefficients derived by the coastdown procedures for the unloaded and loaded test conditions. Also presented are the EPA reported coefficients, obtained from U.S. Environmental Protection Agency publications and provided as a reference for comparison.

	F0 (lbf)	F1 (lbf/mph)	F2 (lbf/mph^2)
EPA Certification	46.57	0.3416	0.035850
AAA Unloaded	44.33	0.4930	0.037641
AAA Loaded	48.80	1.3980	0.040951

Figure 6: Coefficients for AAA test cases and EPA reported coefficients. Image Source: AAA.

The road load curves for both the unloaded and loaded test conditions, as well as the EPA reported road load, are provided in Figure 7. These curves are obtained by substituting the coefficients in the road load equation (Figure 5) with the values provided in Figure 6.

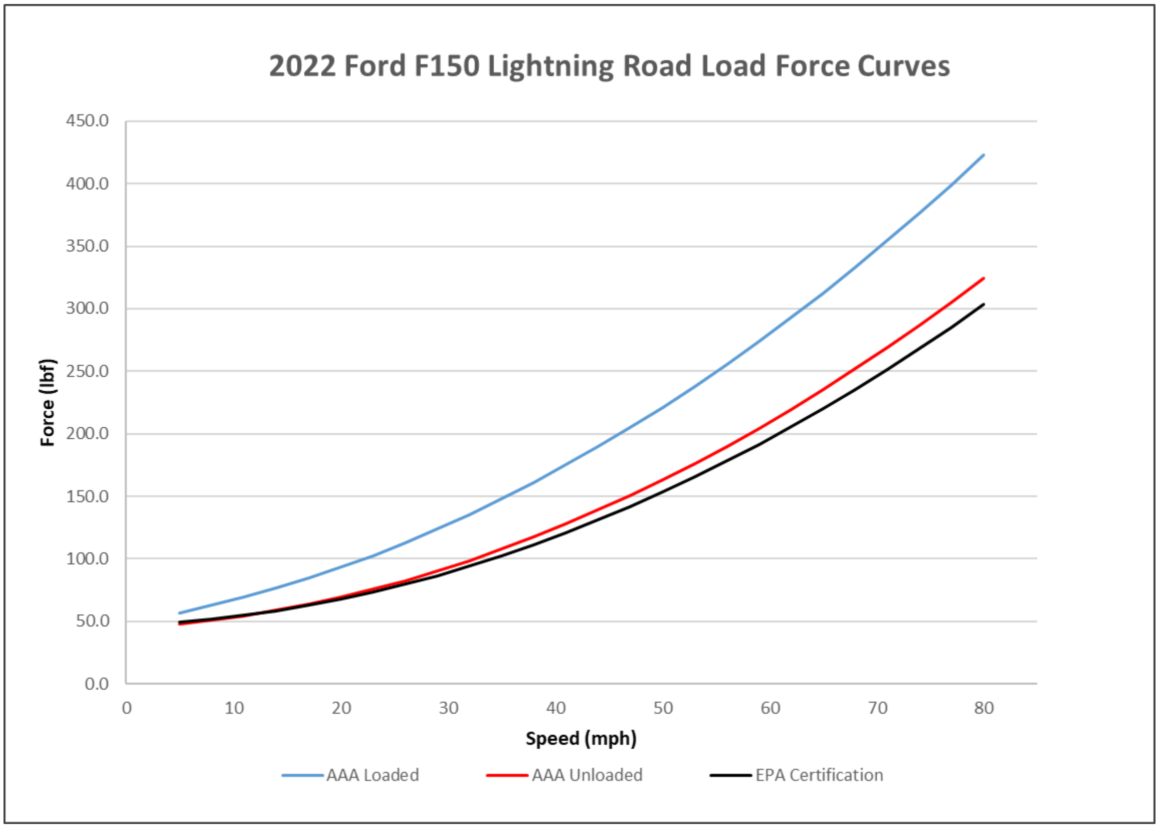

Figure 7: Graphical comparison of certification coefficients and AAA derived coefficients. Image Source: AAA.

The EPA reported and AAA-derived unloaded force curves are similar; however, the curves diverge slightly as vehicle speed increases above 13 mph. On average, the AAA unloaded force curve specifies 5.6 percent more applied force than the EPA reported force curve from 5 to 80 mph. This percentage difference was calculated by integrating the two curves from 5 to 80 mph, and dividing the difference by the value of the integrated EPA force curve.

In the loaded condition (with 1,400 pounds of added payload), the force curve specifies significantly more applied force than both the EPA and AAA unloaded force curves from 5 to 80 mph, diverging quickly as vehicle speed increases. On average, the AAA loaded force curve specifies 33.1 percent more applied force than the AAA unloaded force curve from 5 to 80 mph.

It is important to note that the integrated average of the road load force curves does not directly correlate to the amount of work exerted by the test vehicle during the drive cycles. However, this metric provides a useful method to compare the EPA and AAA-derived curves over the entire speed range.

VI. INQUIRY #2: HOW ARE DRIVING RANGE AND EFFICIENCY AFFECTED BY THE ADDED LOAD?

A. Objective

Perform dynamometer multi-cycle tests and quantify driving range and efficiency of test vehicle according to SAE J1634. Perform tests in both unloaded and loaded conditions to determine the effect of added payload on range and efficiency.

B. Methodology

The test vehicle underwent dynamometer drive cycles according to the multi-cycle test (MCT) as prescribed in SAE J1634. This procedure was performed in both unloaded and loaded conditions as previously described and matching the vehicle weights used in the coastdown procedures. For both unloaded and loaded test conditions, all dynamometer testing was conducted at an ambient temperature of 75°F with the vehicle HVAC switched off as prescribed within SAE J1634. Data processing and calculations were conducted in accordance to SAE J1634 procedures in order to determine efficiency and range results for both test cases. Additionally, vehicle thermal conditioning was not utilized for either test condition.

Figure 8: Ford F-150 Lightning on chassis dynamometer at the Automotive Research Center. Image Source: AAA

For both test conditions, the standard correction factor of 0.70 was applied according to SAE J1634 to obtain range and efficiency values reported herein. In accordance with EPA reporting methodology, the “city” (UDDS) and “highway” (HFEDS) values were multiplied by factors of 0.55 and 0.45, respectively.

The combined driving range and MPGe values were derived according to the following equations:

$$Driving\ Range_{Combined} = 0.55 Driving\ Range_{UDDS} + 0.45 Driving\ Range_{HFEDS}$$

$$MPGe_{Combined} = \frac{1}{\frac{0.55}{MPGe_{UDDS}} + \frac{0.45}{MPGe_{HFEDS}}}$$

C. Test Results

1) Unloaded Range and MPGe:

UDDS1	
Discharge kWh	-2.4934
HWFET1	
Discharge kWh	-4.0527
UDDS2	
Discharge kWh	-2.2735
CSC1	
Discharge kWh	-81.7209
UDDS3	
Discharge kWh	-2.2343
HWFET2	
Discharge kWh	-3.9792
UDDS4	
Discharge kWh	-2.2413
CSC2	
Discharge kWh	-22.4300
TOTAL kWh	**-131.147**
TOTAL RECHARGE kWh	**148.281**
AVG UDDS kWh	**-2.311**
AVG HWFET kWh	**-4.016**

Figure 9: Unloaded DC discharge energy for each drive cycle and battery pack discharge/recharge energy. Image Source: AAA.

DC discharge kWh with respect to drive cycle is provided in Figure 9. The observed total discharge energy is consistent with the reported battery capacity for test vehicle [4]. Phase scaling factors provided in Figure 10 were utilized to calculate DC energy consumption, range, and efficiency values provided in Figures 11–13 according to SAE J1634 procedure.

Phase Scaling Factors	
UDDS 1	**0.019**
UDDS 2-4	**0.327**
HFEDS	**0.500**

Figure 10: Phase scaling factors for unloaded dynamometer testing. Image Source: AAA.

DC Energy Consumption (kWh/mi)	
UDDS 1	0.327
UDDS 2	0.299
UDDS 3	0.294
UDDS 4	0.294
HFEDS 1	0.387
HFEDS 2	0.380

Figure 11: kWh/mile with respect to drive cycle for unloaded dynamometer testing. Image Source: AAA.

EPA adjusted values	
Total DC Energy Consumption (kWh/mi)	
UDDS	0.423
HFEDS	0.548
Range (mi)	
UDDS	310
HFEDS	239
COMBINED	278
MPGe	
UDDS	70
HFEDS	54
COMBINED	62

Figure 12: Unloaded consumption, range, and efficiency metrics with correction factor applied. Image Source: AAA.

According to fueleconomy.gov, the estimated combined driving range and efficiency for the test vehicle are 300 miles and 66 MPGe (1.96 kWh/mi), respectively. AAA derived values for combined driving range and efficiency in the unloaded condition are 278 miles and 62 MPGe (1.84 kWh/mi), respectively (Figure 12). Combined driving range and efficiency values are 7 percent and 6 percent less than EPA reported values, respectively.

Miles per kWh	
UDDS	2.091
HFEDS	1.615

Figure 13: Unloaded miles per kWh with correction factor applied. Image Source: AAA.

The values in Figure 13 utilize measured AC recharge energy to calculate the miles driven per kWh dispensed from the electrical utility for both UDDS and HFEDS drive cycles. This accounts for energy loss resulting from AC-to-DC conversion in course of utilizing a typical AC Level 2 charger.

2) Loaded Range and MPGe:

UDDS1	
Discharge kWh	-3.3071
HFEDS1	
Discharge kWh	-5.3865
UDDS2	
Discharge kWh	-2.9862
CSC1	
Discharge kWh	-86.4272
UDDS3	
Discharge kWh	-2.9378
HFEDS2	
Discharge kWh	-5.3068
UDDS4	
Discharge kWh	-2.9555
CSC2	
Discharge kWh	-20.9370
TOTAL kWh	**-130.251**
TOTAL RECHARGE kWh	**148.006**
AVG UDDS kWh	**-3.047**
AVG HFEDS kWh	**-5.347**

Figure 14: Loaded DC discharge energy for each drive cycle and battery pack discharge/recharge energy. Image Source: AAA.

DC discharge kWh with respect to drive cycle for the loaded test condition is provided in Figure 14. The observed total discharge energy is consistent with the reported battery capacity for extended range models [4]. Phase scaling factors provided in Figure 15 were utilized to calculate DC energy consumption, range, and efficiency values provided in Figures 16–18 according to SAE J1634 procedure.

Phase Scaling Factors	
UDDS 1	**0.025**
UDDS 2-4	**0.325**
HFEDS	**0.500**

Figure 15: Phase scaling factors obtained for loaded dynamometer testing. Image Source: AAA.

DC Energy Consumption (kWh/mi)	
UDDS 1	**0.441**
UDDS 2	**0.391**
UDDS 3	**0.386**
UDDS 4	**0.387**
HFEDS 1	**0.508**
HFEDS 2	**0.506**

Figure 16: kWh/mile with respect to drive cycle for loaded dynamometer testing. Image Source: AAA.

EPA adjusted values	
Total DC Energy Consumption (kWh/mi)	
UDDS	0.556
HFEDS	0.724
Range (mi)	
UDDS	234
HFEDS	180
COMBINED	210
MPGe	
UDDS	53
HFEDS	41
COMBINED	47

Figure 17: Loaded consumption, range, and efficiency metrics with correction factor applied. Image Source: AAA.

As previously provided in Figure 12, the unloaded combined range and efficiency values obtained by AAA are 278 miles and 62 MPGe (1.84 kWh/mi), respectively. The combined range and efficiency values (Figure 17) for the loaded condition were found to be 210 miles and 47 MPGe (1.39 kWh/mi), respectively. With 1,400 pounds of added payload, the combined driving range and efficiency values are 24.5 percent and 24.2 percent less than unloaded values, respectively.

Miles per kWh	
UDDS	1.582
HFEDS	1.215

Figure 18: Loaded miles per kWh with correction factor applied Image Source: AAA

Figure 18 utilizes measured AC recharge energy to calculate the miles driven per kWh dispensed from the electrical utility for both UDDS and HFEDS drive cycles. Compared to baseline values, the miles driven for UDDS and HFEDS drive cycles are reduced by 24 percent and 25 percent, respectively.

VII. DISCUSSION

A. Differences Between AAA Unloaded Results and EPA Reported Estimates

The road load curve derived by AAA using the SAE J2263 coastdown procedure for the unloaded vehicle condition exhibits deviation from EPA reported values, though it is unclear what factors contribute to this difference. For the unloaded test condition, the average applied road load force was 5.6 percent higher than that prescribed by EPA reported coefficients over a speed range of 5 to 80 mph. As these derived road load coefficients were utilized for dynamometer drive cycle testing, it is unsurprising that the range and efficiency metrics found in this study deviated from EPA published values.

Combined driving range and efficiency results for the unloaded test condition were found to be 7.3 percent and 6.1 percent less than EPA published values, respectively. It is unclear why the AAA derived results for the unloaded condition differed from that reported by the EPA for the test vehicle. However, these differences are expectedly relatively minor in comparison to the differences found between AAA derived loaded and unloaded test conditions.

B. Effect of Added Payload on Driving Range

The loaded test condition added 1,400 pounds of ballast to the vehicle weight of the unloaded condition, which included only the vehicle curb weight and the combined weight of the test driver test equipment required (220 pounds). For the loaded test condition, the average applied road load was found to be 33.1 percent higher than that found for the unloaded condition over a speed range of 5 to 80 mph. The combined driving range and efficiency values were found to be 24.5 percent and 24.2 percent less than unloaded values, respectively. When compared to the EPA reported driving range, this is a reduction of 30 percent.

It should be noted that the weight added in the loaded condition brings the test vehicle to just 110 pounds shy of its maximum rated payload. While this may be reasonable for vehicles in road service fleets, typical vehicle owners will likely seldom use their BEV pickup with this much added weight. With lighter payloads, drivers can expect less range loss.

C. Other Factors That May Affect Driving Range

This study has thus far focused on the combined city and highway range and efficiency results. However, the type of driving that a vehicle does greatly affects its efficiency. Gas-powered vehicles typically get better fuel economy in highway driving conditions (higher speeds and little deceleration and acceleration) than in city conditions (slower speeds and frequent deceleration and acceleration). This tends to be reversed for BEVs due to regenerative braking during deceleration and the inherent advantage of electric motor torque when accelerating after a stop.

It was noted that the test vehicle had 30 percent more range during the UDDS drive cycle (representing city driving) than during the HFEDS cycle (representing highway driving) for both unloaded and loaded conditions. The case with the lowest driving range was the loaded condition during the HFEDS (highway) cycle, which had a range of only 180 miles.

Aerodynamic drag is another factor than affects efficiency and driving range. The payload added to the test vehicle in this study was added to the bed and inside the cabin in a manner to not significantly affect the aerodynamic profile. Changes to aerodynamic profile associated with payloads (such as trailers or tall objects in the bed) would reduce the driving range even further.

Additional variables that can affect efficiency that were not considered in this study include but are not limited to: ambient temperature, HVAC use, terrain, towing, and vehicle preconditioning. Each will have additive influences on observed driving range and could result in final increases or decreases, dependent on cumulative parameter attributes.

VIII. CONCLUSION

The 2022 Ford Lightning in the unloaded condition had a combined driving range of 278 miles. With an added payload of 1,400 pounds, it was found to have a combined driving range of 210 miles. This is a reduction of 68 miles (24.5 percent) from the unloaded case. This result may seem discouraging, but it is important to consider that 1,400 pounds of added payload (along with the driver and test equipment) brought the loaded test weight to just 110 pounds under the GVWR of the vehicle.

Prospective buyers who intend to use their BEV pickup to carry heavy payloads should consider the impact this can have to their driving range. However, if users are aware of the potential driving range reduction associated with large payloads, trips can be planned to account for additional charging and downtime considerations. Additionally, users are likely to carry lighter payloads than used in this test in most cases, resulting in a moderated loss of range.

AAA is strongly supportive of BEVs and the significant resources allocated to further development of the platform. It is important to remember that the driving range and fuel economy of ICE platforms are similarly affected by added payload as electrified platforms. As battery technology and the nationwide charging network continue to develop, driving range will likely become less of a concern.

Even when fully loaded or operated in otherwise challenging conditions, electrified platforms are significantly more energy efficient than ICE counterparts. Consider the loaded test condition, which had an efficiency of 47 MPGe (1.39 kWh/mi). This is significantly more efficient than the test vehicle's ICE counterpart (2022 Ford F-150 Platinum SuperCrew 5.5 ft bed), which has an EPA reported combined fuel economy of just 20 MPG without a payload.

IX. KEY FINDINGS

A. Inquiry #1: How does road load force for the loaded test condition compare to the unloaded?

For the unloaded test condition, the AAA-derived road load curve for the 2022 Ford F-150 Lightning prescribes an average of 5.6 percent more applied force than the road load curve used for EPA certification over a speed range of 5 to 80 mph. For the loaded test condition (1,400 pounds added), the AAA-derived road load curve prescribes an average of 33.1 percent more applied force over a speed range of 5 to 80 mph.

B. Inquiry #2: How are driving range and efficiency affected by the added payload?

For the unloaded condition, AAA found the 2022 Ford F-150 Lightning to have an efficiency of 62 MPGe (1.84 kWh/mi). This 6.1 percent less than the EPA reported efficiency of 66 MPGe (1.96 kWh/mi). In the loaded condition (1,400 pounds added), the test vehicle was found to have an efficiency of 47 MPGe (1.39 kWh/mi), a 24.2 percent decrease from the unloaded condition.

The EPA reported driving range for the test vehicle is 300 miles. In the unloaded test condition, AAA found the driving range to be 278 miles (7.3 percent less). In the loaded condition (1,400 pounds added payload), AAA found the range to be 210 miles, a 24.5 percent reduction compared to the unloaded test condition and a 30.0 percent reduction compared to the EPA reported range.

X. RECOMMENDATION

Those considering a BEV pickup with the intention of carrying heavy payloads should consider how this might reduce range, especially compared to EPA reported values. The type of driving the vehicle will see (i.e. city vs highway driving) should also be considered. Heavy payloads combined with highway driving (high speeds and limited braking) can compound to significantly reduce driving range. In the case of battery electric pickups used as work vehicles, permanent loads (such as equipment racks built into the vehicle) will reduce range at all times, even without additional cargo.

XI. REFERENCES

[1] Cox Automotive , "In a Down Market, EV Sales Soar to New Record," 13 January 2023. [Online]. Available: https://www.coxautoinc.com/market-insights/in-a-down-market-ev-sales-soar-to-new-record/#:~:text=Cox%20Automotive%20is%20forecasting%201,Blue%20Book%20EV%20Sales%20Report.. [Accessed 6 February 2023].

[2] Argonne National Laboratory, "Comprehensive Total Cost of Ownership Quantification for Vehicles with Different Size Classes and Powertrains," U.S Department of Energy, 2021.

[3] American Automobile Association, "Americans Reveal Fresh Thoughts on Electric Vehicles," 13 July 2022. [Online]. Available: https://newsroom.aaa.com/2022/07/americans-reveal-fresh-thoughts-on-electric-vehicles/. [Accessed May 2023].

[4] Ford®, "2022 Ford F-150 Lightning Platinum Capacities," [Online]. Available: https://www.ford.com/trucks/f150/f150-lightning/2022/models/f150-platinum/. [Accessed 8 March 2023].

[5] Ford®, "2022 F-150 Lightning Platinum Specifications," [Online]. Available: https://www.ford.com/trucks/f150/f150-lightning/2022/models/f150-platinum/. [Accessed 8 March 2023].

[6] EPA, "Dynamometer Drive Schedules," [Online]. Available: https://www.epa.gov/vehicle-and-fuel-emissions-testing/dynamometer-drive-schedules. [Accessed 15 March 2023].

XII. APPENDIX

Type	Output	Range	Resolution	Accuracy	Specifics	Serial Number
Tire Pressure Gauge	Vehicle Tire Pressure	0-150 psi	0.1 psi	±0.1% of applied pressure	Intercomp Model: 360046-150-BC	0422SS08645
Platform Scales	Vehicle Total, Wheel, and Axle Load	0-2,400,000 lb	0.5 lb	±10 lb	Mettler Toledo Model: 7562	52258315JLB1
Anemometer	Wind Speed, Wind Direction	Speed: 0-100m/s, Direction: 0-360°	N/A	Speed: ±0.3 m/s, Direction: ±3 degrees	RM Young Model: 05103	WM163748
Data Acquisition System	Record Time; Velocity; Heading, Wind Speed; Wind Direction	Sufficient to meet or exceed individual sensors	N/A	Sufficient to meet or exceed individual sensors	HBM Model: eDAQXR Lite	11185
Weather Station	Temperature	-40, -150°F	0.1°F, 1mph	±1°F, ±2mph	Davis Instruments Model: 6152 Vantage Pro2	170215N10
Weather Station	Wind Speed	0-200mph	0.4m/s	±1 m/s	Davis Instruments Model: 6410 Anemometer with 7905L wind cups	191231N01
Weather Station	Pressure	16.00-32.50 in-Hg	0.01 in-Hg	0.03 in-Hg	Davis Instruments Model: 6152 Vantage Pro2	44167
Infrared Temperature Gun	Surface Temperature	-76-932°F	0.1°C	±2%	Metris Instruments Model: TN418L1	E3122018781

Figure 19: Complete list of equipment used for coastdown tests. Image Source: AAA.

Test 1	1	2	3	4	5	6	7	8	9	10	11	12
Ambient Temperature (°F)	47.2	47.2	47	46.7	46.3	46	45.9	46	45.9	45.7	45.6	45.4
Ambient Humidity (%)	37	37	37	38	39	39	40	39	40	40	41	40
Ambient Pressure (in-Hg)	28.74	28.74	28.74	28.75	28.75	28.75	28.75	28.75	28.75	28.75	28.75	28.75
Wind Speed (mph)	6	5	5	5	4	5	5	6	6	6	5	7
Track Surface Temperature (°F)	45.1	41.9	39.2	39.9	42.6	40.2	38.2	39.6	38.8	39.9	39.9	40.8
Run Direction	S	N	S	N	S	N	S	N	S	N	S	N

Test 2	1	2	3	4	5	6	7	8	9	10	11	12
Ambient Temperature (°F)	46.5	46.7	46.9	47.1	47.4	47.9	48.4	49	49.6	50.1	50.5	50.8
Ambient Humidity (%)	91	92	92	92	92	92	92	91	91	90	89	89
Ambient Pressure (in-Hg)	29.01	29.02	29.02	29.02	29.02	29.02	29.02	29.02	29.02	29.02	29.02	29.02
Wind Speed (mph)	0	0	0	0	0	0	0	0	0	3	4	1
Track Surface Temperature (°F)	46.3	44.8	45.3	44.1	46.4	45.7	48.3	47.1	49.6	47.5	48.6	47.8
Run Direction	S	N	S	N	S	N	S	N	S	N	S	N

Figure 20: Weather data for unloaded (Test 1) and loaded (Test 2) coastdown tests. Image Source: AAA.

Calculated Road Load (lbf)				
mph	**Certification**	**AAA Unloaded**	**AAA Loaded**	**Δ (Loaded-Unloaded)**
5	49.2	47.7	56.8	9.1
8	51.6	50.7	62.6	11.9
11	54.7	54.3	69.1	14.8
14	58.4	58.6	76.4	17.8
17	62.7	63.6	84.4	20.8
20	67.7	69.2	93.1	23.9
23	73.4	75.6	102.6	27.0
26	79.7	82.6	112.8	30.2
29	86.6	90.3	123.8	33.5
32	94.2	98.7	135.5	36.8
35	102.4	107.7	147.9	40.2
38	111.3	117.4	161.1	43.6
41	120.8	127.8	175.0	47.1
44	131.0	138.9	189.6	50.7
47	141.8	150.6	205.0	54.3
50	153.3	163.1	221.1	58.0
53	165.4	176.2	237.9	61.7
56	178.1	190.0	255.5	65.5
59	191.5	204.4	273.8	69.4
62	205.6	219.6	292.9	73.3
65	220.2	235.4	312.7	77.3
68	235.6	251.9	333.2	81.3
71	251.5	269.1	354.5	85.4
74	268.2	286.9	376.5	89.6
77	285.4	305.5	399.2	93.8
80	303.3	324.7	422.7	98.1

Figure 21: Calculated road load values based on AAA derived coefficients and certification coefficients. **Image Source: AAA.**