Empirical study of energy consumption of electric vehicle taxies

Data from the Trondheim electric vehicle taxi experiment

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Report

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ABSTRACT

The city of Trondheim has a goal of a more environmentally friendly transport service to and from Trondheim Airport, Værnes, a distance of 30 kilometers from the center of Trondheim. The taxi operators want to use electric vehicles (EV) as taxies serving the urban areas in Trondheim, and trips to and from the airport. The vehicles in the project are off the shelf Nissan Leafs which use a combination of fast and slow charging. This report focuses on the energy consumption part of the Trondheim electric taxi project. The project seeks to evaluate how commercially robust taxi operations are if based on EVs. This report focuses on an empirical study of EV energy consumption observed under real-world conditions. In this dataset the airport service was operated by five Nissan Leaf and data were collected during two periods in 2012, March and June. Based on the data collected from the EVs, the emission was calculated as if the trip had been conducted by a conventional taxi. Thus the reduction in environmental impact due to usage of EVs as taxies could be calculated.

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<td>Final report</td>
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# Table of contents

1 Background .......................................................................................... 5

2 Data collection ...................................................................................... 5
   2.1 Carwings and data types ................................................................. 7
   2.2 Privacy issues .............................................................................. 7
   2.3 Data exchange to another country ................................................ 7

3 Dataset preparation .............................................................................. 8
   3.1 Data processing and challenges ..................................................... 8
   3.2 Emission calculations ................................................................. 9
   3.3 Manual inspection of routing algorithm ....................................... 9
   3.4 Strategy for dealing with errors .................................................. 10

4 Data analysis and results ....................................................................... 10
   4.1 Is average energy consumption different between winter and spring? 11
   4.2 Differences between winter and spring conditions, temperature and humidity 12
   4.3 Can differences in energy consumption be explained by improved driving style? 12
   4.4 Energy consumption in relation to trip type ................................... 12
   4.5 Potential emission reductions switching to EV taxies ........................ 13

5 Conclusion .......................................................................................... 13

6 Acknowledgements ............................................................................. 14
1 Background

The municipality of Trondheim aims for a more environmentally friendly transport service to Trondheim Airport, Værnes. A consortium consisting of the taxi industry, the municipality of Trondheim, a local electrical utility company (Nord-Trøndelag E-verk) and the national airport authority (AVINOR) wanted to evaluate taxi operation based on electric vehicles (EV) as a transport service to and from the airport. The main objective of the Trondheim electric vehicle taxi project is to evaluate taxi operations (airport taxis and local taxi services) running with EVs. The vehicles were off the shelf Nissan Leafs which used a combination of fast and ordinary charging. The goal was to evaluate if EVs as taxies was a commercially sound idea. The project was supported by Transnova (www.transnova.no).

SINTEF Transport Research were asked to participate in the project to evaluate the environmental and climate impacts of introducing EVs in the taxi fleet and compare it to the use of conventional diesel taxis. The project assesses the energy consumption under varied weather and road conditions, temperature and topography. The project focuses only on emissions to air from taxi operations in a "tank to wheel" perspective. The study is not a full lifecycle evaluation and thus there are no emissions calculated in relation to the building and dismantling of vehicles and infrastructure. It is also assumed that electrical energy is supplied from hydroelectric power and thus emissions from consumption of electrical energy is assumed to be 0 gram of pollutants emitted per kilowatt-hour consumed. SINTEF are using analytical methods developed in the research project Green Freight (Norvik et. al., 2011) for calculating both locally and globally affecting emissions. To calculate the potential emission reduction that EVs can have, a simulation of conventional vehicles on the same routes was conducted.

2 Data collection

The basis for this study is the ability to collect data from EV taxis under real world conditions. The study focuses on six EVs bought for taxi operation. The taxis are owned by the drivers themselves, and the drivers are organized in a taxi pool for assignment allocation. One car operates mainly in Stjørdal (Stjørdal Taxi), the other 5 taxis was managed by Trønder Taxi (located in Trondheim). Stjørdal is a small city located in close proximity to the airport, about 35 kilometres north of Trondheim. The EV taxis are in regular taxi operation that mainly consists of three segments; airport taxi service, urban taxi service and taxi driving for schoolchildren and childcare.

![Nissan Leaf's internet interface to vehicle status](image)

Figure 1 Nissan Leaf's internet interface to vehicle status

Data was collected in three specific periods. First a pilot study was conducted in February 2012 to test the data collection routines. The purpose of this testing period was to test the data communication and data
storage. Figure 1 shows an example of how data from the vehicle is presented to the vehicle owner via the internet using Carwings. Carwings can best be described as a fleet management for the private car, where one can monitor the vehicle and control certain features like heating the vehicle while plugged in.

Figure 1 shows that the vehicle is online and is able to report data about itself, in this case battery status. Nissan developed a logging system based on the Carwings technology already available in the vehicles. Data from the pilot was not used in the final evaluation.

To collect data for the analysis two registration periods were chosen. The two periods of four weeks were chosen in cooperation with the taxi owners. The first registration period was in March and the second was in the end of May and beginning of June. The initial plan was to have one winter period and one summer period, in order to see the effect of low temperatures on energy consumption. But controlling the weather is far from an exact science and to our dismay, the winter period turned out to be quite mild and the summer period turned out to be quite cool, 2.7 versus 9.4 degrees Celsius. For the sake of the reader the periods are labeled winter and spring.

The idea was to compare winter (registration period 1) and spring (registration period 2) in relation to energy consumption. Table 1 shows participation of the 6 vehicles that were supposed to be part of the study and their actual participation. The table served as a checklist for the needed activities to be performed in order to get data from the two periods. First the Carwings system had to be updated. Then the vehicle owners had to set a data dump frequency of 30 minutes. This means that the vehicles will transfer the location and energy consumption data to the backend system every 30 minutes. Except for one vehicle (no 5) all vehicles were configured correctly and data was collected from the vehicles.

Table 1 Vehicles, participation and status

<table>
<thead>
<tr>
<th>Vehicle No</th>
<th>Carwings</th>
<th>30 min. frequency</th>
<th>Pilot (13.02-26.02)</th>
<th>Registration 1 (05.03-31.03)</th>
<th>Registration 2 (21.05-17.06)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ok</td>
<td>ok</td>
<td>ok</td>
<td>ok</td>
<td>ok</td>
</tr>
<tr>
<td>2</td>
<td>ok</td>
<td>ok</td>
<td>ok</td>
<td>ok</td>
<td>ok</td>
</tr>
<tr>
<td>3</td>
<td>ok</td>
<td>ok</td>
<td>ok</td>
<td>ok</td>
<td>ok</td>
</tr>
<tr>
<td>4</td>
<td>ok</td>
<td>ok</td>
<td>ok</td>
<td>ok</td>
<td>ok</td>
</tr>
<tr>
<td>5</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>ok</td>
<td>ok</td>
<td>ok</td>
<td>ok</td>
<td>ok</td>
</tr>
</tbody>
</table>

Throughout the registration periods there were two meetings with the drivers. The meetings contributed the project with valuable information and knowledge about the drivers experience in relation to use EVs as taxis. Also how drivers made practical arrangements for coping with low temperatures and the effect on range planning and predictability. One of the owners did not manage to use the EV for taxi purposes so the dataset is based on 5 EV taxis instead of the planned 6. Nissan International SA was very helpful and contributed significantly to the project in terms of modifying the vehicle software to enable logging of the specified parameters.
It was the Nissan Leaf navigation system that was reprogrammed for SINTEF to collect and download vehicle data directly from the five Nissan Leaf's participating in the project. The download process was in addition supported by Nissan Europe R&D department. Each vehicle owner had to make a certain configuration change in order to activate the navigation system and prepare it for transfer of data to Nissans' Data Center for processing.

2.1 Carwings and data types

The 5 taxis were all connected to the Nissan Carwings system, an important part of Nissans' management system for electric vehicles. The Carwings system is a vehicle management system that enables users to control certain parts of the vehicle via the internet. Charging status, vehicle heating and accumulated trip information is communicated from a connected vehicle to a centralized system. The Carwings system also has access to the internal communication bus of the vehicle and hence other data types than standard could be extracted. After a discussion with Nissan a specialized firmware update was sent to the 5 taxis.

The following data types were extracted from the internal vehicle communication bus:

- **VIN** – a unique vehicle identification number
- **Time** – timestamp with time zone set to Universal Coordinated Time (UTC)
- **Latitude** – latitude for the observation
- **Longitude** – longitude for the observation

For each trip (trip defined as period when ignition is on), the following parameters were recorded:

- Outside temperature – outside temperature from the vehicle at the time the ignition was turned on
- Energy consumption per trip (Wh) Motor activate (driving)
- Energy consumption per trip (Wh) Climate control
- Energy consumption per trip (Wh) Others (lighting, auxiliary power, etc.)
- Energy Regeneration per trip (Wh)

The file format was peculiar as the energy consumption data and temperature data for the trip were stored only on the first observation of the trip.

2.2 Privacy issues

To be able to record energy consumption with sufficient detailed data location the project used satellite navigation (GPS). This could possibly violate the taxi drivers' right to privacy as their activities could be retraced when processing the data. All drivers and taxi owners signed consent forms that stated that they agreed that the parameters listed in chapter 2.1 were recorded and used for simulations to estimate emissions from a diesel vehicle used on the same trip. Nissan also implemented a procedure that the driver had to go through to start logging. The driver had to actively start logging each time the ignition was turned on. For data analysis and storage only vehicle identification numbers were recorded. There exist no record of which driver used which vehicle at a specific time. Thus the dataset cannot be used to identify the difference between drivers, but it enables a higher level of privacy for the drivers.

2.3 Data exchange to another country

The Norwegian Data Protection Authority (Datatilsynet) approved the data collection from vehicles participating in the EV taxi research project. Special care had to be taken as data was temporarily stored in a
country not part of the EU (Japan). Each owner of the vehicle and his drivers did sign a Consent form and by that allowed Nissan to collect following data from the vehicle:

- Geographical location (10 seconds interval + time stamp UTC)
- Energy consumption (for driving, air conditioning and others)
- Outside temperature when the ignition was turned on

Data collected from the vehicles was sent to NISSAN’s data center in Japan for temporary storage and then to SINTEF in Norway. The data received from NISSAN were used by SINTEF to assess energy usage patterns for electric vehicles and used as input to simulate energy consumption and emissions from a typical diesel fuelled vehicle. The data collected was only used for energy and emission studies.

3 Dataset preparation

The data was received as a set of text files from Nissan. Each file contained data for one vehicle for a specific time period. The first stage of processing was to organize data by trips. Only complete trips were stored along with the energy consumption figures including an ordered list of time stamped GPS positions. The ordered GPS positions would later on be used to simulate the same trip with a diesel powered vehicle to calculate emissions. A set of custom Python scripts were used for processing the text files. Python is an open source programming language that has very good support for text processing. The processed trips where stored on disk as binary objects that could subsequently be read by other Python scripts. In the next stage routes driven where identified as sets of road links with associated properties.

3.1 Data processing and challenges

In order to calculate the reduction in emissions resulting from a change from diesel taxies to electric taxies the routes driven by the electric powered taxies had to be used as input to the emission calculations. A large European research project took forward a near complete set of emission functions where key input parameters were vehicle speed, vehicle type and road gradient (Boulter and McCrae, 2007). In the Green Freight project a road network containing vehicle speed and gradients was produced, and imported into a special database that had a set of routines for calculating emissions between coordinate pairs (Norvik et al., 2011). Thus a trip could be decomposed into a set of coordinate pairs and the database functions would calculate the route between the coordinates and the resulting emissions based on the vehicle used.

However there are some issues with how the Norwegian road network is coded and the map matching technique used. For roads with more than 2 lanes it is not unusual in the dataset to "draw” test roads as two distinct roads with on way permissions. This can cause issues if GPS quality is weak, thus leading to false positives in the matching in the opposite direction. This leads to vehicles having to travel to the next intersection then return in the other direction. This was solved by excluding GPS positions that where matched to the trunk road network with one way coding. This fix solved the problem, as the shortest path between the last point before the vehicle entered the trunk road network and the point where the vehicle left the trunk road network are used.

The second problem related to map matching was in urban areas, where the GPS drifted when vehicles stopped at intersections. Plots of the GPS data showed that some points drifted into the intersection and were mapped to one of the exit links in the intersection and often the wrong exit links which would results in the
simulated vehicle taking a trip around the block to get back to the intersection again. A fix for this was to exclude points matched to the beginning and end of a road link. If the GPS point was matched to the 10 first or last percent of the link the observation was excluded from the routing algorithm. If faulty routes where simulated then the emissions result would be wrong. Thus maps of the selected routes and the GPS points were drawn for each trip. Then a manual inspection was carried out to find trips where the routing algorithm had failed. 1489 out of 2227 trips passed the visual inspection and where used in the analysis. Not all trips were excluded because of routing errors, some were removed because the vehicle was moved a short distance, i.e. the ignition was turned on and the vehicle moved up a spot in the taxi queue and then the ignition was turned off.

3.2 Emission calculations

The emission calculation that was built from the emission function taken forward in the ARTEMIS project is called SEMBA (SINTEF Emission Module Based on ARTEMIS). The core of SEMBA is a software library of emission functions. These functions are dependent on average vehicle speed, gradient of the road. For the calculations in this project a typical taxi was used. A typical taxi in Trondheim is a Mercedes with a 2-liter diesel engine according to Trønder taxi, the local taxi operator. The emission calculations are done on a link by link basis where average vehicle speed, gradient and link length are inputs. The required input to SEMBA was found using the GPS positions and a routing algorithm.

3.3 Manual inspection of routing algorithm

Figure 2 shows an example of an image file that was produced for control purposes. The trip shown in the figure has a routing error. The blue line shows the simulated route, while the red line shows the GPS track of the vehicle. Where the blue and red line deviates there is a routing error. In this case the routing algorithm has erroneously selected a route through the city center. Images for all trips were created and manually inspected and classified as: ok, routing error, only a single point of data or erroneous distance calculations.
3.4 Strategy for dealing with errors

There are several error types identified in the dataset.

- The trip consists of only one link (very short move < 200 meters)
- Distance is erroneously calculated
- Errors in energy measurement data
- Errors in energy calculation
- Routing errors

Errors are classified into these groups and data from these observations are removed from the dataset. The sources of these errors are either routing issues, the routing algorithm is not able to pick the correct route, or there are errors in the network like extreme gradients that cause energy calculations to be off. There are also two cases where the recorded energy usage seems to be flawed. An explanation for these erroneous recordings could be that the vehicle was plugged into the charger without turning off the ignition, and the continued the trip. Thus the vehicle received more energy, but this was not recorded in the energy consumption figures extracted from the vehicle. Very short trips, shorter than 1 kilometre, were also excluded from the final dataset, because these trips include minor movements by the taxies as they are waiting in taxi lines.

4 Data analysis and results

The complete dataset before removing erroneous and short trips contains 2227 trips with an average trip length of 14.4 kilometres. In the final dataset the average trip is 15.6 kilometres and contains 1489 trips.

For analysis purposes the trips where divided into four categories:

- **Airport trip**
  This trip type consist mostly of motorway driving with speed limits ranging between 80 and 90 km/h. On these trips there are seldom queues or slow moving traffic. Gradients are moderate.
- **Central Trondheim trip**  
  These are trips in the city center of Trondheim. The area has high levels of traffic during short peak periods. The area is close to flat and thus there are no challenging grades. Speed limits range from 30 to 50 km/h.

- **Suburban Trondheim trip**  
  The near city trips can include some motorway driving, and quite significant gradients as this area encompass the hills surrounding the city. Speed limits range from 30 to 80 km/h. There could be sporadic queues in the peaks on this road network, much less than the city center area.

- **Other long-distance trip**  
  Other long-distance trips are trips made to the rural areas surrounding Trondheim. One would expect speed limits between 50 and 80 km/h. Seldom queues, but road gradients could be significant at times.

### Table 2 Number of trips by trip category

<table>
<thead>
<tr>
<th>To and from airport</th>
<th>Central</th>
<th>Suburban</th>
<th>Other long-distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>198</td>
<td>405</td>
<td>824</td>
<td>62</td>
</tr>
</tbody>
</table>

### Table 3 Number of trips in the different time periods (winter, spring)

<table>
<thead>
<tr>
<th>Period 1 (winter)</th>
<th>Period 2 (spring)</th>
</tr>
</thead>
<tbody>
<tr>
<td>489</td>
<td>1000</td>
</tr>
</tbody>
</table>

#### 4.1 Is average energy consumption different between winter and spring?

A simplistic calculation of average energy usage per kilometre shows the difference. In the dataset the average energy consumption per kilometre in the winter period was 185 Wh/km while energy consumption in the summer was 157 Wh/km. The difference is statistically significant at the 95% level. This energy included traction energy, energy to the air condition, miscellaneous energy usage and regenerated energy.

To further understand the difference only energy used for traction was analysed. Here the traction energy per kilometre in the winter period was 183 Wh/km while for the spring period the energy consumption was 181 Wh/km. And this difference is not statistically significant at the 95% level. Thus in terms of energy going to the motor it seems like winter and summer conditions are equal.

Looking at the energy recuperation per kilometre in the summer and winter we see a difference. In the winter vehicles were able to regenerate approximately 45 Wh/km while in the spring the regenerative rate had increased to 54 Wh/km. It is hard to judge what part of this is related to drivers learning how to use their vehicles and the impact of the temperature. There was no snow cover on the roads in the winter period, but there could be patches in the suburbs.

There is a difference in energy consumption between spring and winter conditions, but the difference seems to be linked to energy usage of the air condition system. For the winter period air-condition related energy consumption was 0.33 Wh/second while in the spring the consumption had dropped to 0.17 Wh/second. There could also be a learning factor involved as the winter period came first when the drivers first got their cars. While in the spring period the drivers had used the cars for several months and learned how to maximize the driving range.
4.2 Differences between winter and spring conditions, temperature and humidity

The average temperature weighted by number of trips in each period shows that the mean temperature was greater in the spring than in the winter period: 2.7 degrees Celsius compared to 9.4 degrees Celsius measured at the Voll metrological station in Trondheim.

The vehicles also measured the outside temperature at the onset of each trip. A mean of 3.33 degrees was found for the winter period, while the mean temperature in the spring period was 11.3 degrees Celsius. A simple statistical test (t-test) shows that there is a significant difference between the mean temperatures in the two periods. There is also a difference in the mean relative humidity between the winter and spring period. In the winter the mean relative humidity was 78% while in the spring period the mean relative humidity was 68%.

4.3 Can differences in energy consumption be explained by improved driving style?

Better driving here is defined as better utilizing the vehicles traction energy. To test if there was learning involved the simulated energy consumption for a diesel vehicle was used in conjunction with the vehicle traction energy minus the regenerative energy. Thus there is ratio between the energy that the vehicles should have used and the energy that the vehicles actually used. In the winter period the ratio was 4.1. This means that the electric vehicle used 4.1 times less energy for traction purposes than the diesel powered vehicle. In the spring period this ratio had climbed to 4.6. The difference is statistically significant at the 95% level. This should indicate that the drivers had about 9% better efficiency in the spring period. This indicates that the drivers learned to utilize their vehicles better between the two periods.

4.4 Energy consumption in relation to trip type

In this section we are trying to see if there are any systematic variations between where the vehicle was driven. The taxi trips were split into trip types according to type of trip and location. 4 different trip types were chosen based on local knowledge: trips related to going to the airport, trips in the city center, trips near the city and other long distance trips.

Table 4 Trip types and energy consumption

<table>
<thead>
<tr>
<th>Trip types</th>
<th>Consumption (Wh/Km)</th>
<th>Regenerated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airport trip</td>
<td>195</td>
<td>47</td>
</tr>
<tr>
<td>Central Trondheim</td>
<td>169</td>
<td>56</td>
</tr>
<tr>
<td>Suburban Trondheim</td>
<td>153</td>
<td>49</td>
</tr>
<tr>
<td>Other long distance</td>
<td>185</td>
<td>38</td>
</tr>
</tbody>
</table>

From the data it is clear that there are some differences between where the vehicles are used. Differences are seen with respect to traffic situation, gradients and speed limits. What is striking about the data is the higher energy consumption per kilometer on the routes that have a high degree of motorway driving (high speeds and moderate gradients). It is surprising that the close to city trips have the lowest energy consumption per kilometer as the gradients experienced here are the greatest in magnitude. It was also surprising that the regenerative energy rate was almost as high for the trips to the airport as the suburban trips.
The drivers had limited experience with EV's in the first period. But the energy efficiency improved between the two periods. The data did not indicate that this was linked to weather, thus it is possible that the increased energy efficiency is related to driver learning. This should be studied further in another project to see if there is a real learning effect and if and how this effect levels off.

4.5 Potential emission reductions switching to EV taxies

The potential for emission reductions were calculated by using the SEMBA tool to calculate emissions using the EV taxi routes as input. Thus the resulting emissions were the emissions that one would expect if the routes were driven by typical vehicles. Through discussions with the taxi operator it was decided that a typical taxi would be a 2 liter, large sedan or station wagon. The vehicle would typically follow the Euro 4 emission requirements. Total emissions were calculated from all the trips and then the total emissions where divided by the kilometers driven. This value is an emission factor and can be used to calculate expected annual emissions savings by switching to an EV taxi.

Table 5 Emissions according to trip type

<table>
<thead>
<tr>
<th>Trip type / pollutant</th>
<th>CO₂ (g/km)</th>
<th>NOₓ (g/km)</th>
<th>PM (g/km)</th>
<th>HC (g/km)</th>
<th>CO (g/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airport trip</td>
<td>132,83</td>
<td>0,54</td>
<td>0,06</td>
<td>0,01</td>
<td>0,01</td>
</tr>
<tr>
<td>Central Trondheim</td>
<td>132,91</td>
<td>0,45</td>
<td>0,07</td>
<td>0,01</td>
<td>0,02</td>
</tr>
<tr>
<td>Suburban Trondheim</td>
<td>132,04</td>
<td>0,47</td>
<td>0,06</td>
<td>0,01</td>
<td>0,02</td>
</tr>
<tr>
<td>Other long distance</td>
<td>129,31</td>
<td>0,50</td>
<td>0,06</td>
<td>0,01</td>
<td>0,02</td>
</tr>
<tr>
<td>Total</td>
<td>132,26</td>
<td>0,48</td>
<td>0,06</td>
<td>0,01</td>
<td>0,02</td>
</tr>
</tbody>
</table>

Table 5 shows emissions according to trip type. These factors can be used to calculate annual emission reductions at fleet level. The difference between the trip types is small for all emissions, as expected. The central Trondheim area has the highest CO₂ emission per kilometer, as expected. It should be noted that taxies have access to the public transit lanes and thus can maintain higher speeds in urban traffic, so the emission values should not be used for vehicles that do not have access to the public transit lanes. Thus the effect of congestion is not seen from this table.

5 Conclusion

The study succeeded in collecting empirical data from EV taxies. The main purpose of the project was to gain further knowledge about energy consumption regarding types of trips and winter / spring operations. Unfortunately the winter period was warm and the spring period was cold so that we did not manage to get the span in temperature that we wanted. Still, we saw a difference between the winter- and spring-period in relation to energy efficiency (Wh/km).

There was a significant difference between the winter and spring period. Most of the difference could be explained by increased air-condition usage during the winter period. If one only looks as traction energy, excluding energy recuperation, there is no significant difference. But a comparison that includes recuperated energy showed that the drivers were able to improve their energy efficiency between the two periods, with an observed difference of 9%. This is probably related to that the drivers learned to better utilize their vehicles,
as the drivers had very limited experience with Nissan Leaf in the first period. The vehicles were delivered 2 months before the first registration period.

The second part of the study looked at different trip characteristics in airport trips, trips in and around the Trondheim city center, trips in the suburbs, and other long distance trips. There were differences observed, and trips in the suburbs and in and around the city center proved to be most energy efficient. Given that electric vehicles are (for the moment) a limited resource in the fight against local air pollution, and that the vehicles had good energy efficiency in the city center and suburbs, it makes sense to utilize the vehicles primarily for these trips.

6 Acknowledgements
The project benefitted greatly from the support of NISSAN and their staff in collecting data from the vehicle under real world conditions. SINTEF also gratefully acknowledges financial support from Transnova for this project.

References
