CALIFORNIA AIR RESOURCES BOARD

Electric Bicycle Efficiency Compared to Conventional Delivery Vehicles

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1. Overview

California Air Resources Board (CARB) staff conducted this analysis to determine the Energy Economy Ratio (EER) for electric cargo bicycles (ECBs) for use in the Low Carbon Fuels Standard (LCFS) program. Due to limited availability of data, staff was only able to make a conservative EER estimate of 24.16 for ECBs used for regional package delivery (RPD), and 32.06 for ECBs used for delivery of local goods and services (LGS), as compared with internal combustion engine (ICE) delivery vehicles for both regional and local delivery.

A. What is an EER?

An EER is a dimensionless value that represents the efficiency of a fuel as used in a powertrain as compared to a reference fuel. A "fuel" for purposes of the LCFS Program is any means of propulsion. EERs are often a comparison of miles per gallon of diesel fuel equivalent (mpdge) or gasoline gallon equivalent (MPGe) between two fuels. In this case, the EER represents a comparison between electric cargo bicycles and their diesel or gasoline ICE counterparts, specifically a diesel on-road delivery van. In the LCFS Program, EERs are used in calculations to generate credits. Higher EERs will result in more credits generated.

B. What is an ECB?

For purposes of this analysis an electric cargo bicycle (ECB) is any bicycle used for the commercial delivery of goods or services.

C. What applications are ECBs capable of?

Two general delivery models are assessed for ECB substitution in this EER:

A) Regional package delivery (RPD). The RPD model is used by UPS, FedEx, DHL, Amazon, and other major shipping companies. The comparison here assumes that larger diesel or gasoline trucks and vans are replaced by ECBs. Due to differences in operational characteristics, particularly the smaller capacity of ECBs, a modifier is used (see discussion below).

B) Local Goods and Services (LGS). The LGS model assumes that, in contrast to the RPD model, the delivery of goods and services requires shorter trips with smaller cargo and periodic or no restocking. The comparison here assumes that typical gasoline ICE passenger vehicles are replaced by ECBs one-for-one.

2. DATA SOURCES

A. Electric Cargo Bicycle (ECB) Data

Manufacturers of ECBs typically provide data on range per charge, however this data is widely questioned and may not reflect real-world performance. Manufacturers rarely report the amount of electricity used for a complete charge (e.g., in the form of kWh/charge) in relation to the stated claims of range (e.g., miles/charge or km/charge, which could be used to find kWh/mile which could then be converted to MPGe and compared to the MPG of an appropriate ICE vehicle or the kWh/mi equivalent of said vehicle). In comparison, data on the fuel required for typical recent model year ICE cargo delivery vehicles to travel a given distance (e.g., miles per gallon or MPG), while also generating public skepticism, are more readily available, sometimes from official sources and detailed studies.

Because of the lack of manufacturer data on MPGe or mpdge for ECBs, staff sought independent measurements and conducted a literature review of the energy use of ECBs. A number of academic papers and ECB delivery companies report large carbon emission reductions attributable to substituting ECBs for ICEs, however these studies do not provide key energy and distance measurements that would be suitable for an EER and transferrable to California. A key source for this EER estimate is an academic paper analyzing the comparative lifecycle greenhouse gas (GHG) emissions of an ECB delivery company in Portland, Oregon as compared to an ICE van-based delivery (Saenz, Figliozzi and Faulin, 2016).[1]

The Saenz study estimated a median fuel economy of 69.50 watt-hour/mile (0.034 kWh/mi, 29.36 miles/kWh) for the operations of the fleet across 1,150 real world measurements during the everyday business operation of the fleet.

The Saenz ECB fuel economy finding is further likely to underestimate the relative fuel efficiency of ECBs as a whole because the study measured ECB tricycles which are among the least energy-efficient ECBs available. When compared to ECBs as a whole the ECB tricycles are larger, heavier, and have more rolling resistance (due to their third wheel and resulting inability to lean into turns) than typical ECBs, which significantly reduces their relative energy efficiency (although increases capacity). Moreover, the tricycles studied use lead-acid batteries, typical of ECB tricycles, which are substantially larger and heavier than many common ECB batteries in use today, particularly lithium-ion batteries with roughly 6X the energy density by size and 3X by weight.[2] In this case each tricycle carries two 77.8 pound batteries for a total of 155.6 pounds of on-board battery.

For the foregoing reasons, the Saenz study describes a likely worst-case fuel economy for ECBs. In contrast, a tool funded by the European Union for comparing the use of

[1] Illustrating the lack of available data, the researchers stated in an earlier version of the paper, "Another important outcome of this study is that [for] the first time, to the best of the authors' knowledge, electricity consumption during electric-tricycles operations has been measured." Page 4, https://www.metrans.org/sites/default/files/Figliozzi-SaenzPaper.pdf

[2] It is true that larger capacity may reduce total distance traveled to deliver a given route and given set of packages, which is accounted for below in adjusting for operational differences.

ECBs to ICEs (Occam 2015) cited an ECB fuel economy of 0.0065 kWh/km (0.01 kWh/mi) or approximately three times more efficient than the Saenz study's findings.

B. RPD Model Internal Combustion Engine (ICE) Delivery Van Data

Comparison vehicles:

In the interest of a conservative estimate however a comparison between lead acid tricycle ECBs and two types of RPG vehicles is made. The ICE vehicles are:

a. United Parcel Service (UPS) delivery vans (2006 FCCC MT-45);
b. Amazon Prime delivery vans (Ram 1500 ProMaster)

These two vehicles provide are chosen to estimate the range of ICE delivery vans in use today. Although a variety of vans can be found in some RPG applications today (for example, Amazon contracts to private companies for some services), these two vans are among the most prominent and widely used. In the Sacramento region, Amazon has a fleet of more than 140 Ram 1500 ProMaster vehicles, and the UPS FCCC MT-45 is likely the most commonly identified RPG delivery van throughout California.

The comparison UPS-style ICE delivery van is the 2006 FCCC MT-45 tested on chassis dynamometer by the National Renewable Energy Laboratory (NREL; Barnitt, 2010). Of the duty cycles studied, the Orange County Bus Cycle (OCBC) duty speed is chosen because it best matches a typical UPS van speed which UPS reports is 10 MPH on average. Alternatively the New York City Cycle (NYCC) urban delivery duty cycle with even lower average speed would be over 55.7% more favorable to ECB efficiency and may be more appropriate for a true comparison with ECBs, which are much more likely to deliver in urban areas. In addition the duty cycle of a bus in Orange County may stop less often than a delivery vehicle on an RPD duty cycle. On the other hand, the more conservative OCBC duty cycle is California-specific and may more closely match the land use of California than NYC.

Similarly it would be much more favorable to ECBs to use a fleetwide average. EMFAC 2017 states that for Class 2B-3 vehicles, the average fuel economy is 13.7 mpg; however, this includes heavy-duty pickups which are far less fuel efficient than delivery vans so this value is not representative for the RPD model, although could be applicable for the LGS model.

The MPG on the OCBC duty cycle is 9.5 mi/diesel gallon. Using 37.95 kWh/diesel gallon, results in an equivalent to 3.99 kWh/mi.

Additional vans are also considered for this analysis. A range of common delivery vans and their estimated respective fuel economies are summarized in the table below.

VEHICLE	mpdge	kWh/diesel gallon[5]	kWh/mi	EER v trike
Class 2B-3 vehicles[1]	13.7	37.95	2.77	81.47
Mercedes Sprinter[2]	21	37.95	1.81	53.15
Chevy Express[2]	15	37.95	2.53	74.41
Ford Transit[2]	24	37.95	1.58	46.51
Amazon: RAM 1500 ProMaster[2]	18	37.95	2.11	62.01
UPS: 2006 FCCC MT-45 (OCBC duty cycle) [3]	9.5	37.95	3.99	117.49
Average UPS/Amazon Prime	13.75	37.95	2.76	81.18
Average non-UPS vans (not incl. 2B-3)	19.5	37.95	1.95	57.24
Avg of UPS & Avg of non-UPS vans	14.5	37.95	2.62	76.98
ECB Trike[4]			0.034	

Sources:

1. EMFAC 2017
2. Fuelly.com (limited data, no detail on duty cycle)
3. NREL 2010
4. Saenz et al. 2016
5. Wikipedia 2018

Choosing the ICE van efficiency:
Because the true mix of vehicles is unknown, and because their fuel economy data is mostly very limited and is not clearly matched to the duty cycle of delivery operations, in the table above an example EER is calculated for each data point available, and several averages are taken for comparison purposes. In addition note that engine idle time during delivery, which can be significant for delivery vans, is likely missing from all efficiencies listed here and would reduce those ICE efficiencies per mile.

The average between all non-UPS vans is similar to the representative Amazon van (5.5% higher). These reported efficiencies are likely not based on delivery duty cycles and thus higher than the true fuel efficiency when used in a stop-and-go urban delivery duty cycle on surface streets. As with the UPS duty cycle the bias chosen for this first conservative analysis is toward higher efficiency of the ICE vans. Because the UPS vans are a large portion of the freight mix and that proportion is unknown, and because the efficiency is the most reliable, the working assumption adopted here is an average between the UPS vans and the average of all other vans as a group. The overall fleet efficiency may in fact be a better match but is not used (and would reduce the ICE efficiency used considerably). Note also that the capacity of the UPS vans is estimated here at 3X the Amazon Prime van capacity, which would further reduce the efficiency off the smaller vans if more distance is required per day due to depot restocking trips.

Given the foregoing assumptions, the chosen base efficiency for the RPD model ICE vans, without modification for operational differences, is 14.5 mpgde or 2.62 kWh/mi (unmodified one-for-one EER of ECBs as compared to these ICE vans is 76.98).

C. LGS Model Internal Combustion Engine (ICE) Passenger Vehicle Data

A wide array of ICE passenger vehicle applications may be substituted for by using ECBs. The LGS models local trips typically based in a local store, office or distribution hub. Examples would include local pizza, grocery, and florist deliveries as well as services such as on-site maintenance and repair or other professional site-specific services. Under the LGS model, even for longer distances, for purposes of an EER a bicycle is assumed to substitute one-for-one with a passenger vehicle.

Comparison vehicles:

In the interest of a conservative estimate the same lead acid tricycle ECBs are compared with all types of passenger vehicles including pickup trucks. This is considered conservative because both bicycle and ICE delivery companies will tend to purchase the vehicle best suited for the job. An ECB can perform small/lightweight package delivery as well as delivery loads typically reserved for a pickup truck or delivery van such as furniture, boilers, and other heavy equipment (ample video evidence exists online). In addition, local delivery is assumed to occur predominately on surface streets with relatively inefficient stop-and-go travel patterns.

Weighting coefficients identifying the relative proportions of which vehicles are used for commercial delivery have not been found and likely not available given the rapid change in “last mile” delivery characteristics and rise in App-based delivery, with multiple competing services contracting individual drivers for myriad on-demand tasks. Thus it is further assumed to be reasonable to use a broad average across passenger vehicles.

ICE vehicles identified for LGS model:

According to EMFAC 2017, the average fuel economy of LDA, LDT1 and LDT2 would be 30.6 mpg (gasoline equivalent), which includes passenger cars, SUV’s, minivans, and half-ton and below pickups.

VEHICLE	**MPG**	**kWh/gasoline gallon**[3]	**kWh/mi**	**EER v trike**
Average LD[1]	30.6	33.41	1.09	32.11
ECB Trike[2]			0.034	

Sources:

1. EMFAC 2017
2. Saenz et al. 2016
3. Wikipedia 2018

Given the foregoing assumptions, the chosen base efficiency for the LGS model for ICE passenger vehicles, without modification for operational differences, is 30.6 MPG or 1.09 kWh/mi (unmodified EER of ECBs compared to these vehicles is 32.11).

3. ADJUSTING FOR OPERATIONAL DIFFERENCES BETWEEN ECB AND ICE VEHICLES

A. Adjusting for RPD Operational Differences between ECB and ICE Vehicles
Electric cargo bicycles by nature of smaller capacity cannot perform identically with UPS-style ICE delivery vans for all RPD tasks and therefore a factor adjusting the relative energy economy between the two vehicles is needed.

The Amazon Prime vans are a closer match to ECBs and a maximum capacity ECB might in theory carry the same quantity as the Ram 1500 ProMaster as currently used, but more likely at least 3X a typical cargo bicycle capacity is estimated. Amazon uses a single layer of dry sacks filled with spatially-organized packages. The sacks have a similar appearance to large bicycle paniers. The transition to ECB delivery could in theory directly adopt this existing dry sack system (see photo, below).

Amazon Prime delivery in the Sacramento region is performed by over 140 vans loaded with a single layer of dry sacks of delivery materials packed in order of delivery. (Source: Amazon delivery staff)

There are cases where differences with ECBs may be minimized or may even tip more favorably to ECBs. A recent study from the Supply Chain Transportation and Logistics Center at the University of Washington College of Engineering found that cargo bikes can be a more economical alternative for last-mile deliveries, "but this is contingent upon the distance between [distribution center] and neighborhood, number of stops, the distance between stops, and number of parcels per stop" (Butrina, Sheth, Goodchild and McCormack 2018). ECBs can take advantage in some cases of more direct routes not available to ICE vans, passing through congested traffic and enjoying ease of parking closer to the delivery site minimizing total distance, idling and delivery time, and conflicts at loading docks.

Minimizing distance to the depot/restocking hub and locating in dense areas are key to maximizing ECB efficiency. UPS now operates twenty ECB pilots globally (UPS 2018), in addition to efforts from numerous companies including DHL and FedEx. When a distributed hub model ("mini depot or staging area") is employed, the ECBs can minimize the disadvantage of smaller capacity through optimizing the efficiency of delivery patterns that minimize the distance to cargo reloading (for example, delivering in loops that return to the mini depot, a cloverleaf model). UPS reports that their estimated "break-even point for work productivity" for a cost parity with cargo bikes is 85-90% as efficient as delivery vans (UPS 2018).

"UPS believes that there's a break-even point for the e-trike relative to a truck wherein the additional time / distance spent replenishing the e-trike from the mini depot (and the cost of bringing the packages to the mini depot) evens out to some degree with the lower operating cost of the e-trike, the lessened depreciation / initial investment, the reduced (essentially non-existent apart from charging) fuel cost, etc. This break even point is most likely to occur in places with the right neighborhood typology, and is usually a moderate density urban environment with narrower streets, maybe some mixed use, but also a fair bit of older residential (that's usually closer together but not so close as to possess true vertical density)" (UPS 2018). More optimal delivery environments would be even more efficient.

In addition some ECB applications are fundamentally more favorable to ECB use than the UPS model, such as local deliveries where "last mile" does not mean daily delivery of large volumes throughout entire metropolitan regions. ECB flatbeds for example are suitable for local delivery of large items including furniture and appliances. Inter-office mail and local delivery such as groceries and prepared food, if deliveries per trip are low for both ECB and ICE vehicles, can incur comparable distances traveled for the same task, in some cases ECBs would travel less distance than ICE vehicles to complete the same task.

However, in the interest of a conservative estimate least favorable to ECBs, a comparison between deliveries per mile for ECBs versus UPS-style ICE delivery vans is made here for purposes of an operational efficiency adjustment.

Based on National Renewable Energy Laboratory (NREL) FleetDNA data (NREL 2017) compared with B-Line data (a large functional urban cargo bicycle delivery fleet in Portland, Oregon), the average parcel delivery vehicle distance traveled and stops per mile (excluding cargo bicycles) is 3.35 stops/mile. According to a report by the B-Line tricycle delivery company, B-Line ECBs averaged about 1.05 deliveries per mile (Jones 2017. The B-Line service differs because it is an LGS, not RPD delivery service and is typically delivering larger loads to fewer locations than RPD delivery, however it is the only available datapoint at this time and serves the goal of a conservative estimate even if it overestimates by a factor of three.

If we assume that the stops/mile is equal to the deliveries per mile, then the conventional delivery vans are averaging 3.19 more deliveries per mile traveled, which could be used as an assumption to adjust the overall average carbon savings of ECBs. This may greatly overestimate the penalty of ECBs.

The provision of any mini-depot increases ECB efficiency further but incurs some travel of a heavier vehicle to deliver the depot. However, this distance may be nearly eliminated in some cases, for example the UPS model is exploring solutions where "adjacent area trucks would pull a small trailer (Called a TP-60 in UPS parlance) and then drop those on site en route to their adjacent route" (UPS 2018). Because a truck would make this trip in any case (whether ECBs are employed or not); and because there is limited data on average distance to deliver a mini-depot relative to total travel; the additional distance may be relatively small or eliminated by ECB efficiency; and because mini-depots are not always needed; the ECB activity can be considered distinctly separate from both kinds of depot delivery. For purposes of LCFS the actual travel distance that is substituted is the key metric. Because of these factors and uncertainty, at this time any average effect of delivering a mini-depot is ignored for purposes of this analysis, and only the true "last mile" of delivery activity is analyzed.

B. Adjusting for LGS Operational Differences between ECB and ICE Vehicles

Because ECBs can substitute one-for-one, in some cases accomplishing the same delivery in a shorter distance by nature of bicycle permeability, unlike the RPD model, no factor is used to adjust the relative energy economy between ECBs and ICEs.

4. EER Calculations

A. Staff Estimate of ECB Median Fuel Economy

Based on the Saenz study a relatively inefficient ECB fuel economy is 34.06 watt-hour/mile (0.034 kWh/mi, 29.36 miles/kWh).

RPD Model:

B. Staff Estimate of RPD model ICE Van Average Fuel Economy
The mpgde chosen averages the UPS van (OCBC duty cycle) with the average fuel economy of a group of common delivery vans (limited data, no duty cycle), resulting in 14.5 mpdge. Using 37.95 kWh/diesel gallon, results in an equivalent to 2.62 kWh/mi.

C. Staff Estimate of Raw EER Comparing RPD model ECB to ICE Vehicles
The raw EER without adjusting for operational differences between ECBs and the overall van efficiency is therefore 0.034:2.62 = 0.013 or approximately 77X difference.

D. Adjusting for RPD Model Operational Differences between ECB and ICE Vehicles
Based on the NREL FleetDNA data compared with B-Line data above, conventional trucks are averaging up to 3.19 more deliveries per mile than ECBs. The estimated relative efficiency of ECBs is therefore reduced by 3.19 times. (This is likely a large overestimate as LPD data is used for RPD comparison.)

E. RPD Model - Adjusted Final EER
In this case the preliminary EER is adjusted by the 3.19 factor,

(2.62 kWh/mi ICE vans) / (0.034 kWh/mi ECB * 3.19) = 24.16 EER.

This EER is based on worst-case assumptions with bias unfavorable to ECBs.

LGS Model:

F. Staff Estimate of LGS model ICE Passenger Vehicle Average Fuel Economy
The average fuel economy of the light duty fleet of passenger vehicles is 30.6 MPG. Using 33.41 kWh/diesel gallon, this results in an equivalent to 1.09 kWh/mi.

G. Staff Estimate of Raw EER Comparing LGS model ECB to ICE Vehicles
The raw EER without adjusting for operational differences between ECBs and the overall van efficiency is therefore 0.034:1.09 = 0.0031 or approximately 32X difference.

H. Adjusting for LGS Operational Differences between ECB and ICE Vehicles
In this case the preliminary EER is adjusted by a factor of 1,
(1.09 kWh/mi ICE vans) / (0.034 kWh/mi ECB * 1) = 32.06 EER.

(No adjustment is needed in the LPG model. In some cases ECBs will travel less distance than the comparison ICEs to complete the same delivery tasks.)

5. NEXT STEPS

CARB staff encourages industry stakeholders to engage their expertise and resources to generate and submit additional energy/distance and operational comparison data and analysis for electric cargo bicycles. Staff will evaluate additional data when it becomes available, and will consider amending this ECB EER if such action is supported by more accurate and updated information than what was available for the instant analysis.

This analysis is intended to be the worst case with regard to cargo bikes, as a starting point in order to develop a more accurate EER over time through additional real world data and public input. There is reason to believe that these EERs are too low. The highest calculated theoretical EERs for the RPD model, using the NYCC duty cycle with no operational adjustment, was 211, almost 9X the final RPD model EER identified in this conservative analysis. The Occam 2015 efficiency without modifiers found an even larger RPD EER of 717, almost 30X higher than the final RPD model EER used here.

Please contact Mr. Jing Yuan at jyuan@arb.ca.gov or (916) 322-8875 to provide additional input or with any questions about this analysis.

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