INL/EXT-14-34030

# Advanced Vehicle Testing Activity – Cold Weather On-road Testing of a 2012 Chevrolet Volt

John Smart

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# SUMMARY

On-road testing of a 2012 Chevrolet Volt was performed during the winter and spring months to determine the impact of cold temperature on driving and charging efficiency. A single test vehicle was parked and charged overnight in an unsheltered parking stall and driven by a single driver in the morning along a specified route. The route included a mix of rural, city, and highway roads in the Idaho Falls, Idaho area. Both the vehicle and the charging equipment were instrumented to record energy consumption and other usage parameters during driving and charging.

Ambient temperatures ranged from -17°F to 70°F during testing. Gasoline fuel economy, electrical energy consumption, electric vehicle (EV) mode range, and charge depleting (CD) mode range varied significantly over this temperature range. The Volt was able to complete the test route without consuming any gasoline, provided the ambient temperature stayed above 27°F. At or below 27°F, the vehicle's control system periodically commanded the engine to start, consuming gasoline. The colder the temperature, the more often the engine cycled on and the more fuel was consumed. Gasoline fuel economy (not accounting for electrical energy consumption) was measured at 47 mpg during the coldest CD test, which averaged -15°F. Electrical energy efficiency during this test was 311 Wh/mi, based on measurement of direct current (DC) out of the battery. Electrical energy efficiency across all CD tests with cold starts ranged from 246 DC Wh/mi to 452 DC Wh/mi. This 84% increase in electrical energy consumption can be attributed to the effects of cold temperature and climate control load. The Volt's actual EV range dropped from 42.0 miles at 70°F to 19.7 miles at -15°F, a reduction of 53%. The EV range fell at a rate of 0.6 miles per degree Fahrenheit in tests averaging 50°F to 25°F. CD range diverged from EV range in tests when temperatures dropped to or below 27°F during the test, because engine operation due to cold temperature also slowed the rate of battery depletion. Energy consumption during overnight charging ranged from 12.53 to 13.73 AC kWh and increased with decreasing temperature, although not at a consistent rate.

These results provide trends that can be used to guide the expectations of plug-in electric vehicle consumers and advocates and provide a benchmark for research and development efforts.

# CONTENTS

SUMMARY .......... iii

1. INTRODUCTION .......... 1

2. TEST PROCEDURE .......... 1

    2.1 Test Route .......... 2

    2.2 Start-up and Shut-down Procedure .......... 2

    2.3 Vehicle Settings and Conditions .......... 3

    2.4 Data Acquisition .......... 3

3. RESULTS AND ANALYSIS .......... 5

    3.1 Driving Results .......... 5

    3.2 Charging Results .......... 8

4. CONCLUSION .......... 9

5. REFERENCES AND FOOTNOTES .......... 10

# FIGURES

1. A typical profile of vehicle speed versus time for the Idaho Falls cold weather test route .......... 2

2. Volt charging location with charging equipment in weather-proof container .......... 4

3. Schneider Electric AC Level 2 EVSE unit in series with Eaton IQ250 power and energy meter .......... 4

4. Solar shield housing the temperature data logger .......... 5

5. Unadjusted gasoline fuel economy measured on tests with different operating modes versus ambient temperature .......... 6

6. Electrical energy efficiency in EV mode with respect to ambient temperature .......... 7

7. EV and CD range with respect to ambient temperature .......... 7

8. Charge energy consumed with respect to average ambient temperature .......... 8

8. Time history data for a charging event when the vehicle was left plugged-in over the weekend ........ 9

# TABLES

1. Test time and speed summary statistics ........ 5

# Advanced Vehicle Testing Activity – Cold Weather On-road Testing of a 2012 Chevrolet Volt

## 1. INTRODUCTION

Idaho National Laboratory tests advanced technology vehicles as part of its management of the U.S. Department of Energy's Advanced Vehicle Testing Activity (AVTA). AVTA is part of the U.S. Department of Energy's Vehicle Technologies Office. AVTA performs benchmark testing of grid-connected vehicles and the electric vehicle supply equipment (EVSE) utilized by the vehicles for charging. This report discusses AVTA on-road testing of a 2012 Chevrolet Volt during cold weather months.

The Chevrolet Volt is an all-electric-capable plug-in hybrid electric vehicle, more commonly referred to as an extended-range electric vehicle. As its name suggests, it is capable of operating as a pure electric vehicle while in charge depleting (CD) mode, regardless of the driver's power demand. All of its accessories, including the climate control system, are capable of operating without running the internal combustion engine. Therefore, operation in CD mode is often referred to as electric vehicle (EV) mode. To operate the vehicle in EV mode, the Volt's 16-kWh battery pack must be charged from the electric grid. Fully charging the battery pack provides the 2012 Volt with an estimated EV-mode range of 35 miles [1]. As the vehicle is driven and its battery pack is depleted below a certain state of charge (SOC), it transitions to charge sustaining (CS) mode, also referred to as extended-range mode. When in CS mode, the internal combustion engine cycles on and off to drive an onboard generator, which maintains battery state of charge and provides electricity for other vehicle systems.

The Volt is a highly efficient vehicle. Previous AVTA testing showed that the Volt can complete the Urban Dynamometer Driving Schedule in all-electric mode at an efficiency of 236 Wh/mi [2]. With increased efficiency comes the potential for increased sensitivity to changing conditions. Testing was performed to understand the impact of cold ambient temperature on the Volt's energy efficiency.

The Volt is susceptible to the same losses that all vehicles, including conventional internal combustion engine vehicles, experience in cold weather; namely, increased drag on rotating components, transmission windage, and tire losses. These effects are primarily experienced when vehicles have been left to "soak" in cold ambient temperatures (such as overnight in a parking lot or unheated garage). However, soon after a cold vehicle begins driving, its systems warm up and the effect of cold ambient temperature on efficiency is diminished.

The Volt also experiences sustained efficiency losses in cold weather as a result of its specific design. Cold temperatures typically prompt drivers to run the climate control system to heat and defrost the cabin. For the Volt, this decreases overall vehicle driving efficiency because the climate control system consumes electricity, which could be used otherwise to propel the vehicle. Additionally, in very cold temperatures, the Volt's engine is designed to run when the vehicle is initially turned on and periodically during driving to provide heat to various vehicle systems, regardless of the battery pack's SOC. Finally, the temperature of the Volt's high voltage battery pack is actively managed for performance and longevity. When the battery pack is cold, the vehicle will consume electricity to heat the battery, which is drawn either from the battery itself or from the electric grid if the vehicle is plugged in.

To observe the effect of cold weather on the 2012 Chevrolet Volt's operation and to quantify efficiency losses, a test regime was established to mimic real-world driving and charging of a Volt in a cold climate.

## 2. TEST PROCEDURE

The testing regime specified that a single driver repeatedly drive a single 2012 Chevrolet Volt on a prescribed route on numerous days with varying ambient temperature. Each night, the vehicle was parked in an unsheltered parking stall, plugged in, and the battery pack fully charged. Each day, the driver completed two or more tests (where one test is defined as one lap around the prescribed route) to fully deplete the battery pack. Data were collected to quantify vehicle efficiency on a per-mile basis, distance driven in EV mode, and the distance driven until the vehicle transitioned from CD to CS mode (referred to as CD range). The vehicle and charging equipment were instrumented to record energy consumption, distance driven, engine state, and other parameters. Ambient temperature was logged by a measurement device located at the vehicle's parking location. The driver also recorded data provided by the Volt's instrument panel and center console display.

## 2.1 Test Route

A route was selected on public roads in the Idaho Falls, Idaho area that includes a mix of city, rural, and highway driving. The route was 16.9 miles, starting and ending at the Volt's overnight parking location. The route was not intended to mimic any standardized test cycle. The posted speed limit along this route ranged from 25 to 65 mph. Figure 1 shows a speed trace from a single test, chosen at random.

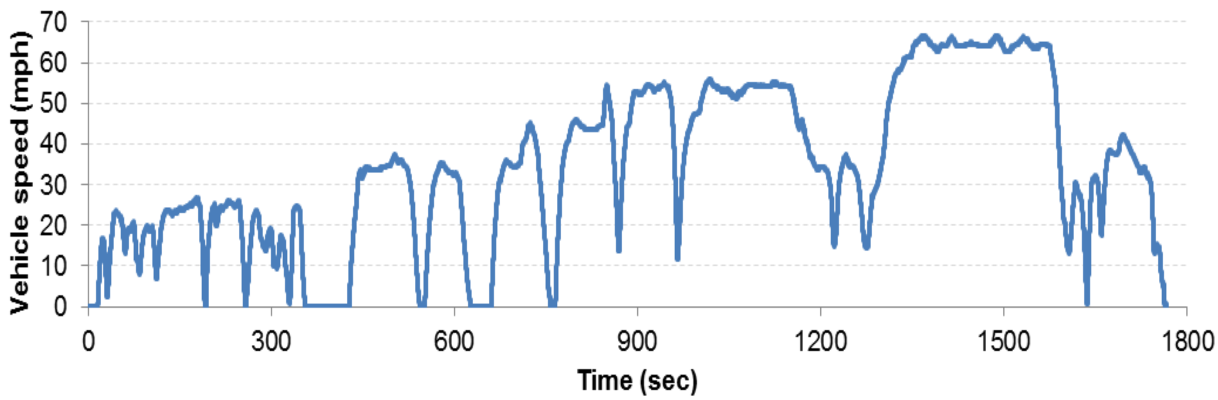


Figure 1. A typical profile of vehicle speed versus time for the Idaho Falls cold weather test route.

To reduce variation in efficiency due to changing driving style or aggressiveness, the driver was instructed to accelerate mildly to the posted speed limit and cruise within 2 mph above or below the posted speed limit. Occasionally, traffic required the driver to slow his speed below this tolerance. The driver was instructed to brake mildly and, to the extent possible, maximize the potential for regenerative braking by following the guide on the Volt's instrument panel.

## 2.2 Start-up and Shut-down Procedure

At the start of the first test of the day, the vehicle was fully powered on by depressing the brake pedal and pushing the power button. (The Volt can also be powered on in accessory-only mode by pushing the power button without depressing the brake pedal.) The front and rear defrosters were turned on, the front defrost blower speed was set to maximum, and the temperature setting was set to 72°F. The vehicle remained in this condition for 5 minutes, during which time the driver cleared the windows of snow or frost, if necessary. Following the 5-minute defrost period, the vehicle's charge cord was unplugged from the charging equipment. The climate control was then set to Auto – Comfort, the temperature setting was left at72°F, and the test drive was performed. At completion of the round-trip test route, the vehicle was parked in the parking stall and powered off. The vehicle was left to soak for 5 minutes. Then the vehicle was turned on and the next test drive was performed, with the climate control settings remaining in the Auto – Comfort mode. On some days, one or more additional test drives were performed, separated by 5-minute soaks.

Following completion of the last test drive of the day, the thermostat was set to the maximum temperature and the fan blower speed was set to maximum. This depleted any surplus charge that had accumulated in the battery pack during CS operation. The vehicle was turned off when the battery pack SOC reached 19.0% (per external instrumentation), at which point the engine would turn on if the vehicle continued to operate. This SOC conditioning ensured that each day of testing ended with a consistently depleted pack. Following SOC conditioning, the vehicle was connected to an AC Level 2 EVSE unit with a J1772 standard connector. The EVSE was set for immediate charging, such that the charging unit's contactors closed within seconds after the EVSE's cord set was plugged into the vehicle. However, the vehicle's charge schedule was set for a 6:00 a.m. departure time, which delayed the flow of power. "Departure" mode delays charging until the time when the vehicle determines it must start charging in order to reach a full charge by the departure time specified. Charging typically started between 1:00 and 2:00 a.m. for a 6:00 a.m. departure time.

## 2.3 Vehicle Settings and Conditions

The following list describes the settings and conditions for all tests:

- A single 185-lb driver performed all tests. There was no cargo in the vehicle.
- Cruise control was prohibited for all tests due to the possibility of icy roads on days below freezing and for consistent driving style for tests performed when ambient temperatures were above freezing.
- No accessories other than the climate control system were used during testing.
- All tests were performed with the vehicle in "normal" mode (as opposed to "sport" or "mountain" modes).
- Prior to the first test in January 2014, tire pressure was set to the manufacturer's recommended inflation pressure of 38 psi. This was done with ambient and tire temperatures at 39°F.
- Testing was only performed on days when the road was clear of snow or slush.
- Chevrolet offered an option for the Volt that allows the driver to select the temperature at which the engine may run to assist heating in electric mode [3]. However, the vehicle tested was not equipped with this option.

## 2.4 Data Acquisition

Data were logged from the Volt's controller area network during driving using a Drew Technologies DashDAQ data logger. The vehicle was charged using a Schneider Electric indoor residential AC Level 2 EVSE unit, wired in series with an Eaton IQ250 revenue grade power and energy meter with data logging capability. The power meter was installed downstream of the EVSE so that it would measure power and energy at the connection to the vehicle. This equipment was stored in a weather-proof container in the parking stall adjacent to the vehicle's parking stall. Figures 2 and 3 show the parking layout and equipment.

An ambient temperature data logger was mounted in a solar shield on the container housing the charging equipment, which is visible in Figure 2. A closer view of the mounted solar shield is shown in Figure 4.

Figure 2. Volt charging location with charging equipment in weather-proof container.


Figure 3. Schneider Electric AC Level 2 EVSE unit in series with Eaton IQ250 power and energy meter.

Figure 4. Solar shield housing the temperature data logger.

# 3. RESULTS AND ANALYSIS

## 3.1 Driving Results

Variations in traffic flow, timing of traffic signals, and other factors caused variation in the profile of speed versus time from test to test. Table 1 provides summary metrics that characterize the test route and variation from test to test.

Table 1. Test time and speed summary statistics.

| | Trip Time (min) | Average Speed (mph) | Average Nonzero Speed (mph) | Max Speed (mph) |
|---|---|---|---|---|
| Maximum | 30.7 | 41.0 | 42.2 | 70.2 |
| Median | 28.3 | 37.2 | 39.5 | 67.1 |
| Minimum | 26.1 | 33.5 | 37.2 | 65.9 |
| Mean | 28.2 | 37.2 | 39.6 | 67.1 |
| Standard deviation | 1.1 | 1.9 | 1.4 | 0.8 |

The 16.9 mile test route was designed to be short enough that it could be completed with the vehicle operating entirely in CD mode. The test was repeated to fully deplete the battery. On most days, this occurred during the second test. Therefore, this test included both CD and CS operation and is referred as a "mixed" test. On some days, an additional test was conducted with the vehicle operating entirely in CS mode. Figure 5 shows the gasoline fuel economy measured and the average ambient temperature for each test conducted. Fuel economy in this figure was calculated by dividing the gallons of gasoline consumed between key-on to key-off during one test by the distance driven in that test. Electrical energy consumption was not factored into this calculation.

For all CD tests with an average ambient temperature above 29°F, the test was completed entirely in EV mode, with no gasoline consumed. Below this temperature, some gasoline was consumed during CD tests. Data from testing showed that the Volt engine comes on when the ambient temperature drops to or below 27°F. When this happens, the vehicle displays the message "Engine on due to temperature." If the temperature was at or below 27°F when the vehicle was started at the beginning of a test day, the engine ran while the vehicle was at rest with the defroster on. By the end of the 5-minute defrost period, the engine had typically turned off and did not come back on until the battery was fully depleted. However, there were tests when the ambient temperature was above 27°F at the start of the test, but it dropped to or below 27°F during the test drive. This caused the engine to come on during driving, reducing the EV miles driven during that test drive. When the temperature was very cold (i.e., 15°F or lower), the engine turned on when the vehicle was first turned on and also periodically during the test drive, even if the vehicle was in CD mode. This explains why CD test and mixed test fuel economy dropped with colder temperatures.

Mixed-mode tests naturally had lower fuel economy than CD mode tests, because the vehicle operated in CS mode for some portion of the test. CS test fuel economy was relatively constant in the temperature range tested and serves as a baseline for comparison. At extremely cold temperatures, CD test fuel economy approached CS test fuel economy. This is because the engine cycled on and off frequently throughout the test due to temperature. The coldest CD test was conducted when ambient temperature averaged -15°F. Gasoline fuel economy was measured at 47 mpg.

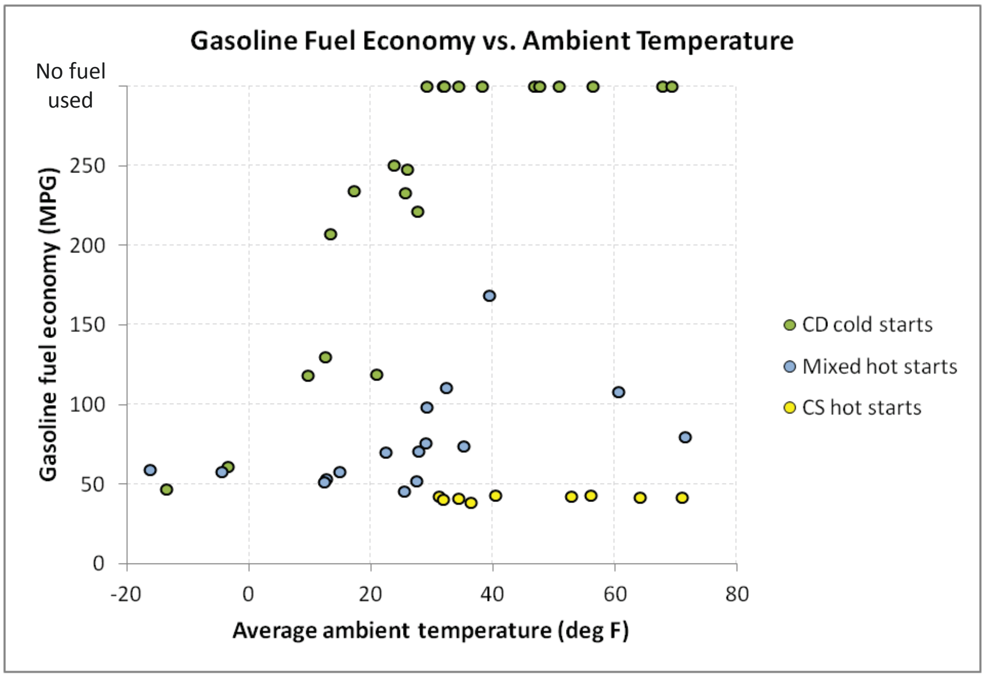


Figure 5. Gasoline fuel economy measured on tests with different operating modes versus ambient temperature.

Because the Volt is a dual-fuel vehicle, electrical energy efficiency must be considered in addition to gasoline fuel economy to understand the overall energy efficiency of the vehicle. Figure 6 shows measured electrical energy efficiency in relation to average ambient temperature for all tests. The metric shown expresses efficiency in terms of electrical energy consumption per mile. It was calculated by dividing total energy discharged from the battery during a test by the distance driven in CD mode during the test. Figure 6 shows that the electrical energy efficiency during the coldest CD test was 311 Wh/mi (based on direct current [DC] measurements).

Figure 6 also shows that electrical energy consumption per mile increased and therefore, efficiency decreased, as temperature decreased to about 15°F. Down to this temperature, consumption in the first test of the day (i.e., when the vehicle started the test "cold") ranged from 246 DC Wh/mi at 68°F to 452 DC Wh/mi at 17°F, an 84% increase. As discussed earlier, this is due to increased losses and climate control accessory loads at colder temperatures. For the tests conducted below 15°F, electrical energy consumption showed a decreasing trend because the engine was on for a greater portion of the test and offset electrical power consumption from the battery.

Mixed-mode tests and three CD tests were performed following the first test of the day, so the vehicle had already been warmed up by the start of these tests (i.e., the vehicle started the test "hot"). This reduced the energy consumption necessary to complete these tests.

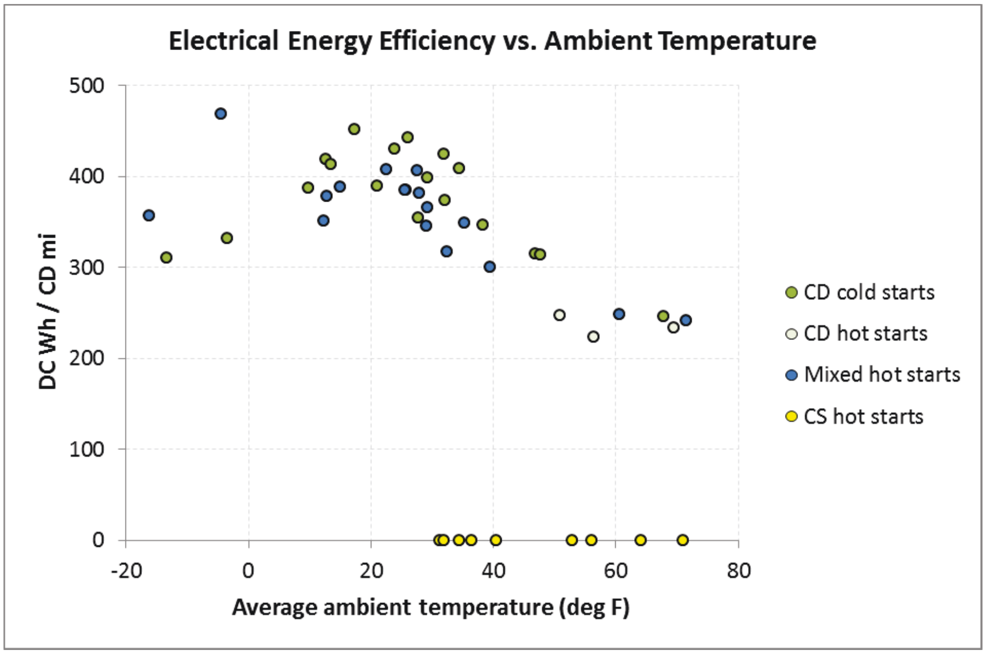


Figure 6. Electrical energy efficiency in EV mode with respect to ambient temperature.

Perhaps the measure of performance most noticeable by the driver is the Volt's EV range. This is typically thought to be equal to CD range, but this is not always the case at cold temperatures. For this paper, EV range was calculated as the distance traveled while the engine was off. Any distance traveled while the engine was on due to temperature was not included. CD range was calculated as the distance traveled, regardless of engine state, until the battery SOC was sufficiently depleted to cause the vehicle to transition to CS mode. CD range did not equal EV range during tests when the engine operated due to cold temperature. Figure 7 shows how the EV range and CD range changed with temperature.

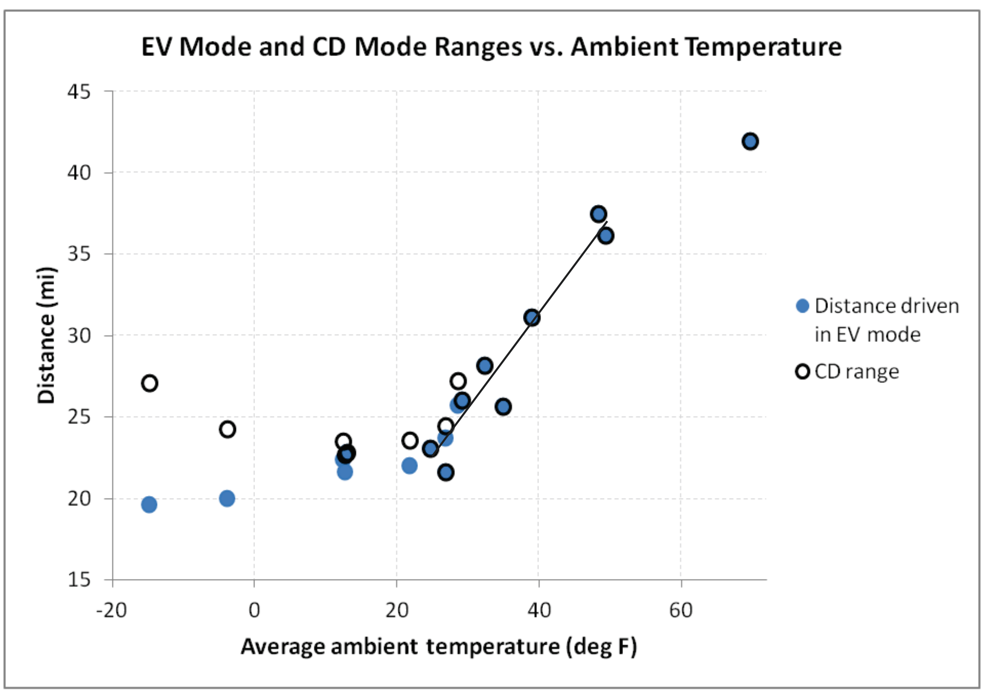


Figure 7. EV and CD range with respect to ambient temperature.

Figure 7 shows a dramatic decrease in EV and CD ranges as temperature decreased. The maximum EV range was 42.0 miles, achieved when ambient temperature averaged 70°F. The minimum EV range was 19.7 miles, which was seen in the test averaging -15°F. A linear trendline fit between the EV range measurements between 25 and 50°F shows an average decrease in EV range of 0.6 miles per degree. EV and CD range began to diverge when average ambient temperatures fell to the upper or mid twenties, because the temperature dropped to or below 27°F at some point during several tests in that range, forcing the engine to come on. CD range actually increased in tests averaging below 20°F, because the engine cycled on frequently due to temperature and apparently offset the power for propulsion discharged from the battery. The rate of decrease in EV range slows below 20°F and is presumably also benefitted by more frequent engine operation.

## 3.2 Charging Results

Charging energy consumption ranged from 12.53 to 13.73 AC kWh, as shown in Figure 8. Charging energy increased with decreasing temperature on some nights up to 18 Wh per degree Fahrenheit. However, charging energy consumption remained nearly constant with decreasing temperature on other nights. Possible reasons for an increase in energy include increased battery resistance at lower temperatures (if the battery had not been heated), recharging of energy lost during battery heating prior to charging, and losses during charging due to active heating of the battery. The reason for inconsistent variation in charging energy consumption with decreasing ambient temperature is not clear. Additional instrumentation of the vehicle is required to understand this.

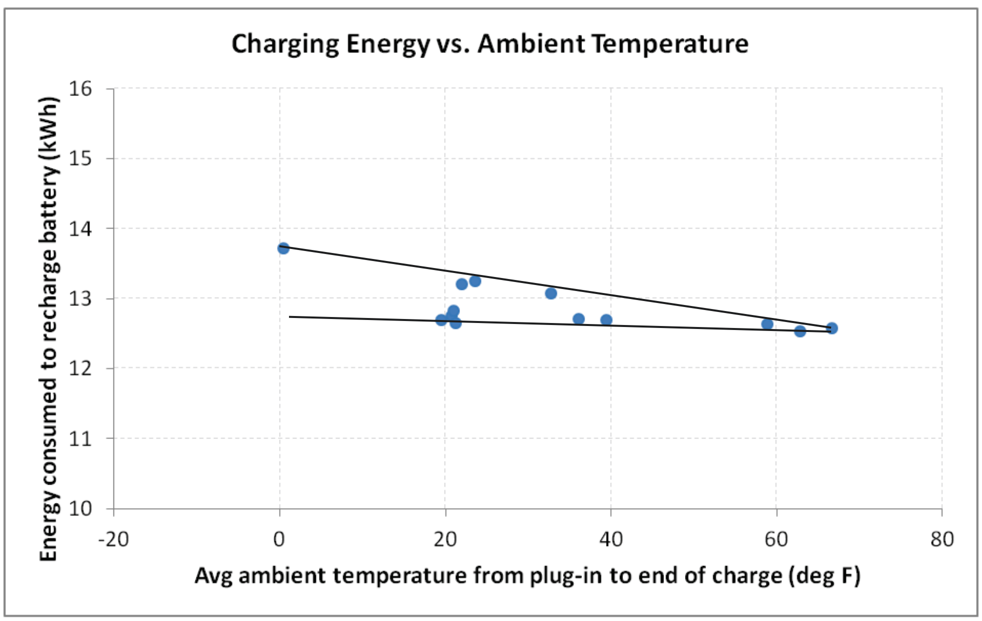


Figure 8. Charge energy consumed with respect to average ambient temperature.

On Friday evenings, the vehicle was plugged in as usual, but it remained plugged in until Monday morning. This provided the opportunity to observe whether the Volt continued to draw power if it remained connected to the grid after the battery was fully charged. Figure 9 shows a trace of the 5-minute average power (blue line), cumulative energy consumption (black line), and ambient temperature (magenta line) over time for a weekend charging event. The period of actual charging took place between hours 12 and 17. The EVSE supplied 12.76 AC kWh to the vehicle during this time. Note the eight power spikes visible after hour 20. This power was presumably drawn to periodically heat the battery. This post-charge power draw resulted in additional energy consumption of 3.56 AC kWh. Naturally, the energy consumed due to post-charge power draw is a function of how long the vehicle remains plugged in. The short power spikes peaked between 1.8 to 2.6 kW and lasted for 10 to 25 minutes. The frequency of occurrence increased as ambient temperature decreased, although not enough data were collected to quantify this relationship.

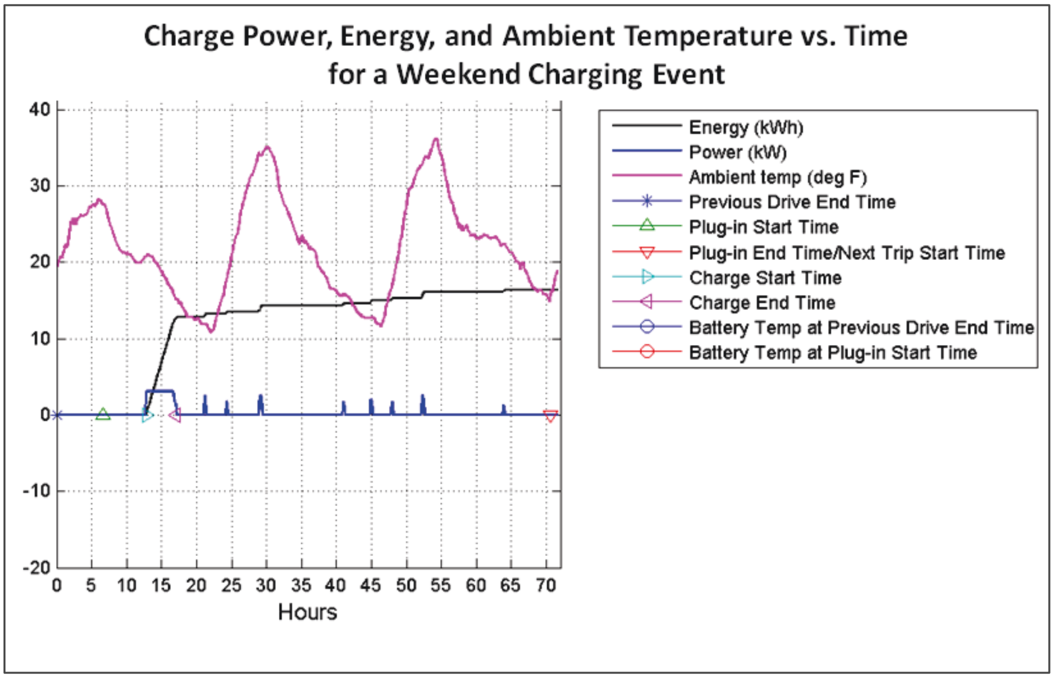


Figure 9. Time history data for a charging event when the vehicle was left plugged-in over the weekend.

When the vehicle was powered on at the start of the first test of the day and when the ambient temperature was above 27°F, the Volt consumed power from the grid to operate the climate control system for defrosting, drawing 2 to 2.6 kW of power during a 5-minute defrosting period. If the temperature was 27°F or below, the engine turned on and no additional power was drawn from the grid.

# 4. CONCLUSION

On-road testing of a 2012 Chevrolet Volt was performed during the winter and spring months to determine the impact of cold temperature on driving and charging efficiency. A single test vehicle was parked and charged overnight in an unsheltered parking stall and driven by a single driver in the morning along a specified route. The route included a mix of rural, city, and highway roads in the Idaho Falls, Idaho area. Tests were repeated until the vehicle's battery was depleted to the point where the vehicle transitioned from CD to CS operation. On some days, an additional test was performed to record CS-only operation. Both the vehicle and the charging equipment were instrumented to record energy consumption and other usage parameters during driving and charging.

Ambient temperatures ranged from -17°F to 70°F during testing. Gasoline fuel economy, electrical energy consumption, EV mode range, and CD mode range varied significantly over this temperature range. As an all-electric capable vehicle, the Volt was able to complete the test route without consuming any gasoline, until the ambient temperature fell to 27°F. At that point, the vehicle's control system commands the engine to start periodically. As tests were performed at even lower temperatures, the engine cycled on more frequently and fuel economy dropped further. The coldest CD test was conducted when ambient temperature averaged -15°F. Fuel economy was measured at 47 mpg. This approached the limiting case when the vehicle's CD fuel economy matches the fuel economy achievable during CS-only operation. Electrical energy efficiency during this test was 311 DC Wh/mi. Electrical energy efficiency across all CD tests with cold starts ranged from 246 DC Wh/mi to 452 DC Wh/mi. This 84% increase in consumption can be attributed to the effects of cold temperature and climate control load. The Volt's full-charge EV range dropped from 42.0 miles at 70°F to 19.7 miles at -15°F, a reduction of 53%. EV range fell off fairly linearly in tests averaging 50 to 25°F at a rate of 0.6 miles per degree Fahrenheit. CD range diverged from EV range in tests when temperatures were 27°F or less, because engine operation due to cold temperature also slowed the rate of battery depletion. Energy consumption during overnight charging ranged from 12.53 to 13.73 AC kWh. Energy consumption increased with decreasing temperature, but not at a consistent rate. Additional instrumentation is required to determine the cause of this variation.

These results do not capture the full range of variation expected in undirected day-to-day vehicle usage, nor do they establish the performance limits of the Chevrolet Volt. Nevertheless, the results presented herein are sufficient to demonstrate significant trends. These trends can be used to guide expectations of plug-in electric vehicle advocates and provide a benchmark for research and development efforts.

# 5. REFERENCES AND FOOTNOTES


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