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Technical Feasibility of a Hydrail Tram–Train in NA: Okanagan Valley Electric Regional Passenger Rail (OVER PR)

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Abstract: Booming population and tourism have increased congestion, collisions, climate-harming emissions, and transport inequities in The Okanagan Valley, Canada. Surveys suggest that over 30% of residents would shift from cars back to public transit and intercity tram–trains if regional service and connections were improved. Intercity streetcars (aka light-rail tram–trains) have not run in Canada since their replacement in the 1950′s by the national highway system. UBC researchers analyzed a tram–train service fashioned after the current Karlsruhe model but powered by zero-emission hydrogen fuel cell/battery hybrid rail power (hydrail) technology, along a 342 km route between Osoyoos, B.C. at the US Border and Kamloops, B.C., the Canadian VIA rail hub. Hydrail trains have operated successfully since 2018 in Germany and were demonstrated in Quebec, Canada in 2023. However, hydrail combined with tram–train technology has never been tried in Canada. Single-train simulations (STSs) confirmed its technical feasibility, showing a roughly 8 h roundtrip travel time, at an average train velocity of 86 km/h. Each hydrail tram–train consumed 2400 kWh of energy, translating to 144 kg of hydrogen fuel per roundtrip. In total, five tons of H_2/day would be consumed over 16 h daily by the 16-tram–train-vehicle fleet. The results provide valuable insights into technical aspects and energy requirements, serving as a foundation for future studies and decision-making processes in developing zero-emission passenger tram–train services not just for Okanagan Valley communities but all of Canada and NA.

Keywords: intercity hydrail passenger tram–train; hydrail; hydrogen power; train–trams; zero emission; interurban streetcars; passenger rail; steep hills; cold climates; vehicle specifications

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1. Introduction

The Okanagan Valley in British Columbia, Canada is experiencing rapid growth in tourism and vehicle-related traffic, resulting in increased traffic congestion, greenhouse gas emissions, and road crash deaths. As the population continues to rise, the demand for intercity travel within the Okanagan Valley is expected to increase, leading to further congestion on Highway 97, the region's main transportation artery. Unfortunately, the current approach of accommodating the growing travel demand with more vehicles and roads is unaffordable and exacerbates these problems. With transportation being a major contributor to greenhouse gas emissions in Canada, it is crucial to explore sustainable and zero-emission transportation solutions. This research investigates the feasibility of introducing a light rail intercity passenger rail service, termed the Okanagan Valley Electric Regional Passenger Rail (OVER PR), connecting communities across the rural mountainous terrain of BC, Canada, as an alternative to private vehicle travel. If technically feasible, it may lead to reduced traffic crashes, congestion, and pollution, while promoting sustainable urban development and providing efficient transportation options for all ages and abilities of residents and visitors alike. Across Canada, hydrogen production potential is predominantly via hydro-electricity, and over 91% in BC, the province where this case study occurred [1,2]. In areas where electricity is predominantly produced from high-carbon sources, hydrogen may have lower emission reductions overall, from a sustainability perspective. However, it is commonly accepted that the low energy density of batteries severely limits their range and makes them infeasible for passenger rail over the long distance and duty cycle analyzed in this paper. Hence, hydrogen fuel cells greatly improve vehicle range, creating a more effective vehicle. For this reason, the scope of this paper does not cover the technology comparison but instead evaluates the use of hydrogen. Therefore, to address transportation equity and pollution issues among communities, this research examines the technical requirements and constraints for implementing an Okanagan Valley Electrical Regional Passenger Rail (OVER PR) route. Specifically, the goals of this study were threefold:

1. Confirm the technical feasibility of running a steel-wheeled, hydrail tram–train vehicle on rails along an alignment similar to Highway 97 between Osoyoos and Kamloops.
2. Confirm the power requirements and hydrail power-train capacity to meet power requirements.
3. Make recommendations on hydrail tram–train vehicle specifications to meet OVER PR needs.

2. Background

Interurban Passenger Rail and Hydrail Drive-Trains

Rail has long been the backbone of Canada's confederation and economy since 1885 when the last railroad spike was pounded to finish construction on the Canadian Pacific Railway and fulfill an 1867 confederation promise. In 2019, Canadian freight rail moved over 332 million tons of freight while transporting more than CAD 455 billion revenue ton-kilometers in support of the Canadian economy [3]. Canada's long-standing reputation in the freight rail industry can serve as a foundation for a new wave of passenger rail in Canada.

Since before the 1980s, passenger rail routes and ridership between cities in Canada have been declining when compared with the large amount of operating freight rail. Beginning in the 1950s with the advent of the national interprovincial highway system, interurban streetcar services and rail lines were removed. More recently, VIA Rail, which operates Canada's national passenger rail service on behalf of the Canadian Government over 12,500 km of track owned by, and shared with, freight companies, carried only 1.5 million passengers in 2021. In comparison, urban light-rail systems in B.C., Ontario, and Quebec transported a record 101.9 million passengers in 2019 [4]. The only long-distance, intercity passenger rail system in B.C. is operated in Metro Vancouver by TransLink, the regional transportation authority, where the 69 km West Coast Express (WCE) heavy-rail commuter service connects travelers from downtown Vancouver to Mission City, but again sharing freight rail tracks [5]. As a commuter passenger rail serving higher-density urban areas, this form of commuter passenger rail travel is only available to community members in the Vancouver area and not accessible to a large portion of British Columbian residents who live in lower-density, more rural regions.

Intercity passenger rail is a form of transportation that primarily serves passengers traveling between urban areas and surrounding suburban regions. To be successful, especially when used by commuters on fixed schedules and high volumes of extraregional tourists, intercity regional passenger rail generally operates on dedicated tracks separate from freight rail. In this case, the trains typically consist of multiple carriages or coaches hauled by one or more locomotives, each weighing over 150 tons, capable of accommodating a large number of passengers each trip. The most successful of such systems in the world have been found when integrated with buses, trams, and subways to provide passengers with a seamless journey from their origin to their destination [6]. The ultimate integration between intercity, regional passenger rail, and in-city trolleys is the essence of the Karlsruhe Tram–Train Model (KTTM), where tram–train technology originated and has been operating since the early 1980s by Verkehrsbetriebe Karlsruhe (VBK) [7] and Albtal–Verkehrs–Gesellschaft (AVG) [8].

Based in Karlsruhe, Germany, the KTTM provides a comprehensive and efficient transportation system and runs on steel rails. In cities, their rails are sunk (i.e., flush mounted) into regular traffic lane pavement, in effect sharing traffic lanes with pedestrians, bicycles, buses, cars, and trucks, which maintains efficient, barrier-free, traffic capacities. Inside and outside cities, these 'light' rail vehicles (i.e., tram–trains) run at the prevailing speed of all other traffic. Outside cities, the vehicle would operate more like a commuter passenger train at prevailing highway speeds, typically either beside car traffic or in the median. The key is that no additional property is needed to accommodate tram–trains when they share the public roadway lanes and right of way.

The successful reintroduction of tram–trains on rails connecting the towns of the Okanagan region, as analyzed in this research, is contingent upon several pivotal factors, including space sharing, light-rail vehicles, and well-integrated intermodel 'last-mile' systems.

- First, the constrained space available on existing roadways for track placement, compounded by the impracticality of procuring land for dedicated tracks, renders a locomotive-hauled solution challenging.
- Second, the connecting Valley route by definition crosses several existing highway bridges, including most significantly the Okanagan Lake floating bridge, which has specified weight limitations that requires self-powered, light-rail vehicle technology (e.g., KTTM tram–trains in Karlsruhe, Germany) comparable in weight to freight trucks, and precludes the use of heavier 150 ton (or more) locomotive vehicles to haul passenger trains (e.g., VIA rail in Canada).
- Third, the Karlsruhe Model promotes the use of public transportation as an attractive alternative to private vehicles by including key features such as synchronized transportation schedules, transit-oriented regional infrastructure, and intermodal fare integration. By emphasizing transportation intermodality, the KTTM intends to reduce traffic crashes and congestion while promoting sustainability [9,10]. Cities in central Europe have shown that it is feasible to integrate urban transit systems into cities which provide convenient and efficient transportation options for people who live in and/or visit urban and suburban regions, with tram–train ridership often more than quadrupling previous transit use levels as a result [11].

Specifically, Kołoś and Taczanowski [11] recommend successfully implementing a feasible passenger rail system with the following key elements:

1. Transport policy needs to be in place in order to help create the modal shift.
2. Organization and integration of the entire public transport system must be conducted.
3. The rail system should be an important instrument of urban renewal and revitalization of spatial and social structures.

This highlights another appealing feature of the KTTM in addition to its applicability to revitalize transit and passenger rail use in North America: its zero-emission (ZE) power train applications. Historically, passenger and freight rail have used low-cost but environmentally unfriendly diesel engines to generate electricity or cost-prohibitive, overhead power lines to power the traction motors that drive the train. However, recent rail innovations in Europe showing light-rail vehicles powered by Hydrogen Fuel Cell-Battery Hybrid (Hydrail) power train technology have been demonstrated as a cost-effective, environmentally friendly transportation solution. Hydrail combines the high-energy density of hydrogen with the high-power density of batteries to provide a viable alternative to diesel and overhead wires. A fuel cell is used to combine hydrogen gas and oxygen gas in a reduction–oxidation reaction that generates electric current, water, and heat as byproducts in an emission-free process. The generated electric current is used to charge the onboard power battery packs which provide electrical power to the tram–train traction motors and other auxiliary systems onboard [12–16].

Hydrail technology was first commercially launched in 2018 when Alstom, a French multinational rolling stock manufacturer, demonstrated its hydrail train in Northern Germany, named the Coradia iLint (Figure 1). Coradia iLint hydrail trains are now being operated in Northern Germany and beginning to be employed in Austria. Alstom sold 41 of these hydrogen-powered trains to Germany and has expanded to other European countries [17]. In 2023, a partnership between the Government of Quebec, Réseau Charlevoix, Chemin de fer Charlevoix, Harnois Énergies, and HTEC launched Canada's first passenger hydrail train, using the same Alstom Coradia iLint vehicles demonstrated in Germany, to transport tourists on a dedicated rail line between Parc de la Chute Montmorency and the city of Baie-St-Paul, along the St. Lawrence River [18].

Figure 1. Coradia iLint owned by LNVG on the first 100% hydrogen-operated route [19]. Used with permission.

Passenger hydrail and electric trains have been scarcely investigated in other parts of Canada. One case study was found that analyzed the implementation and operation of a hydrail train on a 115 km route along cities between Oshawa, Toronto, and Hamilton, Ontario. It demonstrated that the introduction of hydrogen or electric passenger trains to the area would consume less energy per passenger km than other traditional transportation modes when the train is at a minimum half-passenger load and above. Hydrogen trains and electric trains are considered future alternatives to conventionally fueled trains, as electric trains and hydrogen trains are both regarded as zero-emission vehicles when in operation at the point of use. However, the actual emissions associated with their lifecycle are determined by factors beyond the tailpipe, mainly related to energy and hydrogen production methods. The literature suggests electric trains produce lower levels of emissions than hydrogen trains; however, both alternatives produce significantly less emissions than conventionally fueled trains [20,21]. Hydrogen trains present advantages compared with electrification by eliminating the requirement for expensive infrastructure such as catenaries and electrical substations. Moreover, they grant the flexibility to operate in remote rural areas or difficult terrain where electrification might pose challenges, consequently improving their overall effectiveness and adaptability [22].

When hydrogen production is coupled with other forms of renewable energy generation, the environmental benefits are favorable. There are many methods of hydrogen production, such as Stream Methane Reforming (SMR), Coal Gasification, Biomass Gasification, Solar (thermochemical) Water Splitting, and Water Electrolysis from hydroelectricity. The latter two are considered carbon-neutral and green hydrogen sources, as water is considered a sustainably sourced feedstock. Interlinking hydrogen production, hydrogen rail transport, and hydroelectricity production as a means of sector-coupling could be one of the main forces for decarbonizing transportation. The introduction of hydrail operations may require a combination of these technologies, where carbon capture and storage could be used in conjunction to reduce environmental impact [23]. Clean energy production in BC, and a majority of Canada, predominately based in hydroelectricity, provides the unique opportunity to be coupled with green hydrogen production and hydrogen trains, providing a path to advance hydrail technology, adding balance to the renewable energy system, and reducing carbon emissions in the transportation sector.

The ongoing boom in Valley economic and population growth has created a case to revisit passenger rail in the Okanagan Valley. Provincial transport studies have so far ignored rail as an option and instead relied on traditional autocentric solutions that are forecast to not be funded for at least the next 30 years. In the face of growing national and local calls for more sustainable transport options, most recent reports strongly recommend more transit-oriented solutions, including the potential use of light rail. If light rail as a 'backbone' were implemented along Highway 97, integrated with local bus services as 'ribs' in each community, transit would be revitalized. Moreover, it would (i) reduce the increasing greenhouse gases and pollution produced by the transportation sector; (ii) improve traffic safety and congestion on Highway 97 and in regional districts; and (iii) ultimately support the urban revitalization of spatial and social structures in Okanagan communities. Connecting regional communities via centralized transportation and ease of access to community services through inter-regional travel could in turn enhance transport equity and accommodate population growth without its associated auto traffic impacts. To reach the sustainable development goals presented by the United Nations, efforts in clean energy transition must be quickly expedited in a sustainable way for future generations [24].

3. Methods

The Okanagan Valley Route Technical analysis examines the feasibility and energy requirements of implementing a commuter rail line in the Okanagan Valley through a single-train simulation (STS). The analysis conducted models a regional passenger rail route based on Highway 97's gradient between Osoyoos to Kamloops. The research approach used to carry out this study is presented in Figure 2. To address regional public transportation challenges in the Okanagan Valley, this research aims to lay out a base transportation plan by presenting a passenger rail solution, utilizing hydrail trains. The route was modeled and tested by simulation to determine the train's energy and performance requirements. The analysis considers the vehicle specifications, the selected route, and the track structure, as well as factors such as energy consumption, tractive effort, and the power required of the proposed commuter rail line. This analysis is used to evaluate the outcomes of the simulation, discuss the limitations, and provide recommendations for future steps.

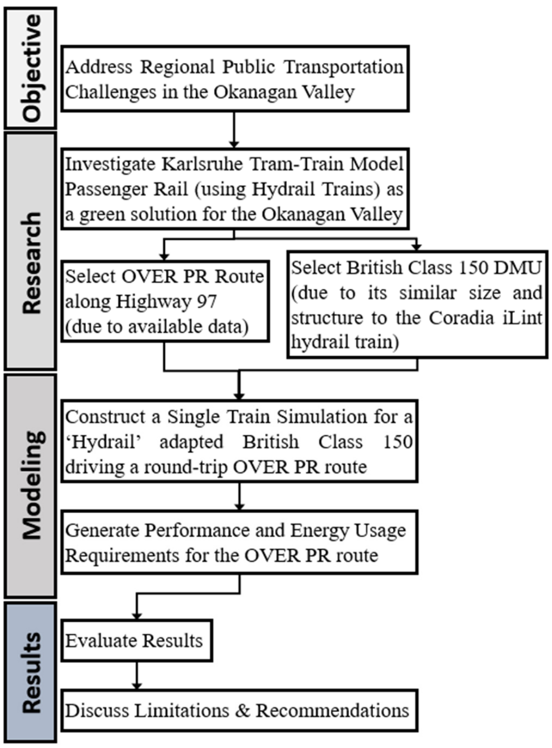

Figure 2. OVER PR technical research methodology flowchart.

3.1. Single-Train Simulation

Single-train simulations (STSs) are a common method to calculate energy requirements for trains over specific routes by solving the equation of motions of a railway vehicle. An Okanagan Valley regional passenger rail route STS was modeled using MATLAB R2018a to investigate the feasibility and energy requirements of implementing a commuter rail line in the Okanagan Valley. The railway line route information was based on geographical data of Highway 97's gradient between Osoyoos to Kamloops, and the vehicle specifications were derived from publicly accessible sources. Certain specifications, such as driving resistance parameters, were adapted from the British Class 150 'Sprinter' Diesel Multiple Unit (DMU) [25], a 2-car DMU that possesses analogous power and mass characteristics to the iLint. The kinematics of rail vehicle motion can be described by using Lomonosoff's Equation (3) [13]. The resistance encountered due to angular forces from the curvature of the Highway 97 road is not considered and thus is neglected in this analysis.

$$\mathrm{F}_a = m(1+\lambda)a \tag{1}$$

$$\mathrm{F}_b = \mathrm{F}_{\mathrm{TE}} - \left(mgsin(\alpha) + Cv^2 + Bv + A\right) \tag{2}$$

$$\text{When } \mathrm{F}_a = \mathrm{F}_b\ ,\ [\mathrm{kN}]$$

$$m(1+\lambda)a = \mathrm{F}_{\mathrm{TE}} - \left(mg\sin(\alpha) + Cv^2 + Bv + A\right) \tag{3}$$

Forces due to railway motion resistance are evaluated using Newton's 2nd law Equation (1), where λ is the rotational allowance which accounts for the increased force required to begin vehicle movement and is set to a rotary allowance, determined by Din and Hillmansen. The value was set to 0.08 to match the British Class 150 'Sprinter' DMU's rotary allowance [13]. The Davies equation is seen in Equation (2) calculates the force due to the rolling resistance of a vehicle, where the Davies coefficients A account for the resistance due to vehicle mass, whereas the velocity-dependent coefficients B and C account for rolling resistance and aerodynamic resistance, respectively. The rail vehicle's velocity and acceleration are denoted by v and a, respectively. The route's slope resistance, $\mathrm{F_a}$, can be computed using m as the vehicle mass and g as the acceleration due to gravity, where α is the slope angle of the track. The equations are an extension of Newton's Laws of Motion, which consider the various forces the rail vehicle will encounter during transit. In order to solve these equations, the distance is discretized and set to step in 1 m increments throughout the roundtrip journey. Numerical integration is used to iteratively calculate the required tractive effort, TE, for a railway vehicle over the selected route [26,27]. It is assumed that the selected driver style was to be as fast as possible, where the vehicle will travel at a maximum of 90 km/h between cities in the highway road lane. Moreover, the vehicle's consumption of hydrogen was calculated by determining the electrical output energy needed from the vehicle's fuel cell(s) in order to then establish the mass of hydrogen required to drive the route. The equation used to calculate the hydrogen mass is shown in Equation (4), where E_{FC} is the electrical output energy of the fuel cell, η_{FC} is the fuel cell efficiency, LHV_{H_2} is hydrogens lower heating value, and m_{H_2} is the required mass of hydrogen fuel. A fuel cell efficiency of 50% is used, which is in keeping with observed fuel cell efficiencies to date and lower than expected emerging hydrail technology currently in development.

$$m_{H_2} = \frac{E_{FC}}{\eta_{FC} \times LHV_{H_2}} \tag{4}$$

3.2. Vehicle Specifications

The commuter rail vehicle used in the OVER PR roundtrip single-train simulation was modeled as a British Class 150 'Sprinter' DMU [28]. This class 150 DMU was selected due to its similarities in size and structure to the Coradia iLint hydrail commuter train. Note that the Class 150 DMU uses a non-eco-friendly diesel engine to power the train, unlike the eco-friendly hydrail Coradia iLint. As technology advances, a hydrail vehicle can be sized to have the same power capabilities as a standard DMU rail vehicle [12,25]. For example, this could be achieved by increasing the amount of onboard fuel cell power and/or battery capacity. To accommodate the gradients encountered along the OVER PR route, the maximum engine power of the vehicle was increased from 425 kW to 1000 kW. Additionally, the ratio of powered axles was increased from that used on the iLint (i.e., 50%) to 100%. The maximum speed of the rail vehicle was unchanged and not reached; however, due to its increased engine power, the maximum acceleration possible was approximately doubled. Table 1 displays the technical data used to model the rail vehicle in the STS, which is closely based on the Class 150 DMU specifications [28]. The vehicle's tractive effort is presented in Figure 3. In order to move the modified Class 150 commuter train initially from rest to 1 km/h, the vehicle must be designed to be capable of providing 75.0 kN of specific traction force.

Table 1. Adapted and Modified from Class 150 DMU Technical Specifications [28].

Modified Specifications for Hydrail Commuter Train	
Vehicle Length, L	40.12 m
Vehicle Width, W	2.8 m
Vehicle Height, H	3.77 m
Tare Mass, m	76.5 tonnes
Davis Equation, $R(v)$	$R(v) = 1.5 + 0.006v + 0.0067v^2$
Maximum Speed, v_{max}	90 km/h
Maximum Acceleration, a_{max}	0.981 m/s2
Numbers of Powered-Axles, A	8
Numbers of Available Seats, S	124
Engine Power, P_E	1000 kW
Drive Train Efficiency (DC-bus to wheels), η_D	88%

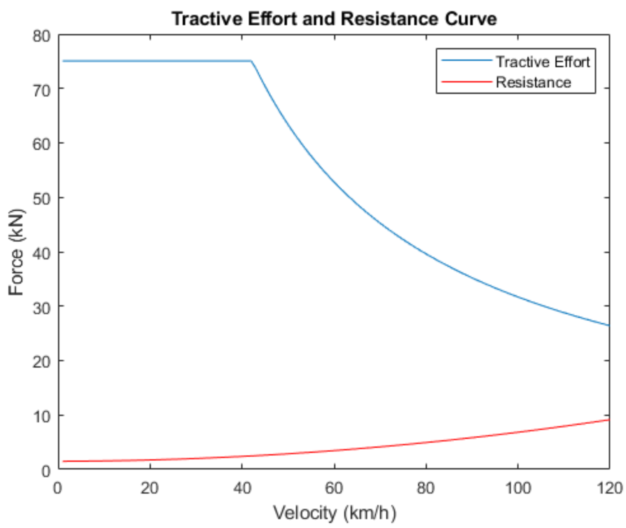

Figure 3. Adapted Class 150 DMU tractive effort curve.

3.3. Selected (Highway 97) Route

Figure 4 shows the conceptual route. The 342 km route selected is modeled to consist of terminals at either end (i.e., Kamloops and Osoyoos) and fourteen stations in intervening cities. The large variations in elevation throughout the route are due to the mountainous and lake inhabited terrain common to the Okanagan Valley region. It was assumed that OVER PR would follow operational procedures similar to the Karlsruhe Tram–Train Model [7] in terms of traveling city speeds in population centers and traveling highway speeds between cities. As noted earlier, the traffic lanes and tracks are a shared driving space in lower-speed urban areas only; at higher speeds above 60 km/h, the tram–train tracks would run alongside or in the median of the highway but still in the right-of-way, although this depends on community leaders as other route choices exist (e.g., abandoned and/or lightly used rail corridors). Using existing roadways and highway rights-of-way would drastically reduce, if not eliminate, the need for OVER PR operations land acquisition. The exact routing path would need to involve community consultation, multicity planning coordination, and a provincial government planning process. The route must also work with regional public transit services to construct an optimal arrival/departure schedule. Modern traffic signaling can prevent stops at city intersections by timing the commuter train with local bus transit schedules; this will save on consumed energy and passenger travel time. For this model's purpose, station dwell times of 1 min were used, along with terminal stop times of 15 min. For this simulation, it was assumed that minimal stopping at road intersections would occur other than at stations, especially where transit prioritization could be used (e.g., highway transit signals, green-time extensions, signal coordination). The OVER PR line connects 16 small and medium-sized cities throughout the Valley. Taken together, the population served by OVER PR approximates the population of a city capable of a tram–train network. Of note, the largest city, Kelowna, has a population of 150,000 residents, which equals Karlsruhe's historic population at the time tram–train service was first invented there in the 1980s, hence the common use of 'Karlsruhe tram–train model' phrasing. Moreover, this study considered OVER PR to be a train–tram route, as the hydrail train travels at tram (city) speeds within city limits and travels at train (highway) speeds between cities.

Figure 4. Map of Okanagan Valley Electrical Regional Passenger Rail (OVER PR) route.

3.4. Track Structure

As opposed to rubber-tired intercity bus travel, rail-based transit can provide greater lateral stability and safety, especially in winter climates on curvilinear mountainous terrain. Indeed, in this region, there have been highway 'coach' buses involved in fatal winter crashes, where lack of lateral stability on icy, snow-covered pavement was a contributing factor [29]. In this analysis, it was assumed that embedded rail tracks would be used as much as possible but mainly in cities. An embedded rail track is a type of railway track construction that differs from conventional railway tracks, as the construction of the track removes the need for typical track ballast. Rail tracks are instead embedded directly into the concrete with a polymer filling, as shown below in Figure 5, which provides the necessary stability and support to the railway track [30]. The railway track behavior is not explicitly modeled in this analysis; however, the track construction to be implemented for the OVER PR route is assumed to be embedded railroad tracks at lower speeds in cities where the route shares traffic lanes and is integrated with other modes, as noted earlier.

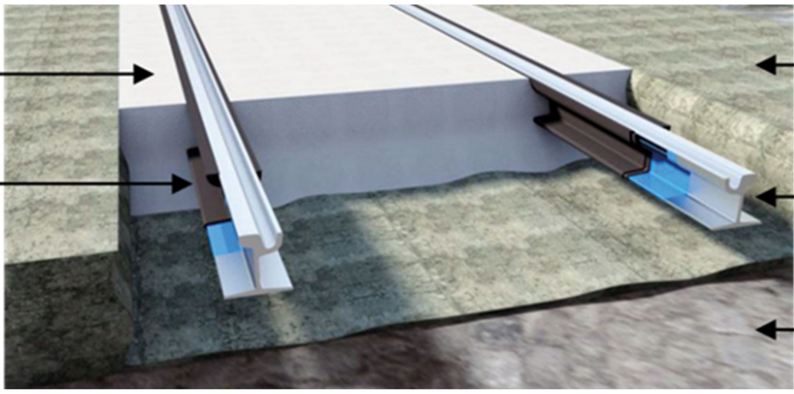

Figure 5. Concept of OVER PR embedded track system [30]. Used with permission.

The proposed Highway 97 corridor in rural areas between cities runs at speeds up to 100 km/h. Following the Karlsruhe model, at these intercity speeds, this analysis assumed the tram–trains would run on a standard rail cross-section, separated from traffic (i.e., in the highway median and/or beside the highway). The American Public Transportation Association (APTA) denotes that such an intercity rail track (class 5 in this case) can have a maximum allowable speed of 90 mph (145 km/h) [31], which is a higher velocity than the maximum speed assumed in this research.

At lower speeds, and despite concerns over the curvilinear nature of the Highway 97 route, embedded rails would be used as much as possible, for several reasons. Compared with conventional railway tracks, embedded rail tracks have several advantages. They are less prone to damage and degradation, as the asphaltic concrete road surface and subgrade provide a stable base for the track that reduces the need for costly maintenance and also have a longer service life, as the concrete slab provides protection against weather, degradation, and corrosion. They are quieter, as the concrete slab reduces the transmission of noise and vibration. The tracks are designed to have low rolling resistance, which reduces energy consumption and improves train performance. Additionally, embedded rail tracks provide a smooth, stable riding surface. While they cost less to maintain and have many benefits, these embedded rails do cost more to install than standard rails. Nonetheless, this study assumed that embedded rail technology would be incorporated into the OVER PR route in order to improve the longevity, safety, and reliability of the rail system [30,32–34].

4. Results and Discussion

4.1. Performance and Energy Usage Modeling

The energy usage requirements for implementing a Hydrail railway vehicle with train specifications similar to a Class 150 DMU are calculated for a roundtrip journey along OVER

PR. The STS model developed examined the commuter train tractive efforts curves, velocity and acceleration profiles for the trip, and traction/braking power conditions experienced over the trip. The energy consumption calculations relied on scaling the at-wheel energy through static efficiencies to arrive at at-tank estimates referenced in the literature [15]. Figure 6 displays the Hydrail commuter train speed, power requirements, and elevation over the roundtrip. Hydrail trains emission levels are tied to energy consumption, which are primarily dependent on the efficiency of hydrogen production, regenerative braking efficiency (which produces emissions from braking friction material), the auxiliary energy needs for systems onboard, and energy conversion efficiency in fuel cells [15]. If hydrogen is produced using renewable energy sources, such as hydroelectric, wind, or solar power, the emissions can be minimal. The exact relationship involves factors such as the efficiency of hydrogen production methods, which can range from renewable to fossil fuel-based production methods, such as electrolysis or steam methane reforming production methods. However, if hydrogen is derived from fossil fuels, emissions will still be present.

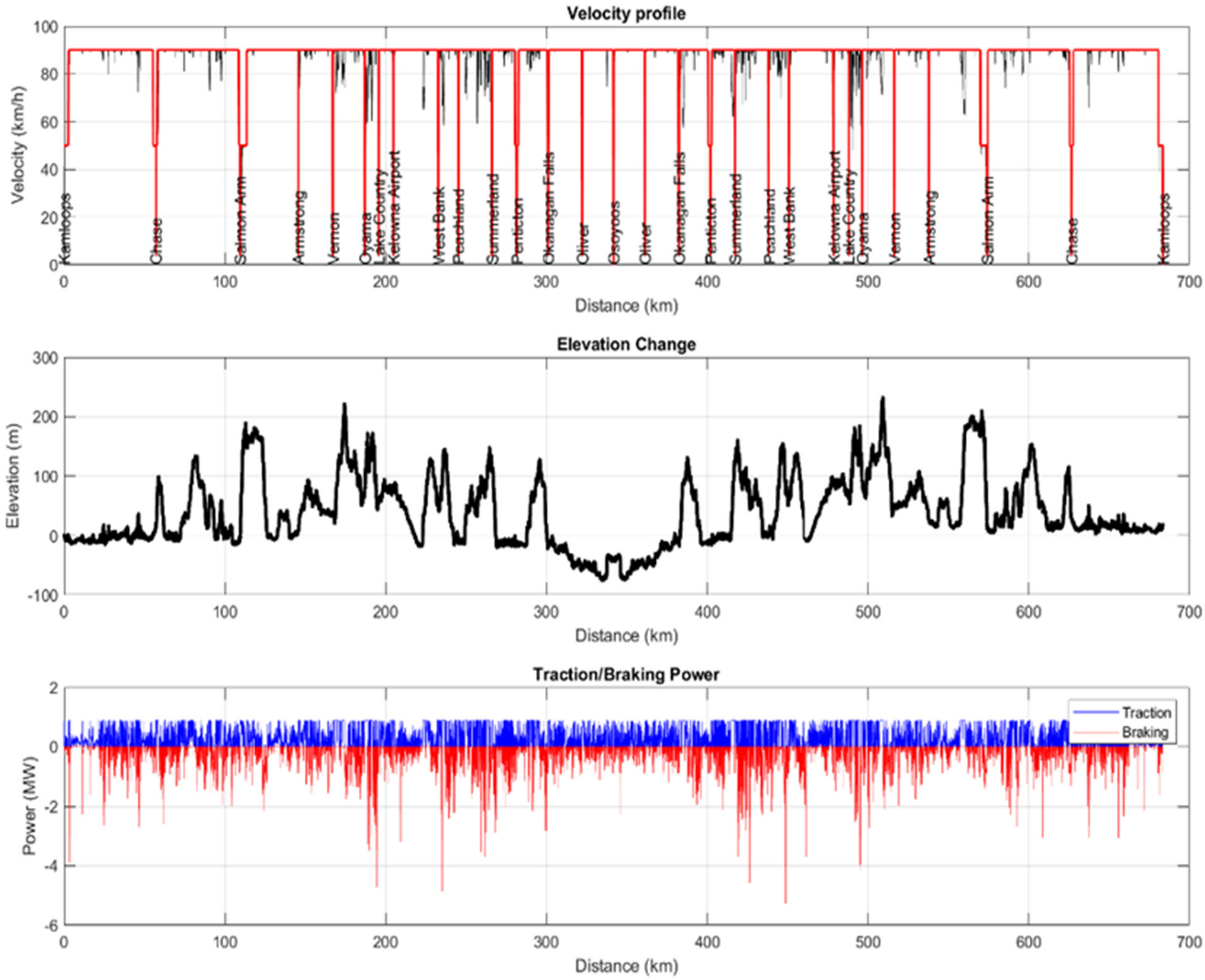

Figure 6. Original OVER PR simulation results (roundtrip).

The analysis, starting from Kamloops BC, showed a total roundtrip time of 8 h 34 min, resulting in an average train velocity of 86 km/h, where maximum speed was limited to 90 km/h. Over the OVER PR roundtrip route, 2400 kWh of energy was consumed by the hydrail train power system. Note that this is at a drivetrain efficiency of 88%, with a modified hydrail vehicle maximum engine power rating of 1000 kW when regenerative braking is not considered. It was determined that if it was able to yield a regeneration efficiency of 41%, the energy consumption decreased to 1950 kWh. This regeneration efficiency assumed a value at the higher end of urban rail regeneration efficiencies, which typically vary between 10–45%, because research has shown that a hydrail energy storage system (ESS) would recapture energy more effectively [35]. Thus, in the case where regenerative braking was considered, significant energy savings of 450 kWh would be achieved. In order to recover this lost energy, an onboard energy storage system would be required to absorb the recaptured energy during braking. Recognizably, 100% dynamic braking would optimize system energy efficiency. However, by design, this analysis did not assume dynamic braking (regeneration), in order to be more conservative regarding the hydrail train hydrogen consumption estimation.

The OVER PR roundtrip consumed 144 kg of hydrogen. When regenerative dynamic braking was considered, the hydrogen consumed was reduced to 117 kg. Moreover, hydrogen fuel consumption rates for the trip reached 0.17 kg/km with regeneration and 0.21 kg/km without regeneration. Given a hydrogen tank energy density of 1633 Wh/kg [12], the anticipated mass of the integral hydrogen storage system, inclusive of tanks, ranges from 1200 kg to 1500 kg. The tram–trains would likely need refueling at each terminal or once per trip given the hydrogen storage limit. Moreover, depending on hotel loads (i.e., onboard auxiliary power needs such as lighting, air conditioning, and appliances), and without regenerative braking, energy consumption would be higher, possibly as high as 0.3 kg/km. The differences in fuel and energy consumption rates on the arrival or return journeys by the train can be attributed to the gradient profile on each of the trips, where the journey from Kamloops to Osoyoos encounters more downhill sections than its return trip from Osoyoos to Kamloops. Assuming an initial 16-vehicle fleet that provides a 16 h passenger transit service, with 30-to-60 min headways, a total of 5 tonnes of H2/day would be consumed by the hydrail train fleet per day, an amount well within the current green hydrogen production capacity in the Province of BC and slightly higher than the payload of one typical liquid hydrogen delivery truck. A summary of the performance measures for the Hydrail OVER PR vehicle is presented in Table 2.

Table 2. OVER PR Energy Usage and Performance.

OVER PR Energy Usage	
Roundtrip Time, *TR*	8 h 34 m
Average Train Velocity, v_{avg}	86 km/h
Peak Traction Power, P_{Peak}	880 kW
Average Traction Power, P_{avg}	276.4 kW
Energy Consumed at Drivetrain Efficiency of 88%, E_D	2400 kWh
Consumed Energy with Regeneration, $E_{D,reg}$	1950 kWh
Hydrogen Consumption of 16 Train Hydrail Fleet for 16 h day Transit Service, $m_{H_2/day}$	5 tonnes H_2/day
Hydrogen Storage System Mass @ 35 MPa, $m_{storage}$	1460 kg
Hydrogen Storage System Mass with Regeneration, $m_{storage,reg}$	1194 kg
Hydrogen Gas Used, m_{H_2}	144 kg
Hydrogen Gas Used with Regeneration @ 35 MPa, $m_{H_2,reg}$	117 kg
Hydrogen Fuel Consumption Rate, Δf_{H_2}	0.21 kg/km
Hydrogen Fuel Consumption Rate with Regeneration, $\Delta f H_{2,reg}$	0.17 kg/km

4.2. Route Gradient Assessment for a Hydrail Tram–Train

The terrain along Highway 97 contains gradients of up to 8%. If OVER PR were to follow it in both directions between Kamloops and Osoyoos, it would average 86 km/h on this 683.5 km two-way roundtrip, and take 8 h and 34 min, allowing for dwell times of 3 min at stations and 15 min running time between stations. For comparison, driving a car this same roundtrip on the Highway 97 route takes 7 h 20 min, roughly 40 min shorter in the absence of traffic congestion but closer to 8 h in congestion, so both modes would comparably be the same if transit priority lanes and/or signals were used to skirt congested areas. Moreover, if the OVER PR vehicle top speed was increased from the 90 km/h used in the simulation to 100 km/h to better represent observed traffic flow speeds, its average trip velocity would be 95.6 km/h and nearly identical to the travel times of personal auto users.

As can be seen in Figures 4 and 6, Highway 97 traverses many curves, hills, and mountain passes, all of which were taken into account in this study. In the absence of a final design and route, horizontal curves were considered and deemed navigable by this tram–train vehicle by comparing its weight with the similar-sized freight trucks that already travel these same horizontal curves at even higher speeds (at a gross vehicle weight of over 50 tonnes). Clearly, the superelevation already existing at each horizontal curve allows these similar-sized vehicles to travel safely, and there is no reason to expect a different result in any future rail track design. Hence, it was reasonable to conclude that OVER PR vehicles could navigate the horizontal curves. Consequently, this single-train simulation study focused on the vertical curves and gradients of the mountainous terrain as the factors to consider when calculating locomotive power, travel time, and fuel requirements, recognizing the need for slower speeds at some sharper horizontal curves.

Peak acceleration and therefore maximum force were encountered on the gradient climbs between Vernon to Oyama and from Summerland to Peachland. In order to preserve a level of comfort along the journey, the maximum vehicle acceleration was constrained to its physical limit of 0.981 m/s^2. Under poor circumstances or weather conditions, a hydrail passenger train could experience a situation where it is required to start and stop on the steepest part of the route's gradient. Using Equation (5), the required forces for the train to overcome can be calculated, where δ is the steepest highway grade in percent, μ is the vehicle's coefficient of adhesion, m is the train mass in tons, and g is the gravitation force. From Figure 3, it was determined that the vehicle must be designed to be capable of providing 75.0 kN of specific traction force. In order to climb a 10% grade, the 69.4 tonne commuter train requires 68.1 kN to overcome the gravitational force. The braking effort was calculated assuming a low coefficient of adhesion of 0.2 or 20% (including frictional braking) present on the tracks to mimic Canadian winter weather conditions on the Valley's mountainous highways. In this case, a braking effort of 136.2 kN would be required, where a coefficient of adhesion reduction to 0.15 results in 102.1 kN, in which the braking force is still much greater than the gravitational force on the train. Therefore, since the modeled hydrail vehicle must be capable of providing 75.0 kN of tractive force, and a braking effort of 136.2 kN in poor conditions, it follows that in either scenario the forces would both be greater than the 68.1 kN of gravitational force. Thus, the vehicle would be able to overcome the largest gradient along Highway 97, as shown in Equation (6). Note that this assumes that all axles present on the hydrail train are powered and also equipped with brakes and have them engaged when stopped.

$$\textit{For Stability}: \mathrm{F_b} \geq \mathrm{F_{TE}} > \mathrm{F_g} \textit{ where } \mathrm{F_g} = \delta mg \textit{ and } \mathrm{F_b} = \mu mg \tag{5}$$

$$\mathrm{F_b} = 136.2\ \mathrm{kN} \geq \mathrm{F_{TE}} = 75.0\ \mathrm{kN} > \mathrm{F_g} = 68.1\ \mathrm{kN} \tag{6}$$

The results of our analysis suggest that an intercity passenger tram–train similar to Alstom's zero emission hydrail Coradia iLint would be capable of completing the OVER PR route. The Coradia iLint unit consists of two cars connected together, where each of the vehicles has a Lithium Nickel Manganese Cobalt Oxide (NMC) battery bank and six hydrogen fuel cell modules [14]. It receives a maximum power output of 225 kW (225 kWh @ 1C) from an NMC battery bank, and 200 kW of fuel cell power can be drawn. Therefore, the combined total available maximum power of both units equates to 850 kW, which is close to the power required to traverse the OVER PR. By design, the iLint limits its power to less than one-quarter of the maximum power needed. Therefore, a vehicle twice as powerful as the Coradia iLint could drive the OVER PR route. By Alstom design standards, which are admittedly conservative by industry standards, a vehicle four times as powerful as the Coradia iLint could comfortably handle the OVER PR route. Therefore, the extra power required by the OVER PR route could involve either or both of the following additions:

1. A larger battery bank (i.e., more battery packs added to the system), which may also consider different battery chemistries, such as Lithium Titanate Oxide (LTO) batteries, due to their improved safety and reliability.
2. The addition of more hydrogen fuel cell modules in parallel to the battery system.

The optimal combination of fuel cells and battery packs would need to be designed in order to accommodate the extra tractive power required to drive the OVER PR route, pending final design. Figure 7 presents the high-level system structure of a Direct Current (DC) Hydrail Power System. In this parallel power system configuration, the fuel cell system connects to the power battery system, which is linked to the motor drive circuit through a DC bus. The controller regulates power flow between the traction control system and hybrid power system while considering operator control inputs.

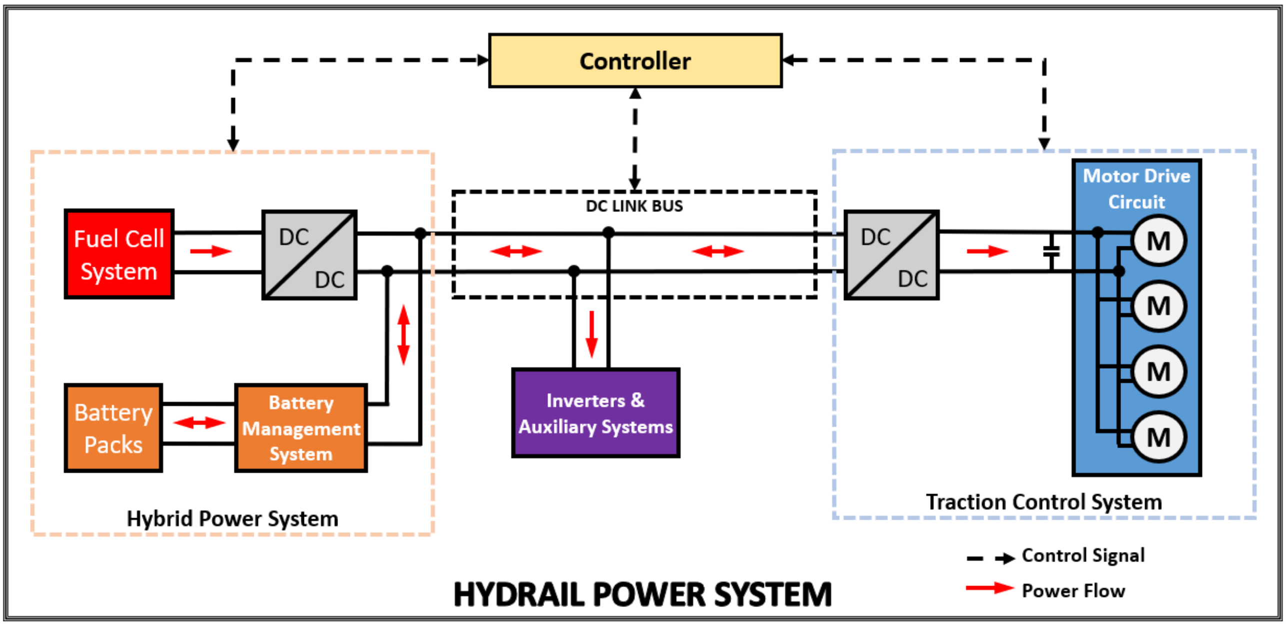

Figure 7. Hydrail Power System Structure Diagram. (The colored dashed lines define each system connected to and controlled by (black dashed lines and arrows) the Controller).

While rubber-tired road vehicles have a higher adhesion to the road than rail vehicles have to rails, it is realistic that the OVER PR vehicle—with its steel wheels on steel rails—could successfully navigate the hills existing on Highway 97 for several reasons. First, our analyses confirmed that the tram–train vehicle could stop, start, and move on its steepest hills, which have up to 10% gradients. Second, road conditions in our local northern climate and on our curvilinear mountainous highways, as noted in this paper, have often been made slippery by snow and ice, causing lateral instabilities. This significant lateral instability for rubber-tired road vehicles occurs for at least six months each year and has been a contributing factor in many fatal crashes on Highway 97 involving not just private passenger cars but professionally driven freight trucks and highway coach buses due to off-road lateral slippages, which a laterally-controlled, rail-based vehicle would not be subject to. Third, and most important of all, it is critical to keep in mind that OVER PR vehicles would not be heavy-rail freight vehicles, with locomotives weighing 150 tonnes or more. OVER PR would be a self-powered, light-rail system with tram–train vehicles in the range of 50 tonnes, and axle loads very similar to freight trucks. There are many widely known examples of trams running on steep slopes of gradients steeper than 2.5% (e.g., Merkur, Karlsruhe, Germany). Even in urban light-rail systems, there are short sections of rail track at 10% and more when retrofitting into cities (e.g., Vancouver Skytrain, Vancouver, BC, Canada).

4.3. Limitations

Hydrail tram–train planning is new to North America, that is, the use of hydrail drive trains on tram–train vehicles. As such, this is the first study of its kind in North America, and one of the first published worldwide. Unique to hydrail tram–trains is self-powered, light-rail vehicle technology, which differs from typical 'VIA Rail' heavy-rail, locomotive-pulled passenger cars. Therefore, as this is the first in-depth research, some assumptions had to be made; in such cases, reasonably conservative assumptions were made and have been noted throughout.

Moreover, this research was conducted in the absence of a final engineering design confirming route telemetry; hence, the conservative assumption was to follow Highway 97 gradients as opposed to conventional near-flat freight gradients. While confident that the route will at least parallel Highway 97, final alignments, stations, and therefore telemetry require a prior comprehensive community consultation and engagement process, including six First Nations, six Regional Districts, and sixteen population centers. The cost of carrying this out was outside the scope and budget of this research. Meanwhile to mitigate, deliberately conservative dwell times, grades, power train, fuel storage, and vehicle specifications were used. Future research and designs will reconcile this limitation.

The environmental impact of current hydrogen production methods and the project scale adds to the necessity for a comprehensive Life Cycle Assessment (LCA) analysis. To accurately assess emission sources and the environmental impact, a holistic approach must consider the entire lifecycle of hydrail trains, as well as the OVER PR project as a whole, encompassing manufacturing, operational efficiency, and eventual disposal of hydrail trains, tracks, and facilities while emphasizing green hydrogen production and efficiency measures.

Finally, while this study indicates that a hydrail tram–train would be technically feasible from power train and onboard hydrogen tank carrying capacity perspectives, there is still work needed to confirm a business case for the OVER PR project. Future research is intended to fill these knowledge gaps.

5. Conclusions

The Okanagan Valley in British Columbia is experiencing significant population growth, tourism, and traffic congestion, leading to increased greenhouse gas emissions, traffic-related injuries, and fatalities. The current reliance on private vehicle travel contributes to these issues, necessitating the exploration of safer and more sustainable transportation solutions. The implementation of an electric passenger rail system, specifically an Okanagan Valley Electrical Regional Passenger Rail (OVER PR) route, offers a promising alternative. The analysis of the Okanagan Valley's Highway 97 alignment as a proxy for the OVER PR route provided insights into the feasibility and energy requirements of such a project. A single-train simulation (STS) analysis allowed for the calculation of energy usage and performance measures for a regional passenger rail route for a modified British Class 150 DMU model as a representation of a vehicle powered by a hydrogen fuel cell/battery hybrid rail drive train system (hydrail). The Class 150 DMU was chosen due to its similarities in size and structure to the desired Coradia iLint hydrail commuter train. The vehicle parameters were adjusted to accommodate the gradients encountered along the route, including an increase in maximum engine power and maximizing the ratio of powered axles. The route itself consists of twelve train stations and two terminals distributed along the Okanagan Valley, with embedded rail tracks implemented along Highway 97 in lower-speed urban areas. The simulation results provide performance and energy usage data. The analysis showed a total roundtrip time of approximately 8.5 h, with an average train velocity of 86 km/h, peaking at 90 km/h. The energy consumption for the hydrail train power system was calculated to be 2400 kWh per roundtrip, which translated to 144 kg of hydrogen fuel per roundtrip. Over the trip, the average traction power required was 276.4 kW, where 75.0 kN of tractive effort was required to move the train. In the absence of regenerative braking, and adding in hotel power requirements, the hydrogen consumption rates for the roundtrip were estimated to be up to 0.3 kg/km. Daily, a total of five tonnes of H_2 would be consumed by a 16-vehicle hydrail tram-train fleet over a 16 h service day. By increasing the vehicle top speed on the highway between stations, the overall trip journey could be shortened, or longer station dwell times could be added; however, each would impact hydrogen fuel consumption.

Overall, the results indicate that a hydrail passenger tram–train would be capable of serving the Okanagan Valley on a route similar to Highway 97. Moreover, while rubber-tired road vehicles have a higher adhesion to the road than rail vehicles have to the rails, it is realistic that the OVER PR vehicle—with its steel wheels on steel rails—could successfully navigate the hills existing on Highway 97. The use of embedded rail tracks provides advantages in terms of lateral stability on icy mountainous roads, lower maintenance requirements, significant noise reduction, and increased energy efficiency. These research findings provide a valuable foundation for future research. Further considerations, such as community consultation, planning coordination, integration with bus transit services, and business case development are seen as next steps if implementation of the OVER PR project is pursued.

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Data Availability Statement: Data supporting reported results were derived as set out in the Methodology, using SPS and associated equations listed above, and have been summarized throughout. Highway 97's terrain (i.e., maps, hills, curves) is publicly viewable online for downloading via GIS analysis and input into SPS analyses (https://www2.gov.bc.ca/gov/content/environment/air-land-water/land/terrain/search-terrain, accessed on 10 January 2024). Resulting datasets compiled and analyzed in this research have been summarized in the tables and figures in this article. All other data cannot be shared due to privacy requirements, as they are the subject of ongoing unpublished research and graduate researcher theses.

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Nomenclature

L	$Hydrail\ vehicle\ length$, [m]
W	$Hydrail\ vehicle\ width$, [m]
H	$Hydrail\ vehicle\ height$, [m]
A	$Number\ of\ powered\ axles$, [#]
s	$Number\ of\ available\ passenger\ seats$, [#]
v_{max}	$Maximum\ vehicle\ velocity$, [km/h]
a_{max}	$Maximum\ vehicle\ acceleration$, [m/s^2]
P_E	$Generated\ engine\ power$, [kW]
η_D	$Vehicle\ drive\ train\ efficiency$, [%]
F_{TE}	$Tractive\ effort\ force$, [kN]
F_g	$Gravitational\ force$, [kN]
F_b	$Braking\ force$, [kN]
T_R	$Round\ trip\ time$, [h]
E_{FC}	$Electrical\ output\ energy\ of\ fuel\ cell$, [kWh]
E_D	$Energy\ consumed\ by\ vehicle$, [kWh]
$m_{storage}$	$Required\ hydrogen\ storage$, [kg]
m_{H_2}	$Hydrogen\ gas\ used$, [kg]
Δf_{H_2}	$Hydrogen\ fuel\ consumption\ rate$, [kg/km]
v_{avg}	$Average\ simulated\ velocity$, [km/h]
m	$Hydrail\ vehicle\ tare\ mass$, [m]
g	$Gravitational\ acceration$, [m/s^2]
μ	$Coefficient\ of\ adhesion$, [%]
δ	$Maximum\ track\ grade\ along\ route$, [%]
λ	$Rotary\ allowance$, [%]
α	$Slope\ angle\ of\ track$, [degrees]
A	$Coefficient\ of\ vehicle\ mass\ resistance$, [%]
B	$Coefficient\ of\ rolling\ resistance$, [%]
C	$Coefficient\ of\ aerodynamic\ resistance$, [%]
v	$Hydrail\ vehicle\ dynamic\ velocity$, [km/h]
P_{Peak}	$Peak\ tractive\ power$, [kW]
P_{avg}	$Average\ traction\ power$, [kW]
η_{FC}	$Effiency\ of\ fuel\ cell$, [%]
LHV_{H_2}	$Lower\ Heating\ Value\ of\ hydrogen$, [kWh/kg]
$E_{D,reg}$	$Energy\ consumed\ with\ regeneration$, [kWh]
$m_{storage,reg}$	$Required\ hydrogen\ storage\ w/regeneration$, [kg]
$m_{H_2,reg}$	$Hydrogen\ gas\ used\ w/regeneration$, [kg]
$\Delta f_{H_{2,reg}}$	$Hydrogen\ fuel\ consumption\ rate\ w/regeneration$, [kg/km]
$m_{H_2/day}$	$Daily\ hydrogen\ fuel\ consumption\ rate$, [tonne/day]

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