CRD-UVic E-bike fleet deployment

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Abstract

The deployment of three E-bikes into the CRD fleet resulted in over 600km of recorded trip data. This data was used to inform several academic research projects as well as determine typical operational capabilities of E-bikes for the CRD fleet. The collected data showed a reduction of emissions by 99% when compared to a typical car found in the CRD fleet. Even compared to battery electric cars, the E-bikes represent a 95% reduction in emissions. Compared to both of these modes, the E-bikes also represent an over 80% reduction in capital and operating costs.

Overall, the deployment of the E-bikes saved approximately 250kg of CO2 if they replaced internal combustion engine car trips. The operating capabilities of E-bikes shows them as having half the pace of cars in urban environments. Where a car can cover 5km in 8.5 minutes, an E-bike typically covered the same distance in only 20 minutes.

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1 Introduction

The CRD E-bike pilot is a joint project between IESVic and the Capital Regional District (CRD) that is funded by a grant from the Federation of Canadian Municipalities (FCM). The E-bike project forms one part of a larger FCM funded transportation program, the Zero Emissions Fleet Initiative (ZEFI) that focuses on reducing the transportation based emissions of the CRD through fleet equipment upgrades, and academic research to support this goal.

The proposed research goals for the E-bike project are:

1. To make recommendations regarding the optimal use of E-bikes in urban commercial fleets

2. To compare the environmental, economic, and logistical performance of the operation of E-bikes in urban fleets to other vehicle modes;

3. to make recommendations regarding the regulatory constraints placed on E-bike use with respect to motor power limits

The research goals are answered through the deployment of three E-bikes outfitted with multiple sensors to capture a variety of data. The purpose of this work is to provide quantifiable, evidence-based results to inform the CRD as to the efficacy of the use of E-bikes in their corporate fleet. Additionally, this project is meant to inform other fleet operators as to the operational costs and benefits of E-bikes in commercial fleets. The final purpose of the project that is of less relevance of the CRD is to provide insight into regulatory constraints and future E-bike design guidelines to manufacturers.

The remainder of this report details the methodology and results that were used to answer the first two research goals, with some of the results that are of less relevance to the CRD detailed in the appendix.

Section 2 provides further details regarding the deployment of equipment and data collection.

Section 3 shows the relevant parts of the raw data before further analysis.

Section 4 presents the results of the analysis and subsequent discussion

2 Project Details

The data collection side of the project was achieved through the deployment of three E-bikes outfitted with sensors that logged performance metrics during each trip: a speed sensor, a GPS sensor, and a power meter. The sensor package installed on each E-bike consisted of a Garmin Edge 520 cycle computer, a Garmin ANT+ protocol speed sensor mounted on the front wheel hub, and an PowerTap ANT+ protocol hub based power meter built into the rear wheel.

Each of these sensors was connected to a Norco VLT R1 E-bike, synced to the Garmin Edge 520, with the data collected from the Garmin Edge on a weekly

Table 1: Data collection equipment for CRD E-bike Trial.

Sensor	Accuracy	Metric	OEM
Edge 520 Cycle Computer	Not listed	GPS	Garmin
Bike Speed Sensor	Not listed	m/s	Garmin
G3 Power Meter	$\pm$ 1.5 %	Watts	PowerTap

basis. The CRD staff involved in the project could reserve an E-bike through the CRD's internal online vehicle booking system. Each time staff rode the E-bike they would simply press a button to initiate data logging, and press the same button to end the ride and save the data. Seventeen users were recruited into the project, with each rider's trip data anonymized to meet CRD privacy concerns.

By the end of data collection, the CRD project resulted in a large number of trips representing over 4 months of data. There was a significant amount of non-compliance when it came to data recording with the E-bike odometers showing a total of nearly 1200km and the actively recorded data only totalling just over 600km. While the data logging was optional for CRD staff, this did likely impact the fidelity of the results as a large number of trips were missed. A summary of the recorded data used in the final analysis is presented in table 2.

Table 2: Summary statistics of E-bike use in urban commercial fleet. Values show mean of results along with one standard deviation

Metric	Value
Total kilometres travelled	607 km
Number of trips	92
Average speed	20.3 $\pm$ 5.9 kph
Average trip length	6.6 $\pm$ 5.8 km
Average trip time	25.9 $\pm$ 25.2 min

3 Energy Results

The recorded energy use while riding the E-bikes comes from the PowerTap G3 power-meter. The power data, along with the other ride characteristics (speed, location, grade) are used to understand how and when energy was expended during the trip. The energy use also allows for determination of the GHG emissions that occur from using the E-bike, as well as the electricity costs.

Table 3 shows the total energy use and power as recorded by the power meter over the course of the experimental campaign. In addition to the summary table, the recorded power data can be categorized into total energy use in response to distance travelled, grade, and speed to provide further insight as to how E-bikes are used in an urban setting.

Table 3: Total energy use and power as recorded by the rear-hub power meter.

Metric	Value
Average per-trip power	234 ± 73 W
Average per-trip energy use	40.3 ± 48.0 Wh
Average per-kilometre energy use	7.8 ± 2.5 Wh/km

Figure 1 shows on the top the per-trip values for total energy use, in the middle the average instantaneous power, and on the bottom the distance per-trip. This is done to provide further insight into how the trips vary. Some of the trips don't have a recorded power value due to issues with the sensors pairing improperly during use by CRD staff. This was remedied early on but the speed and distance values are still useful to include in the overall results.

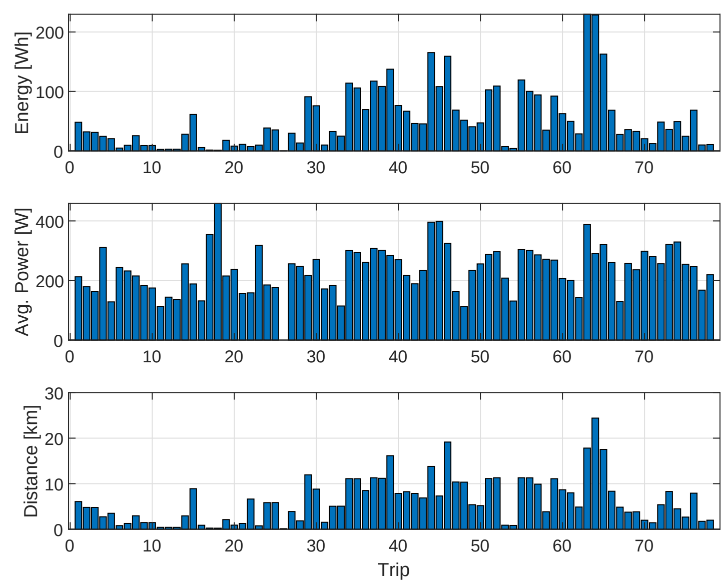

Figure 1: Per-trip energy use, average per-trip power, and trip distance for all recorded CRD project trips.

Figure 2 shows on top the time spent moving on a given grade during all trips, and on the bottom the time spent moving at a given speed during all trips. This figure is shown so that weight can be given to further findings and claims relating to energy use at these different speed, grade, and distance states. The more time spent in one of these states, the more reliable the findings can be

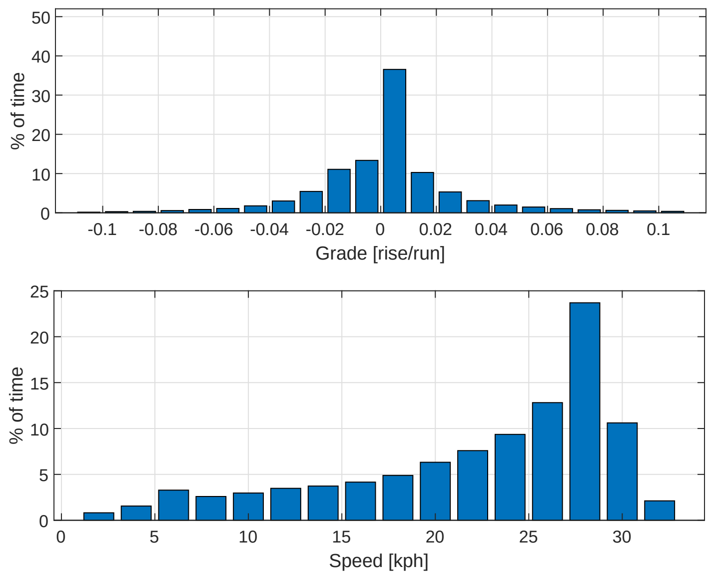

Figure 2: The percentage of total time of occurrence of energy, power, and distance for each trip that had a recorded power value

labelled. The grade portion of the figure can also be thought of as a topological characterization of the riding environment in downtown Victoria for comparisons to any other urban environments with the caveat that it is dependent upon the routes chosen by the CRD participants.

In the bottom half of figure 2 it can be seen that a clear majority of the time (50%) is spent at near the speed limit of the E-bike, meaning that participants are able to reach and maintain optimal speeds during the majority of trips.

Figure 3 shows three different figures. The top shows the energy use per distance travelled as determined by calculating the cumulative energy for each trip, divided by the cumulative distance covered. The middle shows the average instantaneous power within each distance segment. Both the top and middle sub-figure indicate that the participants did not appear to significantly reduce energy expenditure the longer they rode. This would imply that for longer trips, riders did not tire noticeably in total system output, either through maintaining personal exertion or by increasing the assist factor. The energy use remains relatively constant regardless of the distance, which shows that at least for the distances covered, the riders didn't show any major signs of fatigue. The bottom sub-figure shows some consistency in that at positive grades the rider had to output on average more power.

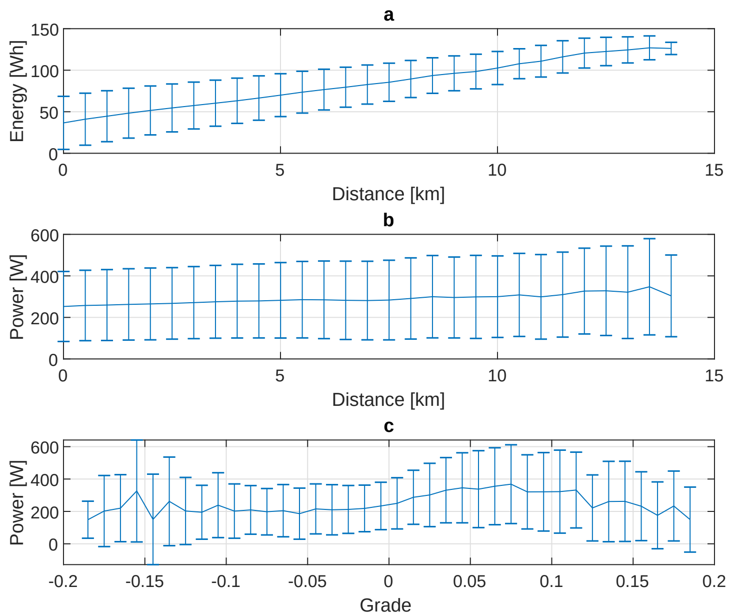

Figure 3: Energy and power related to distance and grade. Mean and standard deviation are shown in each subfigure.

4 Environmental and Economic Assessment

This section covers the quantification of the impacts of the CRD E-bike pilot project as relevant to the CRD or any other commercial fleet operator. Using the energy data detailed in the previous section, the use-phase emissions are reported, along with the operational and capital expenditures. The results are then compared to some standard fleet vehicle values to give further context as to the benefit of E-bikes in commercial fleets.

The emission accounting is straight forward. The electric energy use per kilometre as required to charge the battery at a wall outlet includes the efficiency losses due to the E-bike charger, the battery, the motor, and the losses through the mechanical drive train which are detailed in table 4.

Table 4: E-bike system efficiency estimates that links the recorded power at Powertap power meter to electricity at a wall outlet.

Charger efficiency	0.95
Charging efficiency	0.85
Motor efficiency	0.90
Drive train efficiency η_{DT}	0.96
Total electrical system efficiency η_{Elec}	0.70

The CRD E-bike emission intensity is the product of the efficiencies, times the recorded power, times the BC Hydro electrical emission intensity. The per-kilometre emission intensity is listed in table 5 along with comparative estimates for a typical sedan used in the CRD fleet. The sedan data was obtained from CRD fleet data involved in another ZEFI project. The average pace includes time stopped in traffic so at to best represent typical urban driving conditions.

Table 5: Use-phase emission intensity along with typical urban pace for E-bikes, fossil fuel and electric cars, and walking [1, 2].

Mode	Emission Intensity [kg CO2e/km]	Typical Pace [min/km]
E-bike	0.00009	4
Standard sedan	0.21580	1.7
Electric Car	0.00210	1.7
Walking	0	20

These results show a very favourable comparison for E-bikes. The E-bike offers a relative reduction in emissions of 99% compared to standard fossil fuel power cars, and a relative reduction of 95% compared to electric cars when comparing 'tail-pipe' emissions only. This near complete reduction in use-phase emissions only comes at the cost of being just over two times slower, which can shift a 5 minute trip to nearly 12 minutes.

Walking reduces emissions over E-bikes but E-bikes already represent a bare-fraction of emissions relative to fossil fuel and electric cars such that the trade-offs between emissions and pace aren't as worth-while. Since the E-bike project with the CRD logged approximately 1160 km (the riders only actively logged 623 km), an estimate of the total use-phase emissions from the E-bikes is accounted for and presented in table 6 along with an estimate of the same distance covered by a standard car.

Table 6: CRD Project tail-pipe emissions for E-bikes and comparison to other transportation modes for the same distance.

Mode	Total Emissions [kg CO2e]
E-bike	0.104
Standard Sedan	250
Electric Car	2.44

The other metric of importance is the financial costs for each of these modes. While electric cars reduce emissions versus the traditional fossil fuel car by nearly 99%, they cost significantly more than E-bikes. The financial costs of the E-bikes were detailed by the CRD and are summarized in table 7. E-bike values is sourced from the CRD project and includes safety equipment for users, added security features, and added storage such as panniers and baskets on the E-bike. Also includes regularly scheduled maintenance and an estimate of annual parts replacement costs (tires, drivetrain, etc). It does not include training costs for users or parking requirements for the E-bikes (such as secured storage, charging infrastructure, etc) as these can vary quite widely from one organization to the next and are not included in the car ownership costs.

The vehicle values assume annual travel of 10,000 km which is a low value for a commercial fleet but is meant to make it more comparable to the E-bike with respect to short urban trips. It includes maintenance, license and registration feeds, insurance costs, and upfront vehicle cost. Vehicle capital costs are sourced from respective brand websites, and the operating costs are sourced from the CAA online car costs calculator.

Table 7: E-bike, fossil fuel and electric car capital and operational costs per vehicle representing ownership over 5 years. [3, 4, 5].

mode	Capital costs [$ CAD]	Operational Costs [$ CAD]
E-bike	4,400	1,730
Chevrolet Malibu	22,295	14,000
Kia Soul EV	35,895	8,300

The type of trips the E-bikes are typically used for definitely do not cover the entire range of trip types presented by traditional cars. Cars provide a much wider range of possible trip lengths and cargo capacities. For a smart fleet planner, E-bikes open up a new category in the fleet that is optimal for short urban single occupancy trips. Larger vehicles will still be needed but when appropriate, E-bikes offer a virtual elimination of use-phase emissions as accounted for by the fleet manager, as well as an 83% and 86% cost reduction over 5 years when compared to a typical CRD fleet car and electric car respectively.

5 Conclusion

The deployment of the E-bikes resulted in a substantial amount of data to be collected detailing the costs and capabilities of these vehicles as used in an urban commercial fleet. From this data, it was shown that E-bikes emissions and operating costs are dramatically lower than both internal combustion engine and battery electric cars. E-bikes also have a highly competitive pace in urban environments with travel time only double that of cars on average.

The research also showed that the power output of the rider and E-bike didn't decrease over time even on trips longer than 10 kilometres. The energy in relation to distance in the top sub-figure of figure 2 is linear which means that average energy expenditure remained constant across most trips regardless of distance. This would imply that according to the data collected so far, fatigue is not a major issue for E-bike trips.

The data also incorporated a significant amount of travel along varying road grade. The power and speed measurements on inclines did not show any significant impacts that would indicate riders having to exert themselves or slow down dramatically.

The data collected shows E-bikes as a cost effective, environmentally friendly, and effective urban transportation solution that would fit well in most any fleet that has the appropriate trip types: 10km or less, urban environments with stop and go traffic, and limited cargo requirements.

Appendix

This section of the appendix covers a small portion of the additional analysis that was performed on the collected data. This section is included as an overview of what some of the other research was aiming to achieve.

Human Energy Contributions The typical human energy contributions that occur while riding an E-bike are important because they allow for later analysis to model larger motors while still replicating expected human behaviour. This section estimates the human power contributions that occurred during the CRD project by using a differential equation that is detailed in the author's thesis, along with equation 1 which shows the relationship between human power ($\dot{E}_h$) and motor power ($\dot{E}_m$) as a function of assist level (A).

$$\dot{E}_m = A\dot{E}_h \tag{1}$$

This analysis follows a similar format to that of section 4 but without any human or electrical energy conversion efficiencies. The results of this analysis will show the range of human power contributions as a function of speed of the E-bike as delivered directly to the shaft of the pedals from the motor and the human. Figure 4 was created by discretizing all of the power data from the CRD project into speed bins. Within each speed bin, the power was averaged (not including zero values), and the grade data was also averaged within each bin. The assist varies from a factor of 0.5 up to 2.75, matching the capabilities of the Norco E-bike used in the CRD project.

Figure 4 shows the definitive impacts of the max assisted speed (approximately 30-32 kph) after which the electric motor stops assisting the rider. As the limited speed is approached, the human power contributions diminish rapidly due to the increased power requirements. It also shows that riders don't typically exceed the maximum assisted speed unless they are on a decline (or negative grade) and in doing so have dramatically decreased power requirements.

The discretization process was repeated but now with the filter that only uses data that has a recorded grade less than 0.02 (2%) and greater than -0.02, in an attempt to remove the impact of grade on human power. The results of this process are shown in figure 5 and are used to compare with the results of an external study. Langford et al recorded an average human power contribution of 62 watts at approximately 20 kph while on level ground while using a maximum level of assist on an E-bike. Langford et al's results are very similar to the results of figure 5 which show a power of approximately 60 W at maximum assist and relatively level ground.

Finally, human power as a function of speed and grade is modelled using MATLAB's surface fit function. This fit will act as a look-up table to determine an averaged human power contribution at any particular speed and grade, such that later research can dynamically subtract this amount to determine motor contributions as loads are increased. Figure 6 shows human power as a function of grade and speed.

The surface fit plot in figure 6 has negative power values removed as displayed

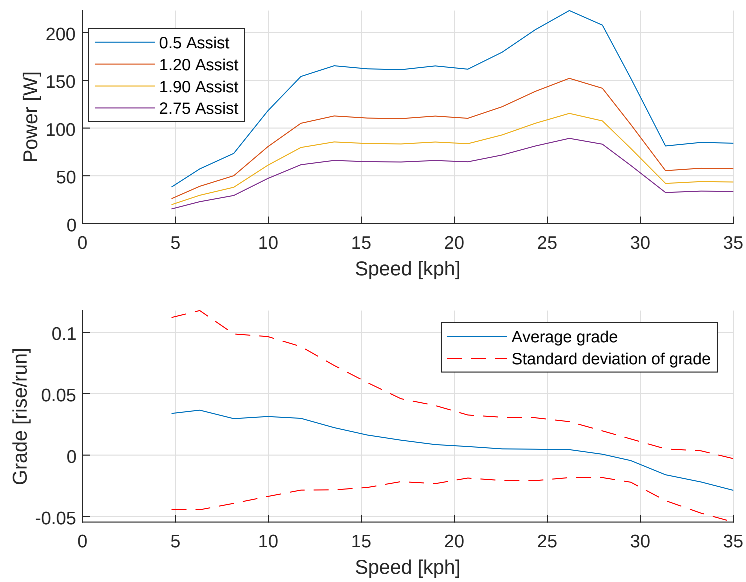

Figure 4: Estimated upper and lower average typical human power contributions for full range of Bosch Assist levels. Corresponding average grade for each speed and power.

by the white space in the figure. A clear trend can be seen that for positive grade values, speed doesn't typically exceed about 30 kph (at which point the electric assist cuts off due to B.C. regulations on pedal assisted E-bikes). In addition, almost all human power input, assuming maximum levels of assist, is less than 150 watts except in a few cases of large grade and high speed when it gets up to approximately 250 to 300 watts.

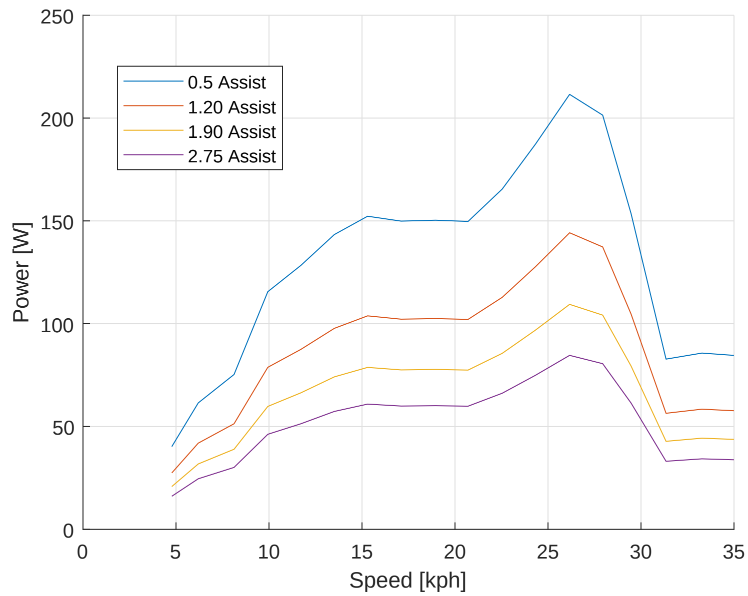

Figure 5: Human power contributions for various assist levels with impacts of grade removed. Filtered to only include power corresponding to grades less than 2%.

References

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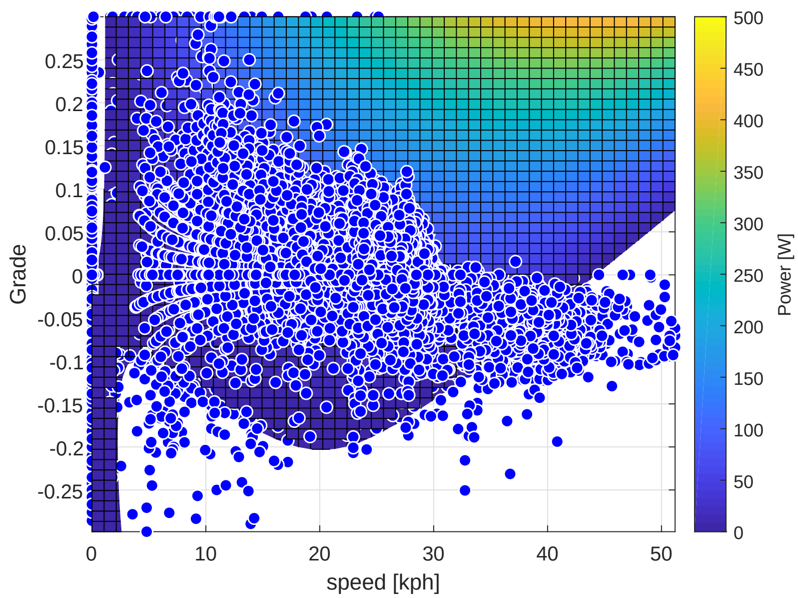

Figure 6: Human power contributions with speed and grade data points at maximum assist factor A = 2.75