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Empirical analysis of battery-electric bus transit operations in Portland, OR, USA

Bogdan Kapatsila [a,*], Emily Grisé [a], Miles Crumley [b], Ahmed El-Geneidy [c]

[a] *School of Urban and Regional Planning, University of Alberta, Edmonton, Alberta T6G 2E3, Canada*
[b] *Operations Planning and Development, TriMet, Portland, OR 97201, USA*
[c] *School of Urban Planning, McGill University, Montreal, Quebec H3A 0C2, Canada*

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ABSTRACT

This study aims to understand the difference in operational performance between electric, hybrid, and diesel buses in Portland, OR. We estimated a running time model, and a distance until a breakdown occurs model using ordinary least squares and multilevel regression frameworks. The results of the running time model suggest that electric buses are faster than diesel buses while controlling for all other operating characteristics. Whilst electric buses do break down sooner if the ramp is used more often, more stops made along the route served by the electric buses increase the distance traveled by the electric buses until a breakdown occurs. Public transport operators are encouraged to continue deploying electric buses, especially along shorter routes with numerous stops, and to undergo preventive maintenance every two weeks. It is also recommended to deploy electric buses to routes where the ramp use is known to be historically infrequent in the short term.

1. Introduction

Transportation is a major source of greenhouse gas (GHG) emissions, accounting roughly for a quarter of human-caused pollution worldwide (Chapman, 2007; Intergovernmental Panel on Climate Change and Edenhofer, 2014). Despite the major climate mitigation efforts, the growing demand for transportation of goods and personal mobility facilitates the increase in emissions from transportation, with some projections suggesting it to increase twice by mid-century (Creutzig et al., 2015). Electrification of the means of transportation is an appealing alternative to fossil-fuel dependence, offering an opportunity for a more sustainable future without the direct need to change human behavior (Weiss et al., 2015). While public transit produces significantly less GHG emissions per passenger when compared to private vehicles (Hodges, 2010), it remains a significant source of pollution, with a single 60 feet diesel bus that is operated for 16 h daily releasing about 100 tons of CO_2 annually (Glotz-Richter & Koch, 2016). Studies have shown that the substitution of conventional diesel buses with electric ones provides numerous societal benefits, like a decrease in life-cycle CO_2 emissions by a third (Zhou et al., 2016), and a reduction in noise and energy use (Borén, 2020). Other zero-emissions technologies are being introduced to transit operations as well, like hydrogen, however, at least in the Australian context only full electrification of a transit fleet has been estimated to bring the most cost-effective and impactful reduction in emissions (Hensher et al., 2022). These factors make electric buses instrumental in tackling climate change and contribute to the increase in their adoption by communities around

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* Corresponding author.
E-mail addresses: kapatsil@ualberta.ca (B. Kapatsila), egrise@ualberta.ca (E. Grisé), crumleym@trimet.org (M. Crumley), ahmed.elgeneidy@mcgill.ca (A. El-Geneidy).

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the world (Li, 2016).

When it comes to forward-thinking transport policies, the State of Oregon has a proven record of pro-environmental planning and decision-making. It dates back to the successful impact of the Land Use, Transportation, and Air Quality study that channeled the resources intended for the development of a new highway into the expansion of the regional public transport system in and around Portland in the 1990s (Howe, 2022), and continues with the Governor Brown's 2020 executive order to cut GHG emissions by at least 80 percent below 1990 baseline by 2050 (Office of the Governor, 2020). In 2022, TriMet, the public transport agency in Oregon's most populous metropolitan region - Portland, adopted its first Climate Action Plan, setting a goal for operating a fully zero-emission fleet by 2040, comprised of predominantly electric buses (e-buses) (TriMet, 2022). This follows the larger US trend of a gradual shift towards e-buses, with many agencies exploring their advantages like lower costs of electricity compared to fossil fuels (Gick et al., 2020). Nevertheless, at this technological stage of development, e-buses are considered to be less flexible when compared to diesel counterparts due to their limited range and relatively long charging periods (Gick et al., 2020). This downside is usually balanced with the theoretically lower maintenance costs for e-buses due to fewer moving parts (5th Innovative Clean Transit Workgroup Meeting, 2017). Given that the main objective of any public transport agency is the provision of quality services at a minimal operational cost (Ibarra-Rojas et al., 2015), the reduction of the latter through lower maintenance and energy expenses can increase the potential buy-in and motivation of transport providers beyond emission reduction goals.

With the aforementioned benefits in mind, this study aimed to investigate the performance of electric buses operated by TriMet in Portland, OR, and provide empirical evidence of some of the operating advantages they bring to public transport providers. We intended to understand if there is a difference in running time between electric, hybrid, and diesel buses, and what operational factors influence the distance an e-bus can travel after regular maintenance before a breakdown takes place. To the best of our knowledge, this paper is the first one to provide evidence on the operations of e-buses. Variations in running times of different types of buses are important and can be both positive and negative, affecting route planning and the reliability of operations. By providing evidence on electric buses, we equip agencies with the knowledge for better service operations and increase confidence in electric technology. As such, the results from this study can be of interest to public transport professionals working towards transforming their fleet to include e-buses as it provides critical information regarding e-buses running time and breakdowns. The study can also be of help to agencies gradually electrifying as it can guide their efforts to operate the newly purchased e-buses along routes where they can maximize their benefits.

2. Literature review

The widespread adoption of e-buses faces numerous barriers, including technological (range limitations and lack of charging infrastructure), financial (inadequate procurement frameworks and fiscal allocations), and institutional (lackluster leadership and policy implementation) (Sclar et al., 2019). Studies have shown that passengers appreciate the on-time performance of buses and shorter travel times (Diab et al., 2015; Murray & Wu, 2003; Yoh et al., 2011), therefore the introduction of e-buses should not lead to the decline of those measures. On the other hand, given that on average e-buses are by a third more expensive than diesel ones (Horrox & Casale, 2019), the claimed savings from their operations due to lower energy and maintenance costs must hold the truth, for the agencies to maintain financial sustainability.

2.1. *Bus running time*

Bus running time is the time it takes for a bus to travel between any two stops along a route. In many instances, it is calculated as the time between leaving the first stop on a route and arriving at the last stop along the same route in a trip. Factors that influence running time can be broadly grouped into endogenous to the agency (i.e. driver experience, route alignment, type of a bus) and exogenous, like precipitation, temperature, or congestion (Strathman & Hopper, 1993). Among those with the most prominent impact are passenger activity (boardings and alightings), the use of a ramp, and the hour of the day the bus is being operated (Abkowitz & Engelstein, 1983; Levinson, 1983; Strathman et al., 2000). A reduction in running time brings benefits to the agencies and riders. For the agency, a shorter running time can lead to fewer operated vehicles along the routes. Whilst for the rider shorter running time increases riders' satisfaction (Hensher & Stanley, 2003) as it leads to lower in-vehicle and waiting times. Unsurprisingly, public transport agencies deploy numerous strategies to improve the running time of vehicles. Literature has shown that dedicated bus lanes, traffic signal priority at intersections, and procurement of low-floor buses speed up passenger activity, while all door boardings (El-Geneidy et al., 2017; Stewart & El-Geneidy, 2014), and consolidation of bus stops have indeed been successful at reducing running time (El-Geneidy et al., 2006). Other policies that can increase comfort for public transport users, such as the use of articulated buses, and the implementation of smart fare collection systems have increased running time (Diab & El-Geneidy, 2012; El-Geneidy et al., 2006; El-Geneidy & Vijayakumar, 2011; Levine & Torng, 1994; Surprenant-Legault & El-Geneidy, 2011; Verbich et al., 2016). Understanding the impacts of using certain bus types on running time is important from an operation and cost standpoint. A negative impact on running time can lead to the number of buses operating a route, while a positive impact on running time can lead to an increase in the number of buses, required to operate a route at a certain headway. To the best of the authors' knowledge, the impacts of e-buses on running time have not been studied previously.

2.2. *Reliability of electric buses*

Although e-buses have risen to a noticeable level of deployment only in recent years, they can hardly be considered a novel technology (Li, 2016). In 1907 a private company in London, UK was operating a fleet of 20 e-buses powered by batteries with a capacity of up to 34 passengers and a range of 37 miles, though by 1909 the service was discontinued due to patent violation (The Economist, 2007). In the US, e-buses were first deployed to reduce emissions in Denver, CO in 1982 (Li, 2016) and in Chattanooga, TN in 1992 (Dugan, 1994), with a range of about 30 miles in each case (Li, 2016). The technology has evolved since then, and modern e-buses can be either charged quickly during operation hours, or have extended battery capacity, and are charged overnight (Gao et al., 2017). The latter group is represented in the US market with buses that have a range of more than 200 miles (Proterra, 2020). Proterra, a US-based electric bus manufacturer, claims annual savings in fuel and maintenance costs for battery-powered buses of $50,000, suggesting that the price difference between electric and diesel buses can be recouped after 5 years, with the remaining service period providing savings to the transit agency (Coren, 2017). A more detailed breakdown of costs suggests that when it comes to maintenance and breaks, electric buses provide savings from $0.19 to $0.26 per mile compared to diesel counterparts, while hybrid buses are $0.11 per mile cheaper to maintain than diesel ones (5th Innovative Clean Transit Workgroup Meeting, 2017; National Renewable Energy Laboratory, 2017).

While more work needs to be done at the policy level to facilitate the transition of fleets to electric buses (Hensher, 2021, 2022), previous studies have shown that it is a feasible technology for urban transit (De Filippo et al., 2014; Miles & Potter, 2014) that has the highest societal benefits when operated in dense urban settings with high levels of congestion due to e-bus energy efficiency and absence of tailpipe emissions (Avenali et al., 2023). At the same time, battery capacity and its impact on the vehicle range remain the primal operational concern for the service providers (Gao et al., 2017). Several factors have been reported as influencing the range of e-buses: the use of air conditioners (AC) can drain almost a third of battery capacity, while operator behavior is a two-side story – slow acceleration and deceleration can increase the operational range of an e-bus by as much as a third, while hasty driving consumes more electric energy (Li, 2016). Similarly, local geography, congestion, weather conditions, and the actual number of stops contribute to the performance of e-buses (Kontou & Miles, 2015; Perrotta et al., 2014). The diversity of these factors introduces uncertainty to the adaptation of e-buses and makes the success of their deployment very context-specific (Nurhadi et al., 2014; Zhou et al., 2016). As such, this study enriches the existing literature by exploring the factors affecting e-bus running time and distance traveled after regular maintenance until a breakdown occurs in the context of relatively moderate weather conditions in the Pacific Northwest of the United

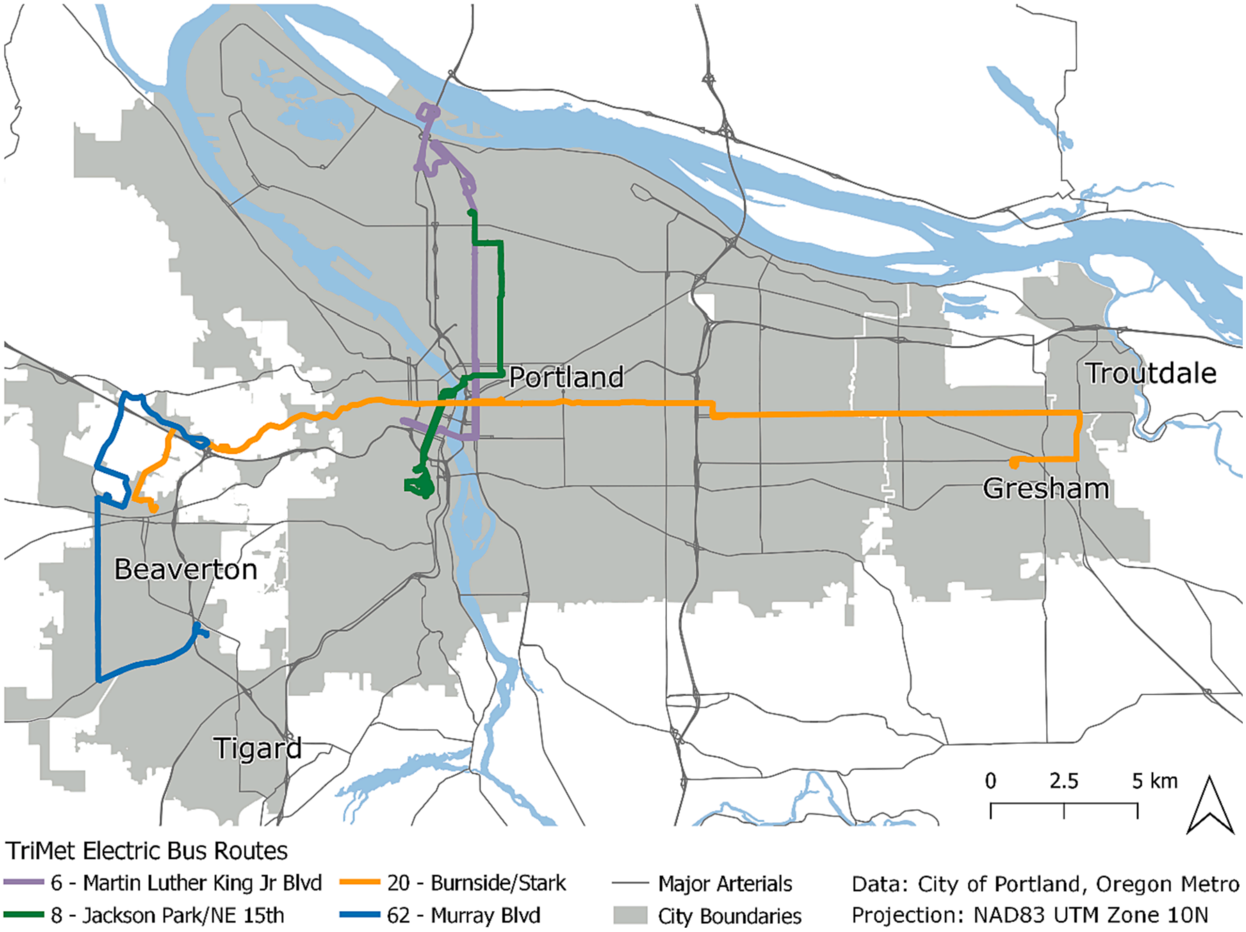

Fig. 1. Geography of the studied region and the routes with electric buses.

States and provides guidance on the planning decisions that need to be made to ensure the optimal performance of e-buses in the similar context.

3. Data & methodology

This study uses archived automatic vehicle location (AVL) and automatic passenger counts (APC) data from TriMet – a regional transit provider in Portland, OR, covering the period of September 5, 2021, to June 6, 2022, to generate running time and distance traveled until breakdown after regular maintenance. AVL/APC data is a common source of information used to generate running time models to understand transit operations (Kimpel et al., 2005; Kimpel et al., 2000). For the distance traveled until breakdown after a regular maintenance model, AVL/APC data is used to supplement historical information on the failures graded as road calls per the National Transit Database from TriMet's vehicle failure records. Lastly, information on the weather conditions (average daily temperature and precipitation) for the studied period w obtained from the meteorological station located at the Portland International Airport (National Climatic Data Center, n.d.).

Portland metropolitan area is the largest urban region in the State of Oregon, US. TriMet is the main transit operator in the region, providing services in Clackamas, Multnomah, and Washington counties. TriMet operates 695 different buses, including 14 e-buses to serve its 85 different routes. TriMet operates 8 e-buses exclusively along 4 routes in the region – 6, 8, 20, and 62. These 8 buses are linked to one garage and rotate between these routes as they require special charging equipment. These 4 routes are also served by a mix of diesel, hybrid, alongside e-buses. In the running time model operations data for diesel and hybrid buses were kept only for the times when they were operating along the respective 4 routes. The spatial alignment of the studied routes is presented in Fig. 1. All of these routes provide service in the City of Portland, while route 62 does not go through downtown Portland, as it connects the western part of Portland with the neighboring Beaverton and Tigard area. Among the 4 studied routes, route 20 is the longest (26 miles) compared to 12.3 miles for route 6, 10.4, and 13.6 miles for routes 8, and 62 respectively.

When performing analysis, we utilized Welch's two-sample t-tests to evaluate the statistical significance of the differences observed in summary tables, linear regression for the running time model, and a multilevel regression for the distance traveled until breakdown after a regular maintenance model. A single trip for a unique bus in either inbound or outbound direction was selected as a unit of analysis for the running time model. A trip was measured in seconds, from the leave time at the first stop until the arrival time at the last stop of the same route. All operating information was aggregated from the stop-level AVL/APC to the trip level during each trip period. This provided a sample of 115,669 trips available for the analysis, 5.4 % (6,246 trips) of which were operated by e-buses, and 0.23 % (273 trips) by hybrid buses, providing sufficient sample sizes for each bus type. Guided by previous studies the running time model included the number of dwells (number of times the door was opened and closed at a stop), average passenger load (number of passengers onboard during a trip), passenger activities (total number of passenger boardings and alightings per trip), number of ramp uses (number of times a ramp was used to service a person with a disability or to help a person who had issues climbing to the bus), the experience of a bus driver measured in years (obtained from the human resources database), as well as an average temperature and precipitation on the day of the trip. At the same time, dummy variables for the weekday schedule and e-buses were introduced, while time of day and route number predictors were included as factor variables. These factor variables were introduced into the model to account for the geographic and temporal differences between the four studied routes (e.g. elevations, number of crossings, and traffic volumes). The hybrid bus dummy variable was also tested but didn't provide statistically significant estimates.

We developed the distance traveled until breakdown after a regular maintenance model to identify the weather and operations characteristics that led to bus breakdown. Operations data for this model was collected in two steps. First, we identified the unique ID of every bus that served the 4 studied routes at any point during the period from September 5, 2021, to June 6, 2022. Second, we obtained all the archived AVL/APC operations data available from the entire TriMet system for the buses identified in step one but covering every route they served during the study period. This approach enabled us to gather information on the bus operations regardless of which route they were serving since buses are regularly rotated between different routes and the breakdown is a unique incident related to the bus and not the route. For this model, the dependent variable was chosen as the planned distance traveled by bus between the day it came out of regular maintenance until a breakdown s recorded. This approach is illustrated in Fig. 2, where d_{nj} stands for the distance a bus j was planned to travel during the time period n before it broke down and went back to the garage for maintenance. An interruption in the continuous records of operations that lasted a day and longer and that was not recorded in the breakdown table was considered a maintenance period, and every operations variable was calculated for the period between a maintenance and a breakdown. If a bus experienced multiple breakdowns over the study period, operations variables for the distance

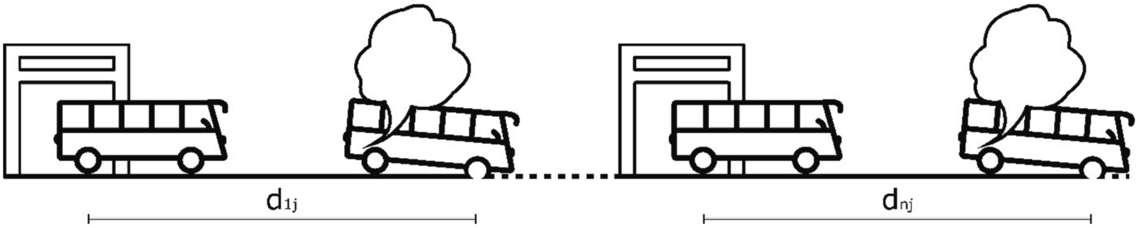

Fig. 2. Methodological approach to the distance traveled until breakdown after a regular maintenance model.

that the bus traveled after the maintenance and before the next breakdown were retained as a new record in a dataset. These multiple records were then accounted for using a multilevel regression model. When multiple breakdowns occurred in one day for a given bus, only a single record was retained. Similarly, in those cases when another breakdown took place before the next maintenance period, it was disregarded from the study. The full list of breakdowns considered for this study excluded any human-related break records (like passenger stop requests, or vandalism), malfunction of non-integral parts (i.e. fare system, wiper/washer system), or those requiring body repair. Based on the abovementioned criteria, the final sample for this model has 2,453 records of breakdowns for 618 buses, with

Table 1
Summary Statistics for Run Time and Break Distance Models.

	Variable	Description	All buses		Diesel		Electric		Hybrid	
			Mean	SD	Mean	SD	Mean	SD	Mean	SD
Running time model	Running time (seconds)	Trip running time in seconds, calculated as a difference between the leave time of the first stop and arrival time of the last stop	3,981	1,668	4,030	1,688	3,213	1,061	3,583	1,309
	Dwells	A number of stops per trip when dwell time was more than 0	25.5	12.8	25.9	12.9	18.8	8.8	22.6	9.9
	Average load	The average value of an estimated number of passengers at a stop	6.1	3.1	6.1	3.2	6.2	2.5	6.4	3.1
	Ons + Offs	Total number of passenger boardings and alightings per trip	48.1	32.6	48.9	33	34.8	22.6	42.2	24.9
	Inbound	A dummy variable for inbound trips	0.5	0.5	0.5	0.5	0.5	0.5		
	Operator experience (years)	Bus driver experience	6.1	4.9	5.9	4.6	9.4	7.6	5.1	3.7
	Ramp	A number of times when the ramp was activated per trip	0.6	1.2	0.7	1.2	0.3	0.8	0.7	1.2
	Week schedule	A dummy variable for the weekday schedule	0.76	0.4	0.76	0.4	0.7	0.4	0.6	0.5
	Time period	A five-level factor variable coded 0 through 4 covering 6:30 pm-3:00am, 3:00am-6:30am, 6:30am-9:30am, 9:30am-3:00 pm, and 3:00 pm-6:30 pm periods respectively	2.2	1.4	2.3	1.4	2.2	1.4	2.4	1.3
	Route	A four-level factor variable coded 0 through 3 for routes 20, 6, 8, 62 respectively	1.3	1	1.2	0.9	2.6	0.9	1.5	0.9
	Precipitation (inches)	The average rainfall recorded for the day of the trip	0.2	0.3	0.2	0.3	0.2	0.3	0.1	0.2
	Average temperature (°F)	The average temperature recorded for the day of the trip	50.7	8.9	50.5	8.9	53.1	8.8	50.1	10
	Electric bus	A dummy variable for electric buses	0.1	0.2	0	0	1	0	0	0
	Hybrid bus	A dummy variable for hybrid buses	0.002	0.05	0	0	0	0	1	0
	N	A number of trips in the sample	115,669		108,745		6,294		273	
	N bus	A number of buses in the sample	642		634		8		2	
Distance traveled until breakdown after a regular maintenance	Miles	Total planned miles for the vehicle, calculated for the period after the maintenance and before the breakdown	4,590	4,600	4,630	4,618	2,124	2,196	3,512	3,625
	Previous breaks	A number of breakdowns that a particular bus had before the last one	2.5	2.4	2.4	2.4	3.1	2.4	3.4	2.7
	Maintenance	A number of times a bus was taken out of service for a day or more	8.7	8.7	8.8	8.7	3.6	3.4	5.7	5.8
	Average load	Average value of estimated number of passengers at a stop per day	5.5	0.9	5.5	0.9	6	0.8	6.9	0.9
	Dwells (00 s)	A number of stops per trip when dwell time was more than 0	57	58.4	57.5	58.7	24.9	25.1	50.4	50.9
	Ramp/Dwell	A number of times a ramp was used per 100 stops when dwell time was more than 0	2.1	1.2	2.1	1.2	2.1	0.9	2.1	0.5
	Average temperature (°F)	The average temperature recorded for the day of the breakdown	49.8	8.4	49.8	8.5	47.6	6.5	48.3	9.3
	Electric bus	A dummy variable for electric buses	0.02	0.1	0	0	1	0	0	0
	Hybrid bus	A dummy variable for hybrid buses	0.006	0.08	0	0	0	0	1	0
	N	A number of breaks in the sample	2453		2414		39		14	
	N bus	A number of buses in the sample	618		611		7		2	
	Breakdowns/Bus	The average number of breakdowns per bus	4		4		5.6		7	

1.6 % of those representing e-bus malfunctions (39 instances) and 0.57 % hybrid breaks (14 instances). Since the number of observations for hybrid bus break instances is below 30 for the breaks model, the model was tested with and without that parameter and showed it having no bias on the overall model results. Nevertheless, it is acknowledged that estimates for the hybrid bus breaks require further investigation with a larger sample size at hand.

4. Results

4.1. Descriptive statistics

Table 1 provides summary statistics for the variables used in the models. The means and standard deviations (SD) are noteworthy in themselves, as the TriMet system has yet to recover from the negative effects of the COVID-19 pandemic on transit use. It is noticeable in the relatively low average loads of 6.1 passengers per stop for the running time model, and of 5.5 passengers in the distance traveled until breakdown after a regular maintenance model – both indicating a significant decline from the 16.5 passengers per stop on TriMet's route 72 evaluated in another study a few years ago (Berkow et al., 2009). While it is possible that part of the difference can be attributed to the route-specific level of ridership, it is obvious that the transit use in Portland metropolitan region has not returned to the pre-pandemic levels. In May 2022 there were 1.7 times more weekly boardings on TriMet when compared to May 2020, but it was still almost twice lower than in May 2019 (TriMet, n.d.). It is also easy to notice the low average operator experience of 6.1 years compared to 11.39 years reported by Strathman (2009) in his earlier TriMet case study. It is likely that due to the retirement, stress, and assaults experienced during the COVID-19 pandemic many experienced operators left the agency. This is reflected in the service cuts that the agency had to make recently due to driver shortage and TriMet's struggle to hire new operators (Silverman, 2022). At the same time, it is evident that more experienced drivers operate electric buses, which is natural given their higher upfront cost and limited institutional knowledge about running electric buses.

When looking at the mean running time of the diesel and electric buses we see a statistically significant difference ($t(9{,}318) = 59.4$, $p = 0$). Smaller running times suggest that e-buses are used predominantly on shorter routes – most likely an indication of the range constraints the technology has and TriMet's adjustment for that. The mean running time for hybrid buses is also lower than for diesel ones ($t(274) = 5.6$, $p = 0$), though slightly higher than for electric ($t(286) = -4.6$, $p = 0$). The average weather conditions over the 9-month study period, including precipitation and temperature, were 57°F and 0.2 in. respectively, with the maximum average rainfall reaching 1.6 in., and minimum average daily temperature of 29.5°F. These outliers can potentially affect the running time and distance traveled until breakdown after a regular maintenance model, in particular, for e-buses at below-freezing temperatures (Kontou & Miles, 2015; Perrotta et al., 2014).

Focusing on the summary statistics for the distance traveled until breakdown after a regular maintenance model, one instantly notices that, on average, diesel buses stayed in service more than twice as long as e-buses until a breakdown (4,630 miles versus 2,124

Table 2
Runtime model estimates.

Variable	Estimate	99 % CI	t-stat
Constant	5055***	5022.73, 5087.15	404.19
Dwells	29.16***	28.19, 30.13	77.54
Average load	−59.61***	−64.06, −55.15	−34.44
Average loadˆ2	1.51***	1.27, 1.76	15.77
Ons + Offs	9.23***	8.66, 9.81	41.42
Ons + Offsˆ2	−0.02***	−0.03, −0.02	−24.87
Inbound	−102.2***	−108.6, −95.72	−40.86
Operator experience (years)	−1.83***	−3.54, −0.11	−2.75
Operator experienceˆ2 (years)	0.07***	0.01, 0.1	2.86
Ramp	23.23***	20.37, 26.08	20.97
Week schedule	−47.65***	−55.42, −39.88	−15.8
Time period 6:30 pm-3:00am	*Reference*		
Time period 3:00am-6:30am	−237.5***	−251.53, −223.51	−43.67
Time period 6:30am-9:30am	14.51***	3.86, 25.16	3.51
Time period 9:30am-3:00 pm	399.8***	389.89, 409.64	104.25
Time period 3:00 pm-6:30 pm	410.4***	399.32, 421.41	95.7
Route 20	*Reference*		
Route 6	−2532***	−2548.29, −2515.65	−399.59
Route 8	−2594***	−2611.27, −2577.08	−390.94
Route 62	−2512***	−2534.25, −2489.96	−292.23
Precipitation (inches)	36.33***	24.91, 47.75	8.19
Average temperature (°F)	−3.34***	−3.71, −2.96	−23.18
Electric bus	**−92.84*****	**−174.77, −10.91**	**−2.92**
Average temperature*Electric bus	**2.62*****	**1.09, 4.15**	**4.42**
N	115,669		
R^2/ Adjusted R^2	0.94/0.94		
F-statistic (21, 115647)/ F signif. (Prob > F)	81,540/ 0.00		

Note: *$p < 0.1$; **$p < 0.05$; ***$p < 0.01$.

miles, the *t*-test is statistically significant at t(43.6) = 6.9, p = 0), while the difference in diesel and hybrid bus distances is not statistically significant (t(13) = 1.15, p = 0.27). Moreover, diesel buses in this study had 4 breakdowns on average, with a maximum of 15, while electric buses had a mean of 5.6 breakdowns and a maximum of 9 breakdowns. Hybrid buses had the highest mean number of previous breakdowns – 7, while the maximum was 10. At the same time, we can observe that e-buses underwent significantly fewer cycles of maintenance before a breakdown took place - t(46.5) = 9.1, p = 0. On average, diesel buses were taken off service for maintenance 8.8 times, compared to just 3.6 for their electric counterparts. The difference in maintenance frequency between diesel and hybrid buses was not statistically significant (t(13) = 1.98, p = 0.07). Lower maintenance frequency for e-buses partially corroborates the previous findings that they are cheaper to maintain (5th Innovative Clean Transit Workgroup Meeting, 2017; National Renewable Energy Laboratory, 2017). On the other hand, Table 1 shows that e-buses made only 24.9 stops, whereas their diesel counterparts stopped 57.5 times, and this difference is statistically significant (t(45) = 7.8, p = 0). While it stems from the earlier observation that e-buses serve on shorter routes, it is also possible that those routes have fewer stops, which leaves the opportunity for e-buses to recharge when breaking (Li, 2016) not fully harnessed.

4.2. Running time model

The descriptive statistics section has shown that over the study period buses were running with much fewer boardings and alightings, and, potentially, without much impedance from other vehicles on the road due to the lingering effects of the COVID-19 pandemic. As result, the estimated running time model has high descriptive power, as captured by the R^2 of 0.94.

We present model estimates in Table 2, where the constant captures the mean travel time in seconds of the average bus in the sample under free-flow conditions, while other variables in the model adjust that time. The results follow intuition and trends identified in previous studies, like that every time a bus makes an actual stop, its running time increases by 29 s. The addition of a single passenger to the average load decreases the running time by almost a minute, which suggests that operators drive faster with more passengers on board. This is something that previous studies have reported (Dueker et al., 2004; Tétreault & El-Geneidy, 2010), however, the quadratic term in our model also tells that adding the 7th passenger to the average of 6 is expected to increase time by 5.3 s on a route. Passenger boardings and alightings (Ons + Offs) increase the running time with each additional passenger, though there is also a diminishing marginal effect of every new rider captured by the quadratic term for the variable of −0.02 s. The last variable in the model that also has a statistically significant quadratic term is operator experience, suggesting that an additional year improves on route performance of a driver by 1.83 s, however, with more experience under their belt, that effect wears off.

When looking at the effect of inbound direction, it is evident that buses going downtown travel faster by more than a minute and a half – something that most likely reflects the intersection design, traffic lights timing, and availability of bus priority lanes in that direction. The use of a ramp adds around 23.23 s to the running time, similar to what Strathman et al. (2001) have also indicated previously. Buses that travel on a weekly schedule travel faster than at other times, probably reflecting the need to make more stops during the workdays. It is also natural, that compared to the evening and late-night period of operations when the ridership generally goes down (6:30pm-3:00am), only buses that travel between 3:00am and 6:30am have shorter running times, with the rest of the times buses move slower. Similarly, since the longest route was selected as a reference for the route variable (route 20), all other routes show significantly lower running times. The effect of the weather can also not be underestimated. An additional inch of rain delays a bus by 36 s, which is consistent with the previous studies (Diab & El-Geneidy, 2013) while one more degree of Fahrenheit speeds up running time by 3.34 s – most likely a reflection of more favorable weather conditions increasing the ease of operations.

Lastly, this model estimated that we can be 99 % confident in e-buses running by a minute and a half faster than diesel ones, ceteris

Table 3
Distance traveled until breakdown after a regular maintenance model.

Variable	Estimate	90 % CI	t-stat
Constant	1,082***	909.16; 1,254.07	10.32
Previous breakdowns	−15.65***	−25.05; −6.24	−2.74
Maintenance	49.40***	43.31; 55.48	13.4
Average load	−126***	−151.05; −101.03	−8.29
Dwells (00 s)	74.88***	73.58; 76.18	95.25
Dwells^2 (00 s)	−0.02***	−0.02; −0.01	−6.36
Ramp/Dwell	−0.02	−11.81; 23.84	0.56
Average temperature (°F)	−7.92***	−10.44; −5.4	−5.19
Hybrid bus	−1,623*	−3,118; −127.68	−1.79
Average temperature* Hybrid bus	31.07*	2.18; 59.93	1.77
Electric bus	**463.5***	**70.33; 856.19**	**1.94**
Dwells*Electric bus	**5.88***	**0.09; 11.68**	**1.67**
Ramp/Dwell*Electric bus	**−204.6****	**−361.52; −48.09**	**−2.15**
N	2,453		
AIC/BIC/Log-likelihood	38,661.7/38,760.3/-19,313.8		
Marginal R^2/Conditional R^2	0.98/0.99		
Random effects (Bus ID): Constant	Variance: 225,347; SD: 474.7		
Random effects (Bus ID): Electric Bus	Variance: 225,356; SD: 474.7		
Random effects: Residual	Variance: 291,962; SD: 540.3		

Note: *$p < 0.1$; **$p < 0.05$; ***$p < 0.01$.

paribus. It is possible that this is the result of the e-bus mechanics, as it gives 100 % torque right away whereas a diesel engine must spin up before it gives 100 % torque, allowing the former to accelerate and decelerate at the stops faster than diesel buses. This premium goes down as the temperature increases, with each additional degree of Fahrenheit adding 2 s to the running time. The effect of the warmer weather can be a reflection of e-buses using the AC units at higher temperatures causing a diversion of some of the power from the motor towards running the AC leading to reduction in speed.

4.3. Distance traveled until breakdown after a regular maintenance model

We provide estimates for distance traveled until breakdown after a regular maintenance model in Table 3, where we explored the effect of operational factors on the distance a TriMet bus can travel after the maintenance and before the breakdown. To account for every instance of breakdown that a single bus experienced, we utilized a multilevel regression model, that has a good fit expressed by the marginal R^2 of 0.98. The signs of the estimated coefficients follow the general logic, corroborating the selected approach for modeling. As such, we can be 99 % confident that every additional breakdown in the past decreased the range of distance driven by the bus after coming out of maintenance by almost 16 miles, holding other things constant at their mean. This likely represents the wear and tear of bus components that even when fixed become less reliable compared to the new ones. Along the same lines, the more passengers a bus carried on average, the sooner it broke down, with a single increase in average load by one rider leading to a 126-mile decrease in range. Lastly, it is natural that we see the negative effect of higher temperatures on bus malfunctions. More extensive use of AC compounded by an increase in ridership that usually comes with weather improvement (Böcker et al., 2013) are likely to blame for this decrease in bus range by 7.71 miles for every degree of Fahrenheit.

On the other hand, we identified a few factors that extend the range of a bus. For example, we can observe the effect of preventive maintenance, with the coefficient suggesting that each check-up and tune-up of a bus extends its range by almost 50 miles, ceteris paribus. The positive effect of actual stops that a bus made (Dwells) is an expected outcome of the linear relationship between the longer distances that a bus traveled with the associated increase in the number of stops it was able to make.

For the hybrid buses, our model suggests that they broke down 1,623 miles sooner than the diesel ones, though, with each degree increase of temperature, the range extended for more than 31 miles, holding everything else constant.

The e-bus estimate and associated interactions provide the most interesting insights into this model. We can be 90 % confident, that when controlling for other parameters, e-buses traveled almost 464 miles more before the breakdown when compared to diesel models. Moreover, every stop made during the time before a breakdown added almost 6 miles to that range of an electric bus, which is potentially due to the charging that takes place when an e-bus uses brakes, as regenerative braking has been found to recover up to 15 % e-bus energy (Kusuma et al., 2021). At the same time, we have identified that each additional use of a ramp per 100 stops decreased the range of an electric bus by 205 miles. The latter estimate is likely to be among the main reasons for a higher rate of e-bus breakdowns observed in the descriptive statistics analysis.

Overall, these findings bolster the argument for the benefits of e-bus use, including shorter running times and fewer operational pauses for maintenance. It also allows to develop guidance for the necessary changes to e-bus operations that can potentially decrease their malfunctions.

5. Discussion

In this study, we examined the performance of diesel, hybrid, and e-buses and evaluated the factors that influence the distance they travel until a breakdown after routine maintenance is performed. We have identified that electric buses run faster while on the route and that they break down sooner if a ramp is used more often, whereas more stops increase the range of a bus powered by electricity. These findings lead to several recommendations on how operators can harness the opportunities that e-buses bring in full.

First and foremost, our findings suggest that e-buses should be used on short routes with many stops. This deployment employs a positive confluence of two different factors of e-bus operations – short running time will allow fewer vehicles to serve the area. The benefits of such deployment would have to be evaluated rigorously in a pilot, though sensitivity analysis of e-bus operations scenarios in different urban contexts in Avenali et al. (2023) supports our hypothesis of a positive effect of more stops on e-bus use. An avenue for such an application can be suggested to use e-buses on feeder routes that take riders to the stops with cross-town buses or rail transit service. Moreover, the integration of e-buses with the region's extensive light rail network can bring further financial savings to TriMet, as the benefits of such combined operations have been observed in the past (Kuah & Perl, 1987). Similarly, buses powered by electricity can be effectively used for on-demand transit operations. This is a relatively new approach to transit provision, which combines modern communication technology with routing algorithms to offer transit services using smaller buses to areas where low ridership and sprawling land use cannot sustain the fixed-route service (Yan et al., 2021). TriMet currently operates electric buses manufactured in North America by New Flyer Industries and GILLIG, and both companies have a 35-foot battery-powered model as their smallest offering. Nevertheless, the predominance of autonomous shuttles that use electric powertrains (Mouratidis & Cobeña Serrano, 2021) suggests that the technology for smaller human-operated electric buses is also on the market. The use of electric buses for on-demand service would not only take advantage of the frequent stops and shorter travel distances but also provide opportunities for quick charging when no rides are requested.

Secondly, as summary statistics have shown, e-buses underwent fewer instances of maintenance which follows the trend observed in previous studies (5th Innovative Clean Transit Workgroup Meeting, 2017; National Renewable Energy Laboratory, 2017). While this indicates their lower running costs compared to diesel buses, it is evident that e-buses could benefit from more preventive maintenance. The benefits of preventive maintenance practice have been recognized in the past (Venezia, 2004), and it is only natural that a similar practice should be applied to e-buses as well. Using the estimates and the average values of parameters for e-buses, we can predict that an average e-bus operated by TriMet will break down after 2,300 miles. It is recommended that e-buses are to be taken for inspection and tune-up before that mileage is reached. Given the data available on average mileage and hours planned for e-buses per day over the study period (161.2 miles and 12.8 h respectively), this translates into a preventive check-up and tune-up every 2 weeks or 181.8 service hours.

The model suggests that a single additional use of a ramp per 100 stops reduces the range of an electric bus by 9 % before the next breakdown. We hypothesize that the more frequent than average use of ramps significantly drains the battery, having an impact similar to the active operation of AC (Li, 2016). It is recommended transit providers consider deploying e-buses on routes known to have fewer requests for the deployment of ramps, using analysis of AVL/APC trends, local demographic characteristics of the areas served, or outside of the clusters with seniors housing. This can be a temporary solution until the ramp impacts are studied in more depth with mechanical engineers to better understand the causes of such an increase in breakdowns, as in the long run, depriving areas with high ramp use of e-buses is an equity concern due to unequal access to environmental benefits of transit electrification for people with limited physical ability. Alternatively, capital projects at known locations with frequent ramp deployment can be designed for near-level or level boarding in the future, as that would alleviate the need for ramp deployment.

Lastly, our findings provide recommendations for the use of hybrid buses. While offering a service range similar to diesel buses, they still have lower emission levels (García et al., 2022), and are not constrained by the service range as e-buses are. At the same time, it is possible that more frequent preventive maintenance can increase their range before a breakdown as well. Given that, it is recommended that agencies prioritize the use of hybrid buses on long routes, while battery-operated technology increases its capacity.

6. Conclusions

The models developed in this study were successful at identifying the operational benefits of e-buses, primarily shorter travel times on the route, and the factors that both increase (more frequent stops) and decrease the distance a battery-powered bus can be operated before a breakdown takes place after regular maintenance is conducted (the use of ramps). The results allowed us to develop operational recommendations for TriMet and other transit operators that provide service in regions with similar climate conditions. It is evident that we are still working our way through the learning curve of mass adoption of this technology, and that at this stage e-buses require additional efforts and experience to make their operations equally reliable as diesel buses are. At the same time, this study proves that there are numerous benefits to using e-buses, that go beyond the reduction of GHG emissions, and thus more communities should consider deploying them.

While this study worked with a rich dataset and employed robust statistical methods, there are ways it could be improved to provide further insights concerning e-bus malfunctions. It would be beneficial to analyze the actual odometer readings for the distance traveled instead of relying on the planned mileage, as well as to have historical data on the distance traveled instead of focusing only on the operations during the study period. More information on malfunctions would also bolster the distance traveled until breakdown after a regular maintenance model, especially with additional details on the event (not only date but hour of a breakdown) and maintenance log, so that the model could focus on a trip as a unit of analysis, instead of a day. On the other hand, casual analysis of electric bus breakdowns can provide additional insights in the reasons behind longer distances they traveled on the routes with more stops. Finally, more information about a driver could provide additional insights into the impact of human actions on e-bus operations.

We also see the benefits of application of the approach developed in this study to other contexts. Methodological frameworks applied in this study for analysis of e-bus operations and breakdowns can be replicated for any single or set of transit agencies that have robust data collection technology (e.g. bus fleet equipped with AVL/APC sensors) and practices (e.g. recording and storage of bus malfunctions), potentially leading to additional discoveries. For example, an agency with a larger e-bus fleet will provide more scenarios for analysis and an opportunity for other benefits of e-bus operations to be discovered. Likewise, TriMet had only 40-foot e-buses in operation, so it remains to be discovered if there are operational differences between e-buses of different sizes. For now, we can only hypothesize that 60-foot e-buses might be slower on routes (as in the case of articulated diesel counterparts (El-Geneidy & Vijayakumar, 2011)). On the other hand, given the relatively moderate weather conditions of the Portland metropolitan region, an investigation into operations and malfunctions of e-buses under harsh negative temperatures and snow can better guide operators on the deployment of battery-powered buses in those communities as well. As such, we encourage researchers to continue exploring this topic and assist forward-thinking agencies in their efforts to provide more sustainable transit services.

CRediT authorship contribution statement

Bogdan Kapatsila: Conceptualization, Data curation, Formal analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Emily Grisé:** Conceptualization, Formal analysis, Investigation, Supervision, Writing – original draft, Writing – review & editing. **Miles Crumley:** Conceptualization, Data curation, Writing – original draft, Writing – review & editing. **Ahmed El-Geneidy:** Conceptualization, Data curation, Formal analysis, Methodology, Supervision, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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