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SUSTAINABILITY BY DESIGN

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A Cost Comparison of Transportation Modes.

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Introduction

Figure 1. Skytrain, a system designed to move people rapidly from the edge of the region to the centre.

What is the optimal relationship between land use and transit, and what transit mode would best support this optimum state. On this there is no agreement - neither here in the Vancouver region nor in the rest of North America. Many transportation planners argue for transit services optimized to serve the long high speed commute trip at the expense of local service. In the Vancouver region this position has held sway, with billions of dollars borrowed to expand the Skytrain system and billions more on the table for future expansions. Others argue in favor of systems that perform better locally but have the slower traveling speeds more suited to shorter trips. Very few metropolitan transit agencies take this position. The City of Portland which invested in its own streetcar system is one of the very few. (see The Case for the Tram: Learning From Portland http://www.sxd.sala.ubc.ca/8_research/sxd_FRB06_tram.pdf). What is the more sustainable option? This bulletin attempts to clarify this question for our region, if not definitively answer it.

Secondly, the question of transportation technology choice can no longer be made while turning a blind eye to the real possibility of peak oil and our national responsibility to reduce greenhouse gases (GHG). Legislation now exists that requires municipalities and regions to arrange land uses and transportation systems in a manner that reduces our greenhouse gas (GHG) emissions (ie. British Columbia's *Greenhouse Gas Reduction Targets Act*). The use of transit, which was heretofore considered solely from the perspective of reducing auto dependence and providing transportation equity to the disadvantaged, now has a broader mandate to help governments meet their GHG targets. For this reason we examine the carbon emissions associated with each mode. What good does it do us if everyone rides the bus yet that bus still produces as much greenhouse gas per passenger mile as the car it replaces?

Figure 2. Shows the dense development and mixed use characteristic of "streetcar neighbourhoods"

Finally, there is the question of long term cost efficiency. Investment decisions made this decade will determine land use and transportation patterns that will last for the next hundred. How can we choose the system that helps create the kind of energy, cost and resource efficient region that the future demands? Against the metrics of trip length, low carbon, and low cost per mile, which strategy is the best, and what transportation and land use combination best achieves this end? This article attempts to clarify these questions.

Sustainability Principles

In keeping with our methodological choice (i.e. to assess this question broadly against sustainability goals rather than narrowly focusing on transportation per se) we organize this information against three fairly well accepted sustainablility principles. First, whatever the mode, we are assuming that shorter trips are better than longer trips. Transporting people requires energy, and energy, even from 'green' sources, has its costs. Thus we ask what is the arrangement of transit and land uses that leads to the lowest average daily per capita demand for vehicle travel of any kind?

Figure 3. The modern Combino tram uses 0.11 kWh of energy per passenger mile (given observed vehicle occupancy).

Figure 4. A trolleybus in Vancouver, BC is powered by overhead electrical wires therefore eliminating any tailpipe emissions. A trolleybus uses 0.36 kWh of energy per passenger mile (given observed vehicle occupancy).

Figure 5. The skytrain in Vancouver, BC uses 0.30 kWh of energy per passenger-mile (given observed vehicle occupancy).

Second, we know that low carbon is better than high carbon. Therefore, what transportation mode has the least carbon emissions per trip? How does the energy source factor in to this carbon calculation? Here in British Columbia most of the electricity used to power the Vancouver Region's Skytrain system and trolley busses comes from hydroelectric sources. Thus these trips, discounting some externalities, are essentially carbon zero. But if the power driving these vehicles came not from hydroelectric sources but from fossil fuels, what would this mean for our carbon calculations?

Finally, we should choose what is most affordable over the long term. Long term capital, operating, maintenance and replacement costs need to be considered and evaluated to find the most efficient transportation mode. The public purse is only so full, and money spent on expensive systems usually translates into other resource demands on the planet that also must be reduced.

Thus the limited purpose of this article is to provide the best available data to help answer these questions and to organize that data against the framework of the three sustainability principles stated above. We do not, however, try to definitively answer this question. Our work is too preliminary to do so. Furthermore it is unlikely that any work however extensive could definitively prove out an unassailable conclusion to such a broadly framed question. These questions, and other sustainability questions like them, have far too many interacting variables to lend themselves to classical proofs. What we CAN accomplish is to suggest how necessarily complex questions may be more intelligently framed than is currently the case, and framed against the broad sustainability goals which are becoming increasingly important to the survival of the planet.

To help frame this argument the following transportation modes are compared throughout the report:

- Modern Tram: based on Siemens' Combino Plus featuring articulated, low floor, rail vehicles with regenerative braking technology, operating in existing street right of ways.
- Trolleybus: based on the Vancouver region's New Flyer electric rubber-wheeled trolley bus featuring low floor vehicles with regenerative braking technology.
- Skytrain: automated, mostly elevated, rapid rail transit Mark I and Mark II vehicles in service in Vancouver, BC.

- LRT: SD-400 and SD-460 90’ single articulated vehicles. Light Rail Transit differs from trams in that it generally operates in separate rights-of-way with less frequent stops and raised boarding platforms.
- Articulated Diesel Bus: 60’ vehicles used in high-capacity, high-frequency BRT express routes (operates in traffic, no signal control).
- Diesel Bus (40’): 1998 40’ Gillig Phantom vehicles in service in St. Louis.
- 2007 Toyota Prius: hybrid electric mid-sized car that won Green Engine of the Year 2008 from International Engine of the Year Awards.
- 2007 Ford Explorer: mid sized sport utility vehicle (SUV) popular in North America.

Figure 6. Shows an articulated diesel bus in service in Vancouver, BC that uses 0.56 kWh of energy per passenger mile (given observed vehicle occupancy).

Principle 1: Shorter trips are better than longer trips

What is the best mode for short trips that act as an extension of the walk trip?

Figure 7. The Toyota Prius is an electric hybrid that provides substantial gains in fuel economy and major reductions in total tailpipe emissions. It uses 0.64 kWh of energy per passenger mile (given observed vehicle occupancy).

If shorter vehicle trips are the goal, what is the best transit option? Most experts agree that for short trips options to the car include the walk, the bike, the bus, or the tram. Certainly the walk and the bike trip have the least impact on the planet and the lowest cost. But to extend the walk trip the bus and the tram are the logical next mode shift. Traditional “streetcar neighbourhoods” of the type that characterize most Vancouver area districts built prior to 1950, generally encourage shorter trip length due to their close proximity of activities, their fine-grained mix of land uses, and their grid-like street networks.

This hypothesis is born out by data that shows that North American districts still served by streetcar, and their kindred rubber tired cousins the trolley bus, exhibit shorter average trip lengths than other modes (2.5 and 1.6 miles respectively). On the other hand, the average daily trip length in a personal automobile in the United States is 9.9 miles. Other trip length averages across the United States were found to be 3.9 miles for local bus, 5.0 miles for BRT, and 4.6 miles for LRT. These values are represented in Figure 9.

Figure 8. This 2007 Ford Explorer uses 1.42 kWh of energy per passenger mile (given observed vehicle occupancy).

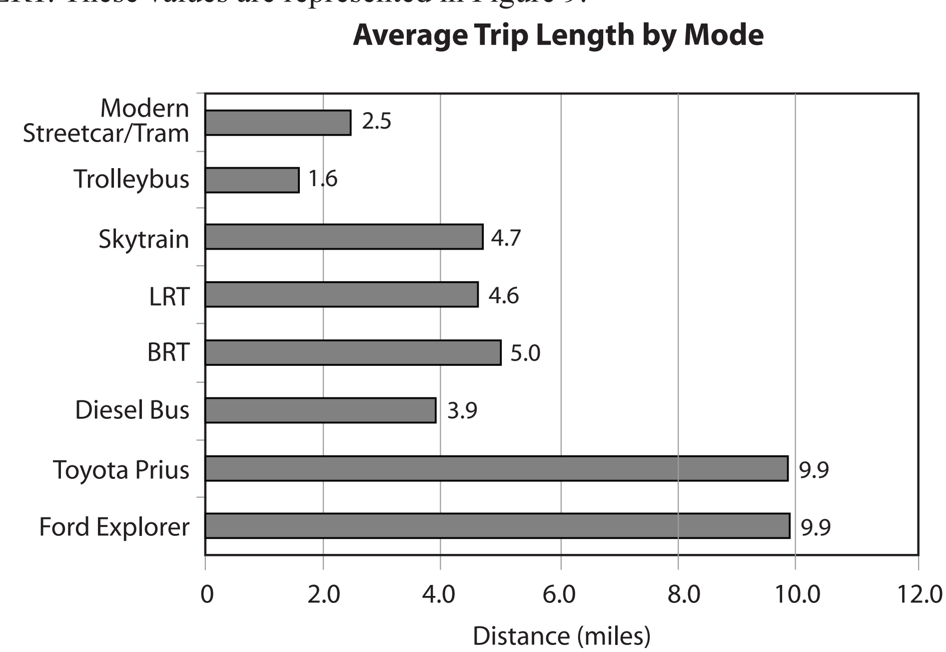

Figure 9. Average trip length by mode (Data from APTA 2009; Buehler et al. 2009; IBI Group 2003)

Principle 2: Low carbon is better than high carbon

What transportation mode is most energy efficient?
While both busses and trams are an effective way to extend the walk trip, trams are inherently more energy efficient than buses because they generally have higher passenger capacities and lose less energy to frictional resistance than rubber wheeled vehicles.

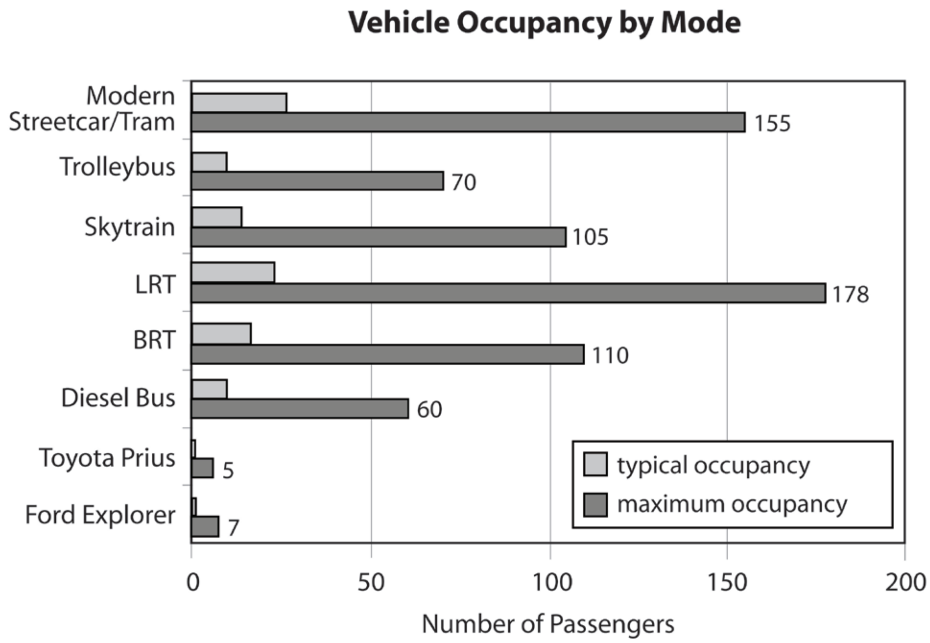

Figure 10. Vehicle Occupancyy
Source: The maximum vehicle capacity for each mode was gathered from manufacturing specifications for the following vehicle models: 2007 Ford Explorer, 2007 Toyota Prius, 1998 Gillig Phantom, 2001 D60LF Articulated Bus, SD-400 and SD-460 90' single articulated LRT, Mark I and Mark II skytrain vehicles, ETI Skoda Trolley Bus and Siemens Combino Plus tram. typical vehicle occupancies for the transit modes were calculated from operating data reported from existing systems using these vehicles. Transit occupancy data from Translink 2003; FTA 2005; NTD 2007; PUTA 2007; Translink 2008b; Davis 2009; VanElsas 2009; TTC 2009. The observed occupancy for private automobiles is based on the average vehicle occupancy for trips to or from work in the United States (BTS 2001).

Trams also more frequently capitalize on regenerative braking technology, which allows them to convert the kinetic energy of the vehicle in motion to electrical energy when it brakes. This energy is either returned to the overhead wires for use by other vehicles or used to power auxiliary equipment such as onboard heating/cooling systems (ExecDigital 2007). Modern trams like Siemens' Combino Plus, are able to recover 30% of the energy used to power the vehicle through this process (Blumenthal et al. 1998). A study of Combino's performance in the field found that at slower average speeds (19 km/hr) energy recovery from regenerative braking was more than 42% (Blumenthal et al. 1998).

When converting energy efficiency into kilowatt hours we found that the energy efficiency of a modern streetcar is approximately 0.11 kWh per passenger-mile, LRT is 0.13, skytrain is 0.30, trolleybus is 0.36, articulated diesel bus is 0.56, the Toyota Prius is 0.64, the 40’ diesel bus is 0.75 and the Ford Explorer is 1.42 kWh per passenger-mile (all figures for actual capacity).

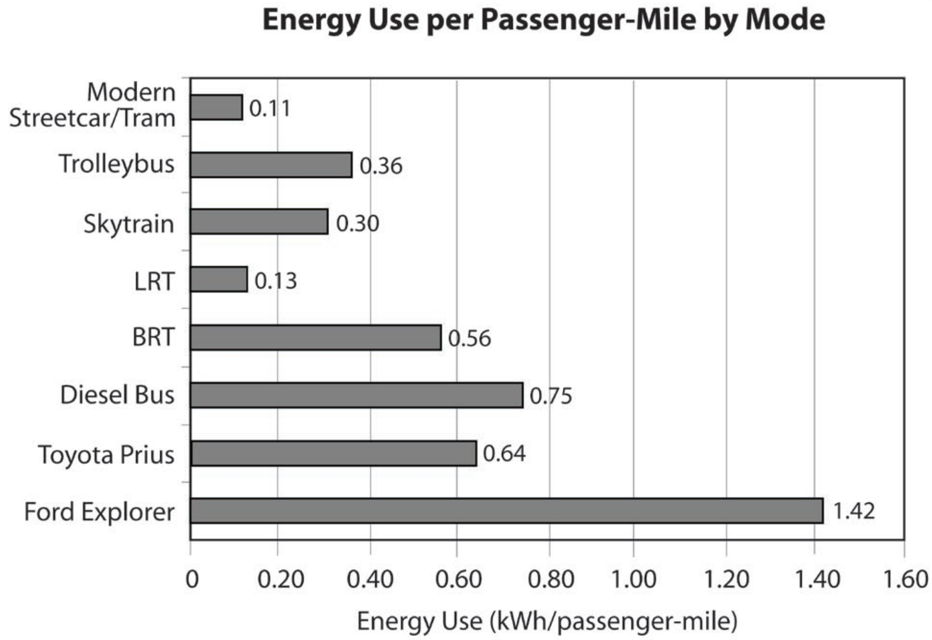

Figure 11. Vehicle energy use data from Strickland 2008. Observed vehicle occupancy from BTS 2001; Translink 2003; FTA 2005; NTD 2007; PUTA 2007; Translink 2008b; Davis 2009; VanElsas 2009; TTC 2009.

What transportation mode has the lowest carbon emissions per passenger-mile?

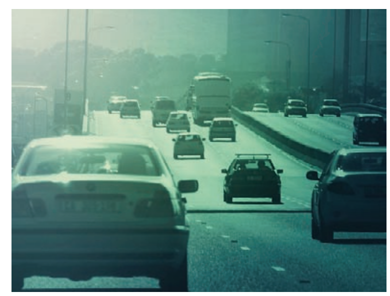

Figure 12. Internal combustion engines contribute significantly to street level pollution levels.

Carbon emissions by different modes of transportation are primarily influenced by the type of fuel the vehicle uses and the efficiency of the motor used to process it. In this study we look at regular gasoline, diesel and electricity as the primary sources of energy in the transportation sector. Because electricity can be generated in a number of different ways we have included electricity generated from a coal plant, a natural gas plant and a hydro-electric plant to highlight the range of potential carbon emissions from this sector.

Carbon Equivalent Emissions by Energy Source

Gasoline	= 262	grams of CO_2 emissions/ kWh
Diesel	= 253	grams of CO_2 emissions/ kWh
Electricity (Coal)	= 206	grams of CO_2 emissions/ kWh
Electricity (Nat. Gas)	= 106	grams of CO_2 emissions/ kWh
Electricity (Hydro)	= 4.4	grams of CO_2 emissions/ kWh

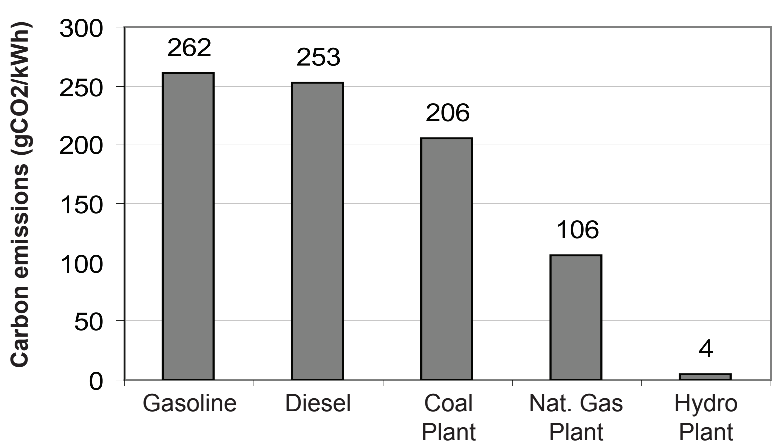

Figure 13. Carbon Emissions by Energy Source
Source: Spadero et al. 2000; EPA 2005; Strickland 2008

Applying these emissions to our transportation modes based on their source of energy we can calculate their carbon emissions per passenger-mile. Even when using electricity generated from a coal burning power plant (Figure 15), the carbon emissions for electric powered vehicles is far lower than vehicles using internal combustion engines.

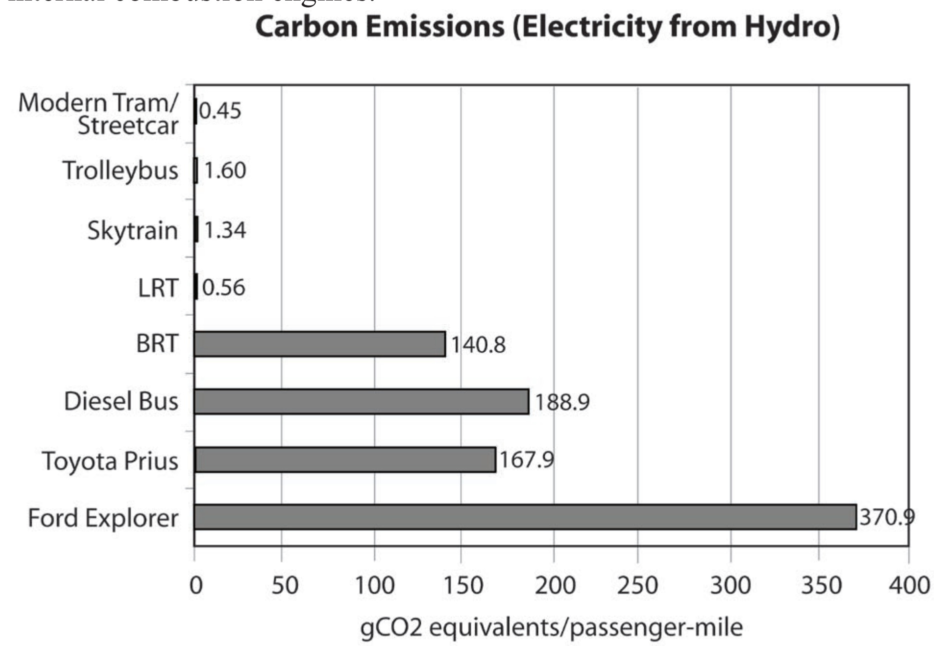

Figure 14. Vehicle energy data from Strickland 2008, energy conversions to carbon equivalents from Spadaro et al. 2000. Observed vehicle occupancy data from BTS 2001; Translink 2003; FTA 2005; NTD 2007; PUTA 2007; Translink 2008b; Davis 2009; VanElsas 2009; TTC 2009.

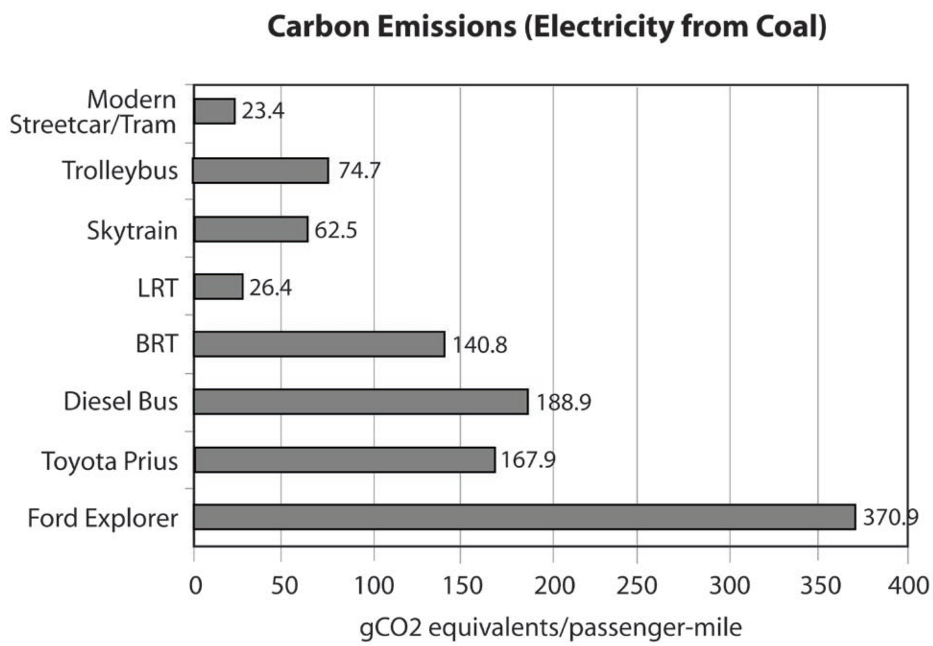

Figure 15. Vehicle energy data from Strickland 2008, energy conversions to carbon equivalents from Spadaro et al. 2000. Observed vehicle occupancy data from BTS 2001; Translink 2003; FTA 2005; NTD 2007; PUTA 2007; Translink 2008b; Davis 2009; VanElsas 2009; TTC 2009.

To better understand why electrically powered vehicles are so much cleaner than gasoline or diesel powered vehicles (even when carbon emissions produced by gasoline, diesel and coal differ by only 56 grams of CO_2 emissions/kWh) we must look at the energy efficiency of the electric motor versus the internal combustion motor. According to Strickland (2008) internal combustion engines typically convert, at best, 1/3 of their energy into useful work while electric motors generally have energy efficiencies of 80-90%. This means that electrically powered vehicles perform significantly better from the perspective of carbon mitigation and energy efficiency in comparison with the relatively inefficient internal combustion engine.

Although we have focused here primarily on the carbon emissions from the actual movement of vehicles, there are also significant carbon emissions associated with vehicle manufacturing and maintenance, infrastructure construction and fuel production. Quantifying the full lifecycle carbon consequences of each mode is far beyond the scope of this article however, recent research by Chester (2008) provides some insight into this question. He found that life-cycle greenhouse gas emissions are 47-65 percent larger than vehicle operation emissions for automobiles, 43 percent for buses, and 39-150 percent for rail (modern trams, with their minimal construction requirements, would be on the lower end of this range while Skytrain would be on the higher end) (Chester 2008). The GHG consequences of all the concrete used in the construction of elevated or buried subway systems such as Skytrain boosts the GHG consequences of this mode significantly making it likely that the investment in this infrastructure will return far less GHG advantage than advertised.

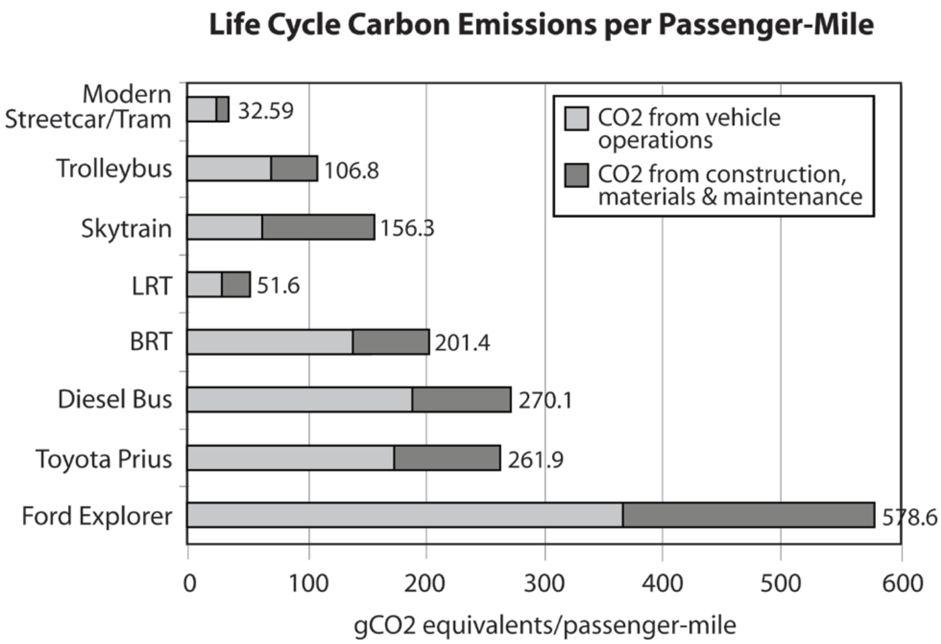

Figure 16. Life cycle carbon emissions per passenger-mile (when electricity is from coal) Caption: Vehicle operation emissions were calculated using typical vehicle occupancy for each mode and energy data from Strickland 2008 and conversion factors from Spadaro et al. 2000. Non-vehicle operation emissions were calculated using results from Chester 2008.

Principle 3: Choose what is most affordable over the long term.

Given the long term capital, operating, maintenance and replacement costs what mode is the most efficient/cheapest?

To make a sound comparison of the long term aggregate costs per passenger-mile associated with each transportation mode we incorporated capital costs associated with acquiring the vehicles and constructing the infrastructure necessary to support them. The total cost was then amortized over the expected life of the system and this annualized cost was divided by the actual annual passenger-miles recorded by the transit authority.

The capital costs for transportation modes such as streetcar, LRT and Skytrain are relatively easy to determine because the large initial investment to build the transportation infrastructure (tunnels and elevated tracks, vehicles, stations etc.)

is generally tied directly to the project. However, many costs associated with personal automobile, local bus service, and to a lesser extent BRT and trolley bus, are more difficult to determine because they operate on existing roadways, the construction and maintenance of which are not included in most cost calculations for these modes. For this reason we have included external costs that begin to place a value on the land and resources dedicated to automobile infrastructure. Because the transportation sector is far from agreement on which external costs should be included in valuations of this kind we have provided a high (full) and a low (basic) estimation of external costs as listed in the caption below left.

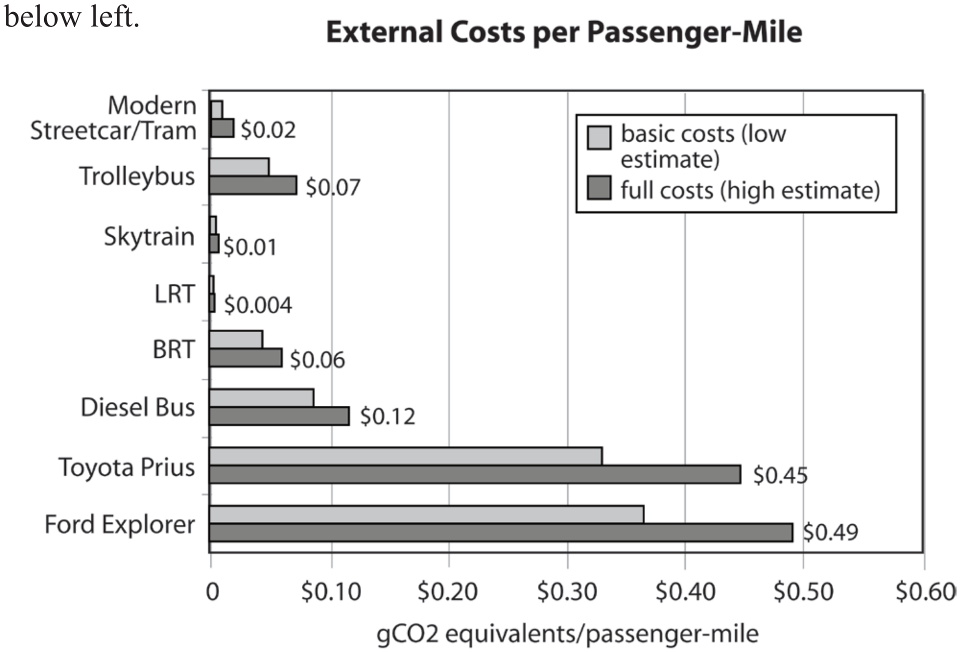

Figure 17. Full external costs include the cost of parking infrastructure, road facilities, land value, land use impacts, resource externalities, congestion, traffic services, transport diversity and barrier effects. They do not include air pollution, GHG, noise, water pollution or waste. Basic external costs include only parking infrastructure, road facilities, land value and resource externalities. Pollution costs are not included in this analysis as estimates vary widely and we itemize the GHG consequences of each mode separately. Definitions and further explanation on each of these externalities can be found online at http://www.vtpi.org/tca/. Data from Litman 2009.

Modes such as LRT and Skytrain have very low external costs because the infrastructure for these types of projects generally have to be built from scratch so the costs are already included in their higher initial capital costs. The capital and full external costs per passenger-mile for each transportation mode are shown in Figure 18.

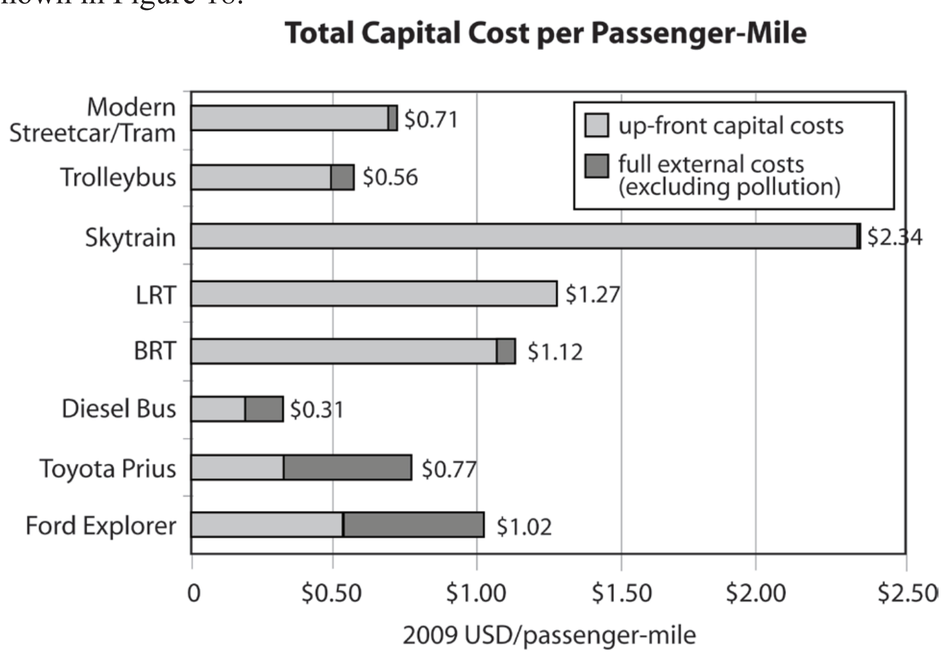

Figure 18. Capital costs were calculated using construction costs and/or vehicle costs ammortised over the expected life of the system and/or vehicles. This annualized cost was then divided by the annual passenger-miles of each mode. Data from American Automobile Association 2009; Translink 2008b; TTC 2007; Translink 2003; National Transit Database 1998-2007; Portland Bureau of Transportation and Portland Streetcar Inc. 2008; Buchanan 2008.

Next, on-going operation and maintenance expenses were calculated. These costs are shown in Figure 19 below.

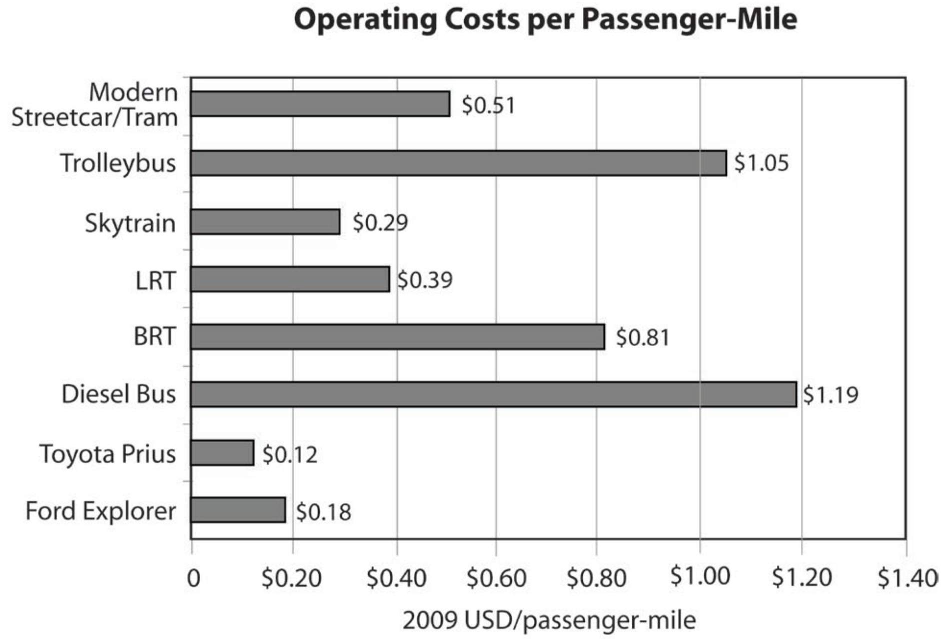

Figure 19. Operating costs for private automobile include parking, insurance, maintenance and fuel. Operating costs for transit modes also include employee salaries.

In Figure 20 the capital costs, full external costs and operating costs were totaled. Figure 21 shows the same calculations but with basic external costs. Both of these figures show the cost that is currently spent on energy for each mode as well as the future increase in energy costs that can be expected as non-renewable fuels such as oil become more scarce. Using full external costs, the Toyota Prius scores best per passenger-mile with a total cost of $1.09 followed by modern tram at $1.23. Even with negligible energy costs, Skytrain is by far the most expensive at $2.66 per passenger-mile.

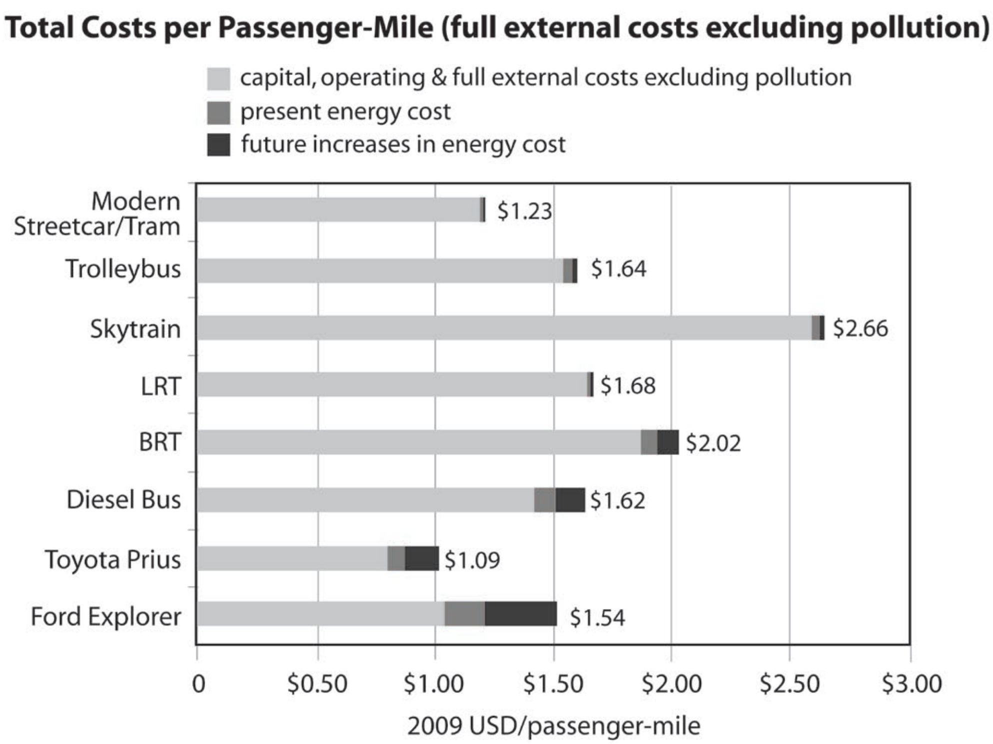

Figure 20. The total cost per passenger-mile was calculated by adding the capital, operating, full external costs (excluding pollution) and present and future energy costs for each mode.

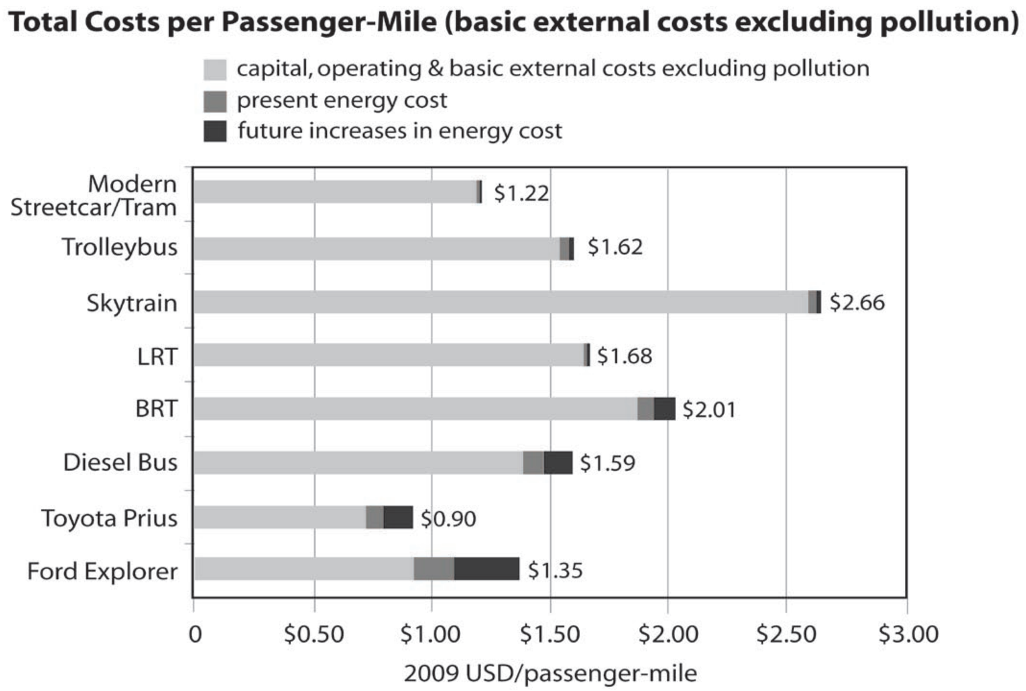

Figure 21. The total cost per passenger-mile was calculated by adding the capital, operating, basic external costs (excluding pollution) and present and future energy costs for each mode.

The results shown in Figure 20 and 21 show the cost of moving one person one mile. This kind of calculation tends to favour modes of transportation that typically travel longer distances. But since shorter trips are, in the context of this argument, more sustainable, we are also interested in, or perhaps more interested in, what is the cost per average *trip*. Low average trip distance is a marker for a more sustainable district, as it indicates that the relationship between mode and land use has been optimized. Conversely, low costs per mile gain us nothing if the relationship between mode and land use is such that all trips are unnecessarily long.

The calculated costs per trip are shown in Figure 22. In this scenario, the transportation modes encouraging land use that support shorter trips (trolleybus and modern tram) are significantly more cost effective than modes that facilitate more spread out land use patterns (ie. modes designed for high speed, long distance trips).

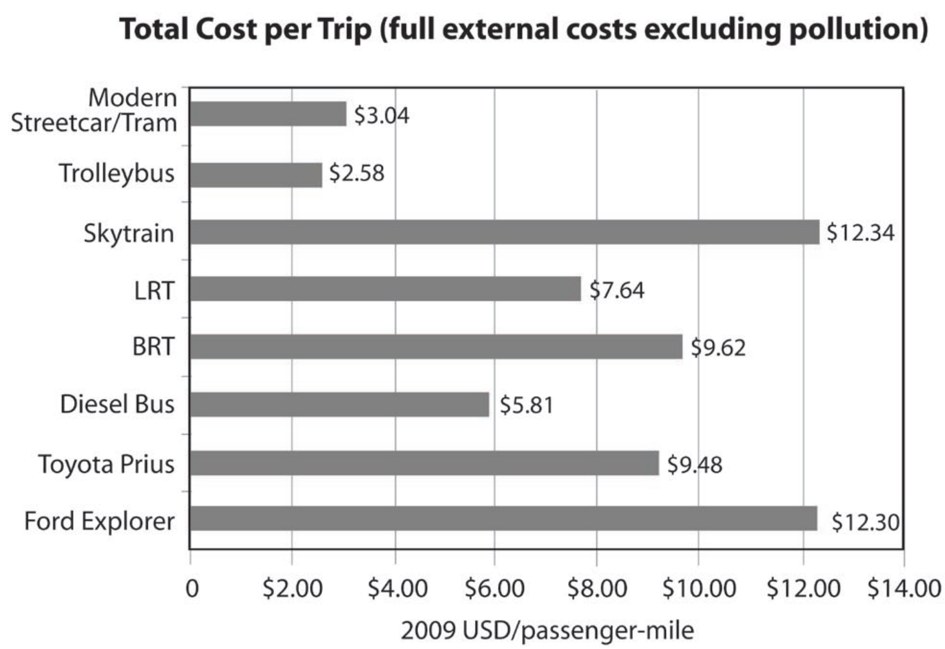

Figure 22. The total cost per trip was calculated using average trip distance and total cost per passenger-mile. This calculation includes the full external costs, excluding the costs associated with air, land and water pollution.

Conclusion

Figure 23. A busy transit stop along a modern Tram line.

Based on the three sustainability criteria, reducing trip length, greenhouse gas reduction, and lifecycle cost, trams represent the best investment. This investment only makes sense if a region and it's officials are committed to a long term strategy of balancing jobs and housing, and to reducing the daily per capita demand for transportation of all kinds. If most trips in the region are short then the rationale for investment in trams is overwhelming. If all trips are long then the rationale for the very expensive Skytrain system may still hold sway. Currently our region is at a tipping point between the two. Decisions made now about which mode to invest in could precipitate very different land use consequences, consequences lasting for decades. These arguments apply to every North American metropolitan area. All are struggling with these same questions. This bulletin does not provide a definitive answer to which path to take, but attempts to illuminate the significance of the choice. We only have till 2050 to radically reduce our carbon and resource demands on the planet, therefore investments made in this decade must be intelligent and set in place the land use and transportation armature that is compatible with that challenging goal. This generation of citizens and decision makers will determine, by its choices, what the Vancouver region, presently home for two million residents, will be like when it contains four million. Hopefully it will be much more sustainable than it is now. How we spend the billions proposed for investment in transit this decade will likely be decisive.

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