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Electrification Case Study in the City of Reno

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SUMMARY

As of this moment, there are three main methods of mass transit: planes, trains, and automobiles. To avert any climate catastrophe, all three must electrify and run off renewable resources. Only one of these three is fully ready for this and has been ready for over 100 years: trains and light rail, though recently cars and busses have joined them as electrically capable. However, these devices still need to be accurately modelled to ascertain their effects on the electrical grid. There are already existing models of how energy consumption affects the grid for both wire-connected and battery-powered vehicles. Therefore, this paper will utilize grading data from a highly trafficked portion of Reno, Nevada to model the hypothetical behavior of an infrastructure upgrade, and its impact upon the grid. This infrastructure will be in the form of already implemented electric busses, as well as a hypothetical rail line in a highly trafficked portion of town with variance given for frequency and speed. This shows that battery-powered busses are the easiest and cheapest to install long term, from both the utility's and transit commission's perspective.

Electric vehicles are sure to be a vital part of the continuing electrification of our transportation, and nowhere is that more possible than through the implementation of public transport. Within public transport there are a number of options, such as battery-powered busses (BPB), catenary-powered busses (also known as trolley busses) and catenary-powered rail (also known as streetcars). BPBs are a rapidly evolving and quickly adopted form of technology, but as it is not the only form of electric transportation on the market, it is worth evaluating whether or not alternative powered methods are worth pursuing, rather than adopting a less proven form of technology. The main method for electrification in the past decade or so has been BPBs, due to their quickly falling cost and not needing to install overhead wires to transport electricity. However, these systems are not necessarily the best simply because they are the most widely adopted. Therefore, this paper will serve as an audit of sorts on which of these technologies is the best strategy for the electrification of public transit. These are all better than diesel systems, both from an economic and environmental perspective, so this paper is more concerned with determining which system is best suited to any given area's needs.

In this paper, each method of electrification, BPBs, trolley busses, and streetcars, will be compared via a brief cost-benefit analysis for factors such as installation cost, energy consumption, and running fuel costs. At the end of this, each system will be evaluated for the cheapest installation cost, least energy consumed, and what would be the best option for any group interested in electrifying their system.

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I. Introduction

There is already a large swath of information on how to model trains and electric cars in things such as MATLAB and RTDS, including a paper written on the Portland MAX light rail line. In these, the main focus is put on how grading can impact certain kinds of technology, and how complicated it can be to model the motors of these systems. These also have difficulty due to how catenary-powered loads move along a transmission line, making them non-static and far more difficult to model than battery loads. Therefore, it would be difficult to model these kinds of systems without real-time simulation. They also afford a large amount of data which can be used as a baseline for the accuracy of the model.

Previous analyses of these methods do exist, and are useful for constructing consumption models, but rarely do they cross-examine the other methods of conveyance. For example, [1] does an analysis of purely buses, and even includes diesel systems, which are completely outside the scope of this research due to them only technically being an electrical system. The work in [2] analyzes different kinds of streetcars, though it does not analyze busses in its research. This paper aims to see the pros and cons of each method, and hopefully understand which method would be best to invest in, or to continue investing in.

As for modeling electrical busses, these are also similarly understood, though it is slightly more difficult to find adequate sources on them, as there is difficulty in disambiguation between an electric bus and an electrically powered bus. Therefore, electrically powered busses will either be referred to by being “battery-powered busses” or “trolley busses”, to avoid confusion.

The paper is structured as follows. Section II will serve as a review of the different methods of transit that are available for power planners. Section III will show a basic cost-benefit analysis of installing each new system, both from a power planning perspective and from the perspective of the Regional Transportation Commission (RTC) of Washoe. Finally, section IV serves as a conclusion and analysis of all the results shown in the paper.

II. METHODS OF TRANSPORTATION

A. Battery-powered Bus

A battery powered bus is, from the perspective of an installation, one of the simpler systems to work with. It can be modelled identically to an electric vehicle because that is precisely what it is. A battery-powered bus is merely a larger version of a Tesla, Chevy Volt, or any other kind of Electric Vehicle. It can therefore be modelled in power systems in exactly the same way, save for changes in charging characteristics and capacity.

Battery-powered busses have a distinct disadvantage over both streetcars and trolley busses, and that is that they need to recharge. This can be somewhat avoided if they are charged during off-peak hours or with a high enough capacity, but if planned or managed improperly, battery-powered buses will always have an inherently lower capacity factor in how long or how frequently they can run. Considering that current models of busses utilized by the Washoe RTC have a capacity of approximately 440 kWh, it is unlikely that they will run out of power during a typical operating day, but it does mean that they will need to wait longer at transit centers to maintain a healthy state of charge.

The Washoe RTC already has a majority of its bus fleet electrified through battery-powered busses, according to [3], which states that the RTC has approximately 51% of its fleet electrified as of this year and has not bought a new fossil fuel-powered bus since 2013, with its oldest model being from 2005. Therefore, using those trends, one can state that by the year 2030 it is likely that the Washoe RTC will have nearly its entire fleet electrified, as the age differential between the current year and then will be the same, at around 17 years.
For the battery-powered buses, power was obtained experimentally via energy readings given by the City of Reno, though can be captured experimentally.

B. Streetcar

The major advantage that a streetcar has over other systems of public transit is that it has a far lower friction coefficient than busses of any variety. This means that they can move a lot more for a lot less. Their friction coefficient can range from 0.7 to 0.05, according to [4]. This can serve as both a strength and weakness of the system, because whilst it means that it can consume less power, it also means that it has a far more difficult time gaining traction along steep hills, potentially increasing energy consumption by 2 kWh/km per percentage change in elevation rate, which can add up quickly. Therefore, these systems are best implemented along flat areas, or in more circuitous routes to allow for switchbacks.

Streetcars also differ from BPBs in their method of energy conveyance. Rather than charging through a battery charging station, these systems consume their energy directly when they require it through catenary wires and pantographs which directly connect to said overhead wires. An example of this can be seen in Fig. 1. The system then either has the power grounded into the tracks themselves or is fed back into the system. They also have regenerative braking which allows them to reduce power consumption by converting kinetic energy back into electrical energy when slowing down. These also do not have one of the key advantages of battery-powered systems, which is that they do not need to consume their power exactly when they need to. This means that they can be more efficient, as they are lighter, but it also means that they may contribute to peak loads, rather than being able to take advantage of off-peak hours by charging through the night. They also do not need to worry about the round-trip energy loss that batteries have, as there is less energy lost when going directly from the wires to the motors.

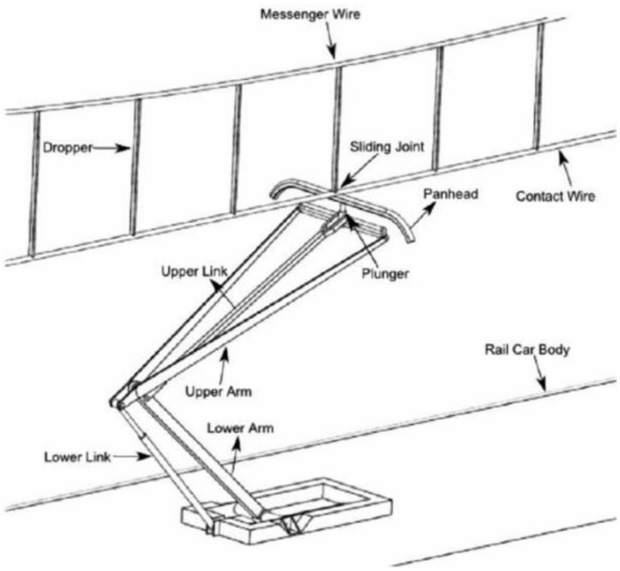

Fig. 1. A diagram of a pantograph [5]

The power consumed by a streetcar at any given moment is determined using an equation found in [2], which is given in (1).

$$P = F \times u \times 0.746 / (375 \times 1.61) \quad (1)$$

where F is the tractive force of the motors, u is the instantaneous speed, and the other terms are used to convert all of these values into kWh from hp. The calculation of force is performed via the following expression.

$$F(t) = [(0.6 + \frac{20}{w_p} + \frac{0.01u(t)}{1.61} + \frac{K(u(t)/1.61)^2}{w_p n_p} + 20\,\theta)] * M * 4.4482 \quad (2)$$

wherein wp is the weight put on each wheel of the streetcar, including passengers, u(t) is the again the speed, M is the total average weight in tons, and θ is the grading of the curve at a given moment measured in degrees. Therefore, if one had a 2◦ grade, that would result in an increase of 40 lbs/ton of force for the car to go at the same speed. It has also been derived from [2].

C. Trolley Bus

Trolley busses are like battery-powered busses, but with the same method of power conveyance as a streetcar. This means that it can have lower power consumption, but a higher peak hour contribution. This can vary depending on the model, but typically can mean around a 5% efficiency boost due to a lack of weight and having no need for the inefficiencies caused by cycling the battery. Both trolley busses and streetcars are far more difficult to model than BPBs, due to how they are not only a non-static form of load, meaning they necessitate a ZIP load model but also that they are non-static geographically, so their power consumption moves along the power line rather than being fixed in one place. There are few, if any, other kinds of loads that can move along a distribution line in this manner.

Trolley busses are older kinds of technology than BPBs, so they may more frequently be powered by induction, rather than by DC motors, as they also do not have to convert between DC and AC power when operating.

Power determination for a trolley bus can be in a similar manner to the way that one would capture the data for a BPB. The formulae for them can be seen below, as a summation of various sub-powers, some of which are defined here:

$$P_{tr} = P_{tre} + P_f + P_u + P_v + P_a \quad (3)$$

$$P_{tre} = (1 - \mu)\, P_{tr} \quad (4)$$

$$P_f = f\, G \cos(\alpha v)/3600 = f_0(1 + bv2)\, G \cos(\alpha v)/3600 \quad (5)$$

$$Pu = G \sin(\alpha v)/3600 \quad (6)$$

$$Pv = kAv^3/46.656 \quad (7)$$

$$Pa = G*\delta*a*v/ (g*3600) \quad (8)$$

wherein P_{tr} is the total power consumed, P_{tre} is the power consumed by electrical motor losses the power consumed by the electrical motor loses, P_f is the power to overcome rolling resistance—a fairly common occurrence with the frequent stops and starts along a bus route; Pu is the power to overcome the grading of the road, which will be relevant when considering the massive changes seen in Fig. 2; Pv is the power necessary to overcome wind resistance; Pa is the power necessary to overcome inertial resistance; and P_{aux} is the power necessary to power all supplementary systems—lighting, air conditioning, steering controls, power electronics, etc. Within these terms, μ is the efficiency of the motor, f is the rolling resistance of the surface, G is the weight of the bus, α is the road angle measured in degrees, v is the velocity, a is the acceleration, A is the area of the bus face, and k, f0, b, g, and δ are all various constants depending upon the conditions of the road (f0 and b), the air (k), and the acceleration (g and δ). All of these equations were taken from [1], which conducted similar experiments to the one submitted here. Speed and acceleration can be gathered experimentally via riding the system a sufficient number of times.

TABLE I
RELEVANT DATA FOR THE STREETCAR AND BPBS [6], [7]

	Model	**Weight (kg)**	**Horsepower (kW)**	**Voltage**
Streetcar	Siemens S700	46000	130x4	750 V DC
BPB	Proterra BE40	13500	220	750 V DC

A. RESULTS

As for the amount of energy consumed, both the trolley bus and the streetcar require elevation change data in order to accurately assess the amount of power they consume over a typical run time [1], [2]. Data for these two pieces of equipment can be found in Table I, and data for the relevant elevation changes was derived from publicly available data found on Google Maps. Using equations found in [2] implemented into MATLAB, we were able to determine the energy consumed from all three models.

As can be clearly seen in table II, the most cost-effective installation method is the battery-powered bus (BPB). Its installation is a mere 2.3% of the cost of installing a trolley bus, and only 0.23% of the cost of installing a streetcar system. Therefore, from a cost perspective, it is impossible to ignore how much money is saved from a cost-benefit analysis perspective. Surprisingly, it seems that the battery-powered bus has greater efficiency than the trolleybus by a wide margin, consuming a whole 100 MWh less per year, assuming an equivalent fleet of systems. Therefore, considering the efficiency gains from this system, it is clear that the most efficient method of public transportation, both from a cost and energy consumption perspective, is the battery-powered bus. This was not the expected outcome, as it was expected that the extra weight from the batteries from this model would make it such that the energy consumption would be far greater on the battery bus compared to the trolley bus, and the lower friction afforded by the streetcar. However, it seems that the model is far more efficient per unit than either other model.

The best theory as to why this is the case that can be surmised is that the streetcar had a far more difficult time reaching the top of the hill seen in Fig. 2's beginning elevation. Streetcars have a very difficult time dealing with high rates of elevation change, and the area around Lawlor Center, at the start of the route, has a maximum grading of roughly 9%. This means that the kWh/mi at that portion would rapidly increase relative to the rest of the area, and thus would be much less efficient. As for the trolleybus, it seems that the same may be true for its handling of hills as well, though specifically as a result of its energy transmission method. The power consumed by the system along a large number of lines may have caused a strong drop in the efficiency of the load, and unnecessary line losses compared to battery chargers that are able to operate far closer to substations with higher voltages.

Considering all of this information, it would be best to consider the growth in load with regards to the current battery powered fleet and the energy consumed per year as seen in Table II. As a result of this, as well as data found in [3], one can see that the Washoe RTC fleet is currently half electrified. Noting this, one can extrapolate the amount of energy consumed per bus on the Virginia RAPID route as approximately 63.4 MWh/(bus*year), as the schedule requires 6 buses to operate properly. Therefore, that would mean that the total energy consumed by a battery-powered system would be around 3.2 GWh when each bus on the Washoe RTC system has a similar load across the span of a year.

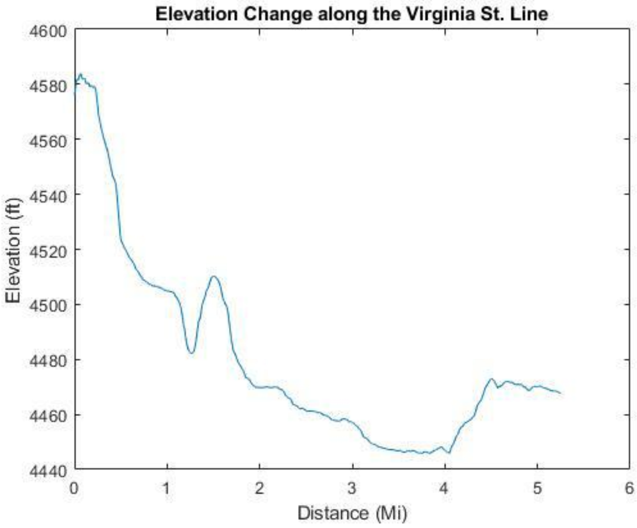

Fig. 2. Elevation changes from Lawlor Center to Meadowood Mall along the Virgian St. line

Lawlor Station - RAPID Station	RTC 4TH STREET STATION	S Virginia Street at Orchard Plaza	S Virginia Street and W Peckham Lane	RTC Transfer Center / Meadowood Mall
6:00am	6:08am	6:17am	6:21am	6:29am
6:30am	6:38am	6:47am	6:51am	6:59am
7:00am	7:08am	7:17am	7:21am	7:29am
↓	↓	↓	↓	↓
7:00pm	7:08pm	7:17pm	7:21pm	7:29pm
7:30pm	7:38pm	7:47pm	7:51pm	7:59pm
8:00pm	8:08pm	8:17pm	8:21pm	8:29pm
8:30pm	8:38pm	8:47pm	8:51pm	8:59pm
9:00pm	9:08pm	9:17pm	9:21pm	9:29pm
10:00pm	10:08pm	10:17pm	10:21pm	10:29pm
11:00pm	11:08pm	11:17pm	11:21pm	11:29pm

↓ = Next bus approximately every 10-minutes

Fig. 3. Schedule of the RTC RAPID Virginia Line [8]

A. Impacts on Peak Load and Load Growth

The methods for determining the change in peak load will differ between overhead-powered systems when compared to battery-powered systems.

TABLE II
AN OVERVIEW OF THE COST TO INSTALL AND OPERATE A SYSTEM [1], [9]

	Installation Cost ($Mil)	Energy Consumeed (MWh/Year)	Power Cost ($/year)	Cost/Vehicle ($Mil)
BPB	0.32	380.6	3130	0.5
Streetcar	137.5-275	4552	37470	2.3
Trolley Bus	12.65	480	3940	0.5

On overhead powered systems, the hourly peak load can be determined via equation (9), wherein n is the number of busses running at a given time, P is the power of each motor on the system, and m is the number of motors per bus. This is a trivial method of determination for the impacts on the peak load.

$$\Delta PeakLoad = n * P * m \quad (9)$$

If the RTC were to substitute in all of their future powered busses with the streetcars, i.e., six busses, they would increase the peak load on the Virginia Line by the following amount:

$$\Delta PeakLoadStreetcar = 130 * 4 * 6 = 3120kW = 3.12M\ W \quad (10)$$

This appears to be a fairly sizable amount of power, but considering that according to [10], the peak load in northern Nevada is 2,106 MW, this would represent a less than 0.5% increase in peak load across the region, which the NV energy network would be more than capable of matching.

A battery-powered bus may not need to be considered for its impacts on peak load, as most charging strategies are done off-peak hours to take advantage of lower energy costs during such hours.

B. Comparison with Fossil Fuel-powered Busses

It is worth covering in brief how the costs of an electrical system would compare with the costs of the current system, at least from a fuel perspective. This can be done far more simply, by merely multiplying the average MPG by the number of miles on the trip, taken from [11]. One can then divide the length of the route by said fuel efficiency and the number of times a route is completed per day to have a rough estimate of the amount of fuel consumed per day. Then, multiplying that value over the course of a year will give the equivalent cost in fuel. The volatility of fuel costs would make an accurate assessment difficult, but a basic evaluation of $5/gallon would be accurate enough for the moment. Put into a symbolic form this would be equivalent to:

$$\$fuel = 365 \times l \times n \times \$/gal\ (mpg) \quad (11)$$

The Virginia line, being 5.25 miles long, run 83 times a day, with a fuel efficiency of approximately 4.75 mpg [11], would cost RTC $165,400 per year alone. Even the worst-case scenario of the streetcar is less than a quarter as expensive as what a fossil fuel system would cost, considering only the cost of fuel. Installation cost would of course make it less optimal in the short term, but it clearly demonstrates that from solely a cost perspective, any method of electrification is more ideal for a public transit group than current fossil fuel technology.

B. CONCLUSION

After having seen all of the given data, one must conclude that the most efficient method of transportation is the battery-powered bus. Washoe RTC is completely justified in their current electrification strategy, both from an environmental and cost perspective. This was unexpected from the initial

hypothesis that the trolleybus with its lower weight necessity, or the streetcar with its lower friction coefficient, would be a better option from the perspective of the utility. It has been shown that both systems are expensive to install, purchase, and maintain, so it is therefore very clear that BPBs are the best method of electrification currently on the market.

Future research will be applied by analyzing the different methods of electrification along flatter routes, such as the Lincoln Line, which runs east to west, rather than north to south, which is far more difficult for light rail, which may have been put at an unfair disadvantage. It will also be prudent to analyze different models of each kind of equipment, to see if any kinds of vehicles may have been poorly chosen or outdated relative to the others. Regardless, this has been enlightening, and shown that lithium-ion batteries are highly capable and efficient methods of storing, and even transporting, energy.

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