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ELECTRIC VEHICLE PERFORMANCE IN NORTHERN CLIMATES

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Abstract

Electric vehicles were tested for winter cabin comfort, battery thermal management efficiency, effect of lubricant stiffness on power use, and the applicability of low rolling resistance tires to winter conditions. Low temperatures increase cabin heating requirements and degrade battery performance, thus, a thermal (heating) model was developed to evaluate heating and insulation alternatives. Increased frictional resistance to vehicle motion accounts for a further increase in power consumption during winter months. Some of the increased resistance can be abated by the use of lubricants suitable to winter temperatures. Additionally, low rolling resistance tires can decrease the vehicle resistance (increasing range) in all weather conditions; however, these tires may not have adequate traction for winter environments. Laboratory tests in cold rooms and on-road vehicle testing were used to evaluate the effects of temperature on the components of vehicle resistance, focusing on lubricants and tires, and to measure the snow traction of low rolling resistance tires.

Thermal Measurements and Modeling

Two of the many concerns related to the operation of electric-powered vehicles in winter are battery performance and occupant comfort. Measurements of temperatures and energy use during environmental chamber tests were made and compared with thermal models developed for the cabin and battery enclosures. Environmental chamber tests were conducted at 4°, -7°, -18°, and -32°C. The test procedure simulated driving for one hour with and without preheating the vehicle cabin. Additional tests examined the effects of adding thermal insulation to the floor, doors, and roof. The complete set of data and model descriptions are presented by Richmond[1].

The test vehicle (Fig. 1), was a 1995 Solectria *Force*, an after-market, all-electric conversion of General Motor's Geo Metro four-door sedan. Received with the car were insulation panels sized to fit on the floor, doors and headliner. The panels were made of 1.27-cm fiberglass mat.

The vehicle contains two battery enclosures, one located in the trunk area, the other in the engine compartment (13 batteries total). A battery thermal management system supplies heat to the batteries while the charger is plugged in. The system consists of insulated battery enclosures, with a heating pad under the batteries, and a thermostat.

Environmental Chamber Tests

The controlled temperature tests were conducted in CRREL's Materiel Test Facility, where temperatures can be maintained as low as -54°C. For these tests, two large evacuation fans were placed in front of the vehicle to simulate the air flow during driving at 40 to 48 km/h. A series of heaters setup outside the building served as a battery load. Thermocouples were located throughout the interior and exterior of the cabin and battery enclosures. The stock cabin heater (2000 W) was disconnected from the vehicle batteries and powered through a power transducer. Three additional 1500W heaters were placed on the floor at the driver's side (one heater) and on the passenger's side (two heaters). The temperatures measured by three of the cabin thermocouples were used to control activation of the heaters when temperature dropped below 20°C. The cabin heater controls were set for recirculating air, with air flow from the floor and dash vents. Heater fan speed and temperature were set on high, and the doors remained closed.

Two scenarios were simulated: preheating the vehicle followed by driving for about one hour, and a "quick" start test in which there was no preheating before driving. Driving was simulated using fans to force air flow over the vehicle and connecting an electrical load of approximately 40 A (3.56 Ω) to the vehicle battery bank.

The vehicle cabin was assumed to be at a steady thermal state, when the interior temperature was at 20°C and the energy supplied was nearly constant. When the test chamber was above -18°C, the cabin air quickly rose to the desired temperature using only the vehicle heater. The temperatures from a thermocouple located near the center of the steering wheel (Fig. 2) approached the desired interior temperature of 20°C within the 1 hour of preheating, except for the test at -32°C. At 60 minutes, additional heaters were turned on, accounting for the change in slope of the temperature curves; this is seen prominently for the test at -32°C. Typical measurements made using the data from the power transducers are plotted in Fig. 3.

When these tests were completed, insulation was added to the floor, the door panels, and roof. Some air gaps were created between the panels and the doors due to the handles, contoured arm rests, and dome light. Additionally, the plastic covering on the headliner panel sagged, creating an additional air gap. These gaps enhanced the insulating quality of the panels (and were not modeled), reducing the energy that otherwise would be required. The addition of the panels resulted in a 15% energy savings.

Cabin heating requirements are in Table 1 for still air (cabin preheat phase), simulated driving with preheating, and simulated driving without preheating. At the temperature of -32°C, during the one-hour test segment where only the vehicle's 2000W heater was used, cabin temperatures were raised only to 13°C and 9°C for still air and moving air (simulated driving), respectively.

Table 1
Cabin Heating Requirements

Test temperature, °C	4°	-7°	-18°	-32°
Steady state, still air, W	475	863	1302	1919
Simulated driving w/ preheat, W h[1]	550	1128	1517	2323
Simulated driving w/o preheat, W h[1]	900	1532	2020	2013

[1] These two conditions represent transient conditions; the heating requirement is thus the total energy used during each test phase.

Steady-State Thermal Cabin Model

A simple steady-state thermal model of the vehicle cabin was developed using the methodology for determining building heating loads. The procedure assumes a uniform interior cabin temperature. Table 2 contains a comparison of values predicted with the model and those measured during the tests.

Battery Enclosure Model

The battery enclosure model attempted to model the steady-state heat loss of a two-dimensional cross section of the front battery enclosure. A finite difference approach was used. Comparisons are not as good as expected. This seems to be due to unknown thermal conductivities of the plastic bubble type material used as insulation, and, an effective or average conductivity value for the batteries.

Transient Cabin Model

A transient heat transfer model of cabin heating was developed to model the time dependent energy requirements of the vehicle cabin, while being warmed by a given heat source from an initial cold condition corresponding to the exterior temperature. The model is based on a lumped capacity method[2], and is basically a transient heat balance using the temperatures and heat sources (sinks) shown in Fig. 4. Material properties of the composite sections are based on weighted averages, using surface thickness and area as weighting factors. Comparisons of the model with test results are shown in Fig. 3. In general, good agreement is observed in both the initial (transient) warmup period and in the steady solution.

Table 2
Comparisons between the Steady-State Model and Test Measurements

	Temperature 4°C		Temperature -7°C	
Condition	Model	Test	Model	Test
Still air	434 W	475 W	789 W	863 W
Moving air (fans on)	716	550	1220	1128
Still air w/ floor insulation	437	---	745	812
w/floor and door insulation	392	---	668	754
w/floor, door and headliner insul.	368	---	629	733

Figure 1
The Solectria *FORCE* Test Vehicle

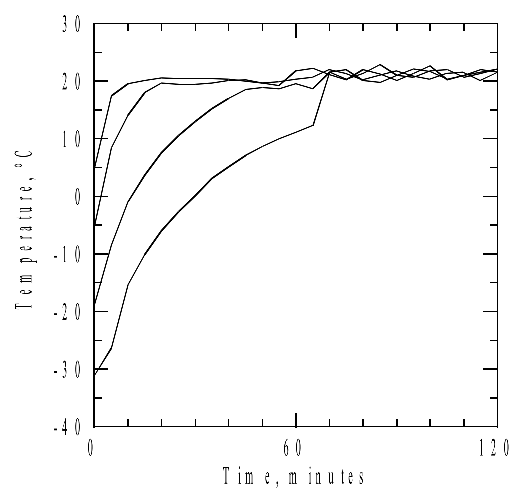


Figure 2
Air Temperature near the Steering Wheel

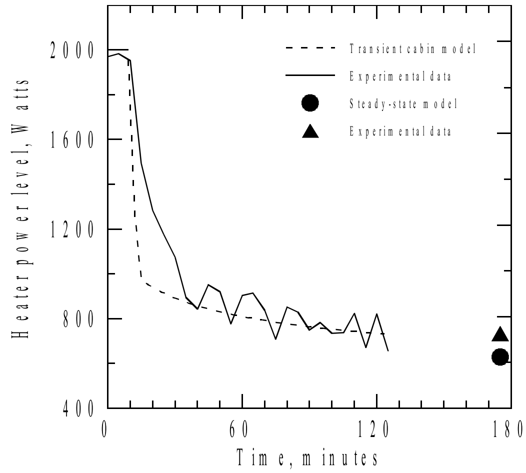


Figure 3
Comparison of Cabin Models and Experimental Data at -7° C

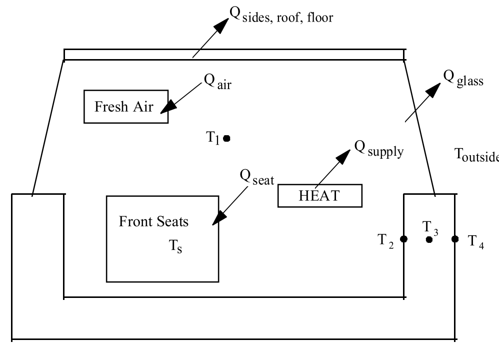


Figure 4
Temperature and Heat Flow Locations for the Transient Cabin Model

Role of Lubricants in Winter Power Consumption

One factor that may contribute to the reduction in the range of electric vehicles in cold conditions is the increased viscosity of lubricants, which increases the power requirement to move the vehicle. Using a 1995 electric conversion of a Geo Metro, we hoped that by replacing the standard, factory-installed lubricants with those with superior low-temperature properties, a significant improvement would be realized in the useful range at low temperatures.

There are three lubricated assemblies in the modified '95 Geo Metro: the motor bearings, the differential, and the wheel bearings. Since the motor operates at high speeds and is in a comparatively warm and protected area of the vehicle, the power losses from low-temperature stiffening of lubricants in these bearings probably would not contribute significantly to the overall power losses. The differential assembly is lubricated with gear oil, which may thicken somewhat at low temperatures. However, the differential is also in a fairly sheltered location, and is warmed slightly by heat lost from the battery box. Therefore it is also not likely to contribute significantly to any power loss due to thickened lubricants. Finally, the wheel bearings are sealed and packed with standard, factory-applied grease. They are in a very exposed location and the grease could be significantly affected by environmental temperatures. They were the primary focus of the lubrication testing.

The study involved two phases. In the first phase, conducted in a refrigerated chamber, we made measurements of the breakaway torque (the force necessary to overcome the increased viscosity of the grease after a prolonged, undisturbed period) and the running torque (the steady-state force required to maintain rotation of the bearing after the grease has softened) of a number of greases at temperatures near -18°C. The plan was to identify the best overall performer in the cold, that is, the grease that provided the lowest breakaway torque and running torque. In the second phase the power consumption of the vehicle in normal operation was measured for two weeks with the standard supplied bearings, and then for a second two-week period with bearings packed with the low-temperature grease identified in the first phase. Experimental procedures and results are fully described in Diemand and Stanley[3].

Phase 1: Torque Measurements of Chosen Greases

Since the grade of grease used in the wheel bearings of passenger vehicles is normally NLGI 2, six NLGI-2 greases specifically formulated for low-temperature use were chosen (Table 3).

Lubriplate Mag-1 (an NLGI 1 grease) and Lubrimatic (an inexpensive, all-purpose grease not formulated for low-temperature use) were included to define the lower and upper ranges of the torque expected in these tests. Shell Alvania, the factory-installed grease, is also included in the table, although we were unable to obtain a sample for testing until Phase 2 was nearly complete. It was wrongly assumed that it would be similar to Lubrimatic.

Table 3
Summary of the Greases Tested

	Manufacturer's specs			Breakaway torque[2] (g-cm)	Running torque[3] (g-cm)
	NLGI[1] grade	Viscosity in Centistokes 40ºC	100ºC		
Lubriplate Mag-1	1	23	unknown	364	191
Novagard Silicone G330M	≈ 2	25-40	25-40	759	251
Summit Low Temp Lith.	2	23	5.1	794	331
Summit Mil-G 10924F	2	30.8	5.8	1281	59
Kendall SHP	2	130	14	1363	233
Shell Alvania EP 2	*2*	*165*	*16*	*1431*	*234*
Citgo MP Lithoplex	2	220	23.8	1614	345
Lubriplate 1200-2	2	183	17	1855	241
Lubrimatic	2	unknown	unknown	3489	544

[1] NLGI = National Lubrication and Grease Institute.
[2] The breakaway torque is the single highest reading, usually the first, in the data file.
[3] The running torque is the average of the last 100 points in the data series.

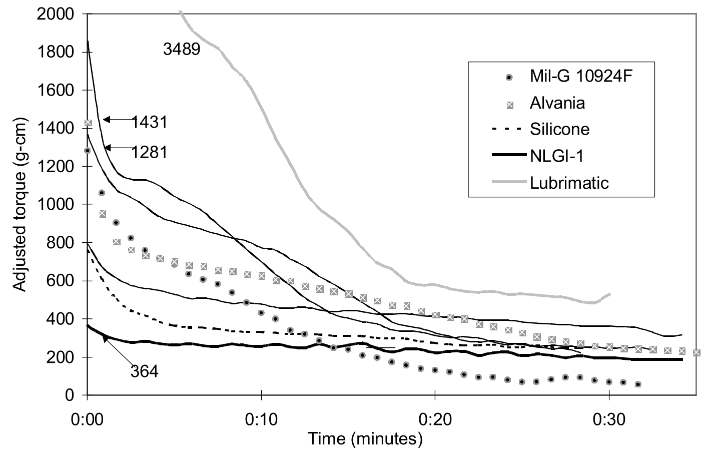
The test method used to compare the candidate greases was slightly modified from the *Standard Test Method for Low-Temperature Torque of Ball Bearing Grease* (ASTM D 1478-91). The tests were done in an insulated refrigerated box at -18°C. Sets of bearings were packed with the grease samples and left to cold soak overnight. One after another the bearings were mounted in the test apparatus. The test began after the temperature in the cold chamber returned to -18°C. Data were taken for periods up to about 30 minutes, or until the torque was no longer decreasing.

These raw data were reduced by taking running, one-second averages, and a comparison of this selection of greases is given in Table 3 and Fig. 5. Summit Mil-G 10924F was chosen for phase 2 testing because of its good breakaway torque and excellent running torque as shown in Fig. 5. It is also clear that the performance of Shell Alvania was very similar to that of our chosen candidate.

Phase 2: Field Tests

The objective of the field tests was, first, to determine whether a measurable reduction in the power loss associated with winter conditions could be realized by using a lubricant specifically formulated for low-temperature applications, and, second, to quantify this power saving.

The car was operated normally for 2 weeks, during which we recorded temperature and power consumption for each trip. At the end of this time we changed the grease in the wheel bearings to Summit Mil-G 10924F and again operated the car normally, recording temperature and power consumption as before. The power consumption was calculated from the measured electrical current and voltage to the motor. The front bearing temperature at the start of each trip was taken to be the ambient temperature.



Curves not specifically identified in the legend are rejected candidate greases.

Figure 5
A Comparison of the Performance at Low Temperatures of Greases Tested in Phase 1 as well as the Factory-Installed Grease (Alvania)

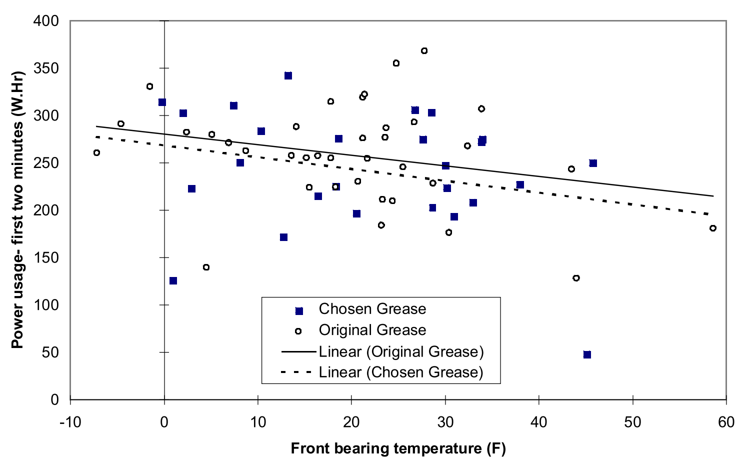


Figure 6
Relationship of the Front Bearing Temperature at the Start of the Trip to Power Consumed During the First 2 Minutes of the Trip

Figure 6 shows the power consumption during the first 2 minutes of each trip. These initial data, rather than the overall consumption, were used because there was considerable variation in the trips as a whole, both in duration and in nature (that is, highway vs. stop-and-go). In general, the first two minutes were more uniform and could provide a more reliable comparison.

It is clear from Fig. 5 that Alvania's performance in the cold was similar to that of the low-temperature greases chosen for this test. It is not surprising, then, that there was little difference between the performance of the car before the grease change, and after the Summit grease had been applied. The performance of these two lubricants appears to have been virtually identical.

Winter Traction and Rolling Resistance

Increased frictional resistance to vehicle motion accounts for a significant reduction in vehicle operating range during winter months. Although tires designed specifically for use on electric vehicles optimize rolling resistance (maximizing operational range), their rolling resistance increases as temperature drops and traction may not be suitable for snow and ice. Conversely, snow tires have good traction on snow and ice, but have high rolling resistance, which causes an increase in the power needs and, therefore, reduces vehicle range.

Eight test tires were used in the evaluation of traction and motion resistance in winter conditions: five were chosen to represent tires that are commonly specified for electric vehicle use (labeled EV), and three represent tires commonly used in winter conditions in northern climates (labeled SNOW). To eliminate some of the variability, tires were of the same size whenever possible. Each tire was operated at the pressure specified by the manufacturer and at 60% of the specified pressure. A temporary reduction to 60% of normal operating pressure was estimated to improve winter traction while keeping the increase in resistance and energy consumption at a reasonable value. Additional details on testing and analysis can be found in Shoop[4].

Winter Traction

Winter traction testing was completed using the Uniroyal-Goodrich Traction Tester[5]. The test procedure was a modification of the SAE standard test procedure J1466 for straight-line driving traction in snow.

Five different winter surfaces were tested as reported in Table 4. Three of the snow surfaces were on a prepared test course that was tilled and compacted specifically for snow traction testing. The warm snow (0.6°C) was also tilled and compacted but was not generally suitable for production traction testing. A fifth test surface was completed on buffed ice at above-freezing air temperatures, the worst possible case for traction.

Analysis of the traction curves established that the snow tires maintained a high level of traction even with high wheel slip, while the EV tire traction was highest at low wheel slip. Traction was also compared using a traction coefficient based on either a peak value or an average value over a specified range of wheel slip. The data were normalized by dividing by the equivalent traction of the Standard Reference Test Tire (SRTT). Figure 7 shows that the traction values averaged of a range of 40% to 300% slip (with respect to vehicle speed). The EV tires have ratings less than the SRTT for all but one case. Snow tires 1 and 2 perform better than the SRTT on all surfaces, while snow tire 3 performs better than the SRTT for three of the five surfaces.

When tire pressures were reduced to 60% of the specified inflation pressure, the traction ratings increased for nearly all cases, and in some cases the EV tire traction exceeded that of the SRTT and was close to the performance of a snow tire (at a specified inflation pressure).

Comparing the performance on the different surfaces, the snow tires had the best traction on cold snow, and the EV tires tended to have better traction on the warmer surfaces than on the cold snow.

Table 4
Winter Traction Test Surfaces

Test Date	Test Surface	Air Temp. (°C)	Surface Temp. (°C)
20 Jan. 1996	Groomed snow	-19.2	-10.9
23 Jan. 1996	Groomed snow	-8.8	-7.8
31 Jan. and 4 Feb. 1996	Groomed snow	-3.6	-5.3
6 Feb. 1996	Snow road	3.0	0.6
8 and 9 Feb. 1996	Buffed ice	0.4	0.0

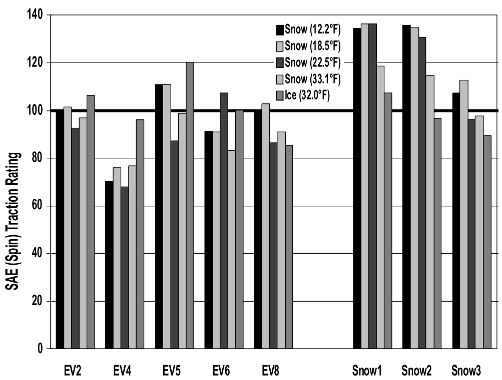


Figure 7
Traction ratings as a percent of

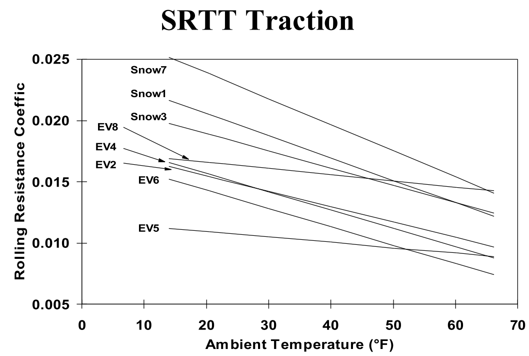


Figure 8
Rolling Resistance Coefficient Increases as Temperature Drops

Resistance (Road Load) Measurements

The components of vehicle motion resistance were measured using a Solectria *E10* (an electric conversion of the Chevrolet S10) instrumented to measure torque, motor power, vehicle speed, and wheel speed. The torque meters are designed to measure either the torque in-board or out-board of the torque meter, depending on how the test is performed, and were used to measure wheel bearing torque, driving gear (driveline) torque, brake drag, and tire rolling resistance. Temperature was measured at various location on the vehicle as well as the tire, road, and air temperature.

Tire Rolling Resistance

Rolling resistance coefficient, the rolling resistance force divided by the vehicle weight, is presented as a function of temperature in Fig. 8. Each line represents a linear best fit to a minimum of four data points for each tire. All tires show an increase in resistance as temperature drops, and the snow tires clearly have more resistance than the EV tires. The degree of temperature dependence is a function of tire construction; the snow tires consistently show a larger effect than did the EV tires. The drop in inflation pressure causes a substantial increase in resistance for all tires, although EV tire rolling resistance was "on average" still lower than the resistance of the snow tires at normal pressure. At the lower pressure, some of the EV tires show a large increase (39% to 83%) in temperature dependence.

Because rolling resistance is related to energy consumption (*Power loss = RR coeff. × veh. speed × tire load*), the DOT/EPA has proposed the following guidelines to rate the fuel efficiency of tires based on rolling resistance coefficient: [6]

- Fuel economy rating of A for tire rolling resistance coefficient below 0.01
- Fuel economy rating of B for tire rolling resistance coefficient from 0.01 to 0.015
- Fuel economy rating of C for tire rolling resistance coefficient greater than 0.015

Rolling resistance coefficients at 0° and 24°C are shown in Fig. 9. Most of the EV tires fall within the A grade at 24°C, but only EV5 and EV6 make the A grade at 0°C (and specified pressure). Some snow tires have a grade A rating at 24°C but drop to grade B or C at 0°C. None of the tires have an A grade at low pressure and low temperature.

Total Vehicle Resistance

Total vehicle resistance, or road load, is the sum of the air drag, wheel bearing resistance, brake drag, driveline resistance, and tire rolling resistance. Therefore, the temperature effect on total vehicle resistance and the relative contributions of each factor can be calculated based on the data collected with the Solectria *E10*. This is shown in Fig. 10 for the *E10* vehicle with tire EV5.

At low speeds (8 km/h), tire rolling resistance was the major contributor to both the total vehicle resistance, and to the increase in vehicle resistance due to low temperatures (even when using low rolling resistance tires). At highway speeds (88 km/h), the tires are still the major contributor, but the effects of air drag are significant, accounting for 40% of the increased resistance at low temperature for this vehicle-tire combination. Because the amount of air drag depends on speed, drag coefficient and area, it is lower for small aerodynamic vehicles, such as the GM *Impact*. Thus, a different (smaller) vehicle may exhibit a higher "percentage" increase in vehicle resistance at low temperatures[7,8] due to the lower value used to normalize the data; however, the absolute value of the increased tire resistance is probably similar to what was measured here.

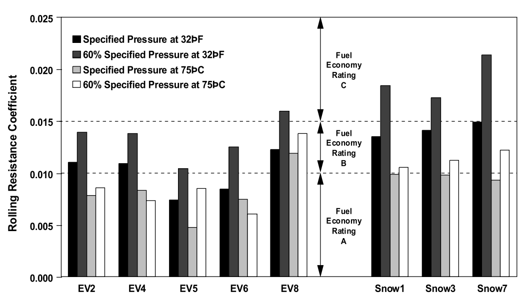


Figure 9
Rolling Resistance Coefficients at 0° and 24° C and Proposed Fuel Economy

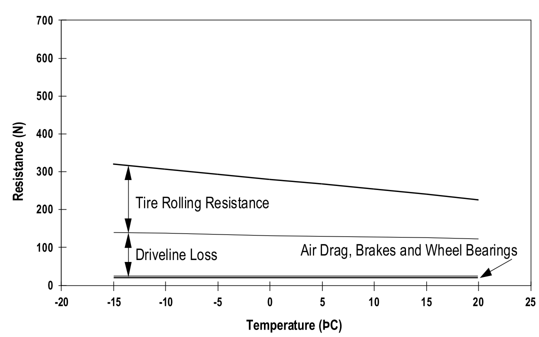


Figure 10
Total Vehicle Resistance at 8 km/h (EV5)

Summary

Environmental chamber tests were used to monitor cabin and battery enclosure temperatures, and heating requirements for the Solectria *Force*. The 2000W cabin heater could preheat the cabin to 20°C within two hours for outdoor air temperatures as low as -18°C. Additional insulation reduced heating (power) requirements by 15%. Thermal models of the cabin were used to compare various insulation schemes but the two-dimensional model of the battery enclosure did not perform well. Further work is needed to identify thermal properties of the vehicle materials.

In terms of lubricant-related low-temperature effects, the scatter in our data may somewhat obscure the relationship between temperature and power consumption, as well as the relative performance of the two greases. Nontheless, Figure 6 suggests that for both greases, “start-up” power consumption increases by about 10% with a 11°C decrease in temperature. Further, the chosen candidate performs slightly better than standard grease. However, since these data place greater emphasis on breakaway torque than would be the case in normal operation, the relative performance may differ for longer trips. The lab tests of our chosen grease and the supplied grease indicated that they were very similar products – that is, both were competent, low-temperature performers. This is reflected in their nearly congruent power curves (Fig. 6). The implication is that the use of either of these offer considerable power savings over a standard grease, such as Lubrimatic, whose breakaway and running torque may be two to three times greater.

Low rolling resistance tires are important for optimizing the economy of electric vehicle operation. Five types of electric vehicle tires were evaluated under cold winter conditions and compared to traditional winter tires in terms of traction and rolling resistance. Other contributions to vehicle resistance (brake drag, wheel bearing resistance, driveline resistance, and air drag) were measured to estimate changes in the different components of vehicle resistance with temperature. Tire rolling resistance is the primary contribution to increased vehicle resistance at cold temperatures, with snow tires having both higher resistance and a stronger dependence on temperature than low rolling resistance tires. Lowering tire pressure increases both resistance and the temperature dependence for most tires, but it also improves traction and therefore may serve as a temporary measure in winter conditions.

Acknowledgments

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