EVS27
Barcelona, Spain, November 17-20, 2013

Article Template for the EVS27 Symposium

Pierre Ducharme[1,4], Simon Ouellette[3]
[1]*Pierre Ducharme, MARCON, pducharme@marcon.qc.ca*
[2]*Simon Ouellette,* CrossChasm Technologies, *souellette@crosschasm.com*
,

Abstract

The number of options available to transit fleets is growing and the pressures to select the "optimal" propulsion technology are also increasing. Given that there is no one optimal bus for an entire transit system, there's a need to optimize the fleet, identifying the most appropriate mix of technologies reflecting the system's requirements and realities.

This presentation will discuss factors to be evaluated as well as the measurement and analytical technology enabling objective calculations on a per route basis. This 360º analysis facilitates the optimal propulsion technology purchase decision and demonstrates the validity of electric bus technology.

Keywords: alternate fuel bus, bus fleet optimization, route characterization, duty cycle, fuel consumption

1 Introduction

The backbone of urban public transportation in North America has been the autonomous bus for a very long time. Subways are expensive and complex to build, particularly in a densely populated area where they are most needed. Aerial trains are aesthetically unpopular and land based ones are space constrained where rights-of-way have not been planned long ago. Tramways and trolley buses require a network of wires that is also difficult to sell to the public, particularly when they have not traditionally been part of the urban landscape.

As a result, well over 50% of all public transportation trips are completed by bus with heavy rail ranking a distant second at a third of the trips and light and commuter rail representing less than 5% of annual urban trips each.

Thanks to greater environmental awareness and the rising price of fuel, public transportation usage is growing in North America, limited only by public funding for vehicles, infrastructure and system operations.

Buses are likely to retain the largest share of the market as they are quickly put in service and very flexible when time comes to deploy them on the ground. This certainly has been the case over the last decade with diesel electric hybrid buses making very significant inroads in the urban transit fleet across the continent.

But more recently, the abundance and consequently very low price of natural gas are making CNG and LNG buses even bigger competitors that they were only a few months ago with their sales now growing faster than those of electric buses. It is still early to tell whether CNG-electric hybrid bus sales will ever pick up from their dismal performance to date.

But the complexity of selecting the right vehicles and optimising the vehicle mix in the fleet is also growing with the arrival of multiple propulsion technologies on the market. Such complexity and the lack of familiarity of most transit operators with electric vehicles makes it harder for electric and hybrid-electric buses to make significant inroads in the urban transit industry.

2 The Challenge

In North America, National (in the USA) and/or State/Provincial governments heavily subsidize the acquisition cost of urban transit vehicles by private operators and/or municipal/local governments who are responsible for operating expenses such as fuel, maintenance and manpower. Fleet managers therefore have a strong incentive to select vehicles with low fuel consumption, low cost fuel and low maintenance costs. The added bonus is that low fuel consumption usually translates into low carbon footprint. These factors, fuel and maintenance, added to reliability of the vehicles, define "performance" in the mind of transit fleet operators.

But the performance of any vehicle is highly dependent on its usage. In the language of fleet operators, usage is largely synonymous with "*duty cycle*". So, in the past, managers used several *typical* duty cycles to benchmark their fleet against a few industry standards. The two main variables in determining a "duty cycle" are the average speed of the bus and the number of stops it makes in a given distance. But this method remains very inaccurate for several reasons.

2.1 What drives performance

Bus fleet run several routes that are not at all identical to one another, nor to a specific duty cycle. In fact, traffic and weather conditions may well yield different duty cycles on the same route, with the same driver operating the same bus. And duty cycle explains only a portion of the overall bus performance. The following characteristics also contribute :

TABLE 1 Determinants of Performance
Vehicle speed
Engine Speed
Actual Engine Per Torque
Engine Demand - Percent Torque
Drivers Behaviour: - Demand (Percent Torque) - Breaking
Bus loading (number of passengers)
Environmental conditions - temperature - road conditions - wind speed and direction - traffic density

However, characterising a duty cycle, indeed a number of duty cycles within a given fleet, has been very expensive to date. For several decades, diesel buses were the only option on the market (CNG buses had their chance when the successive energy crisis hit North America in the 70's and 80's, but failed miserably on account of their lack of reliability). Given the small difference in performance offered by the bus manufacturers equipping their vehicles with the same (or very similar) engines, life cycle cost calculations and technology comparisons were superfluous.

But the game has changed.

2.2 Technologies and choices

It is one thing to compare one diesel bus model to two others, but it is much more complicated to look at the following range of technologies available to urban fleet managers:

TABLE 2 Urban Bus Technologies
Propulsion type: - Hybrid electric (partially electric bus where, the motor is electric, but the on-board energy source is not): o Hybrid electric-petroleum buses (such as diesel-electric buses, the most commercially popular) o Hybrid electric- natural gas buses (where the ICE is powered by either CNG or LNG) o Hybrid electric- mechanical buses (with a mechanical device [pneumatic, flywheel. …] acting as a second source of power) o Hybrid electric (two sources of electric power) buses (such as fuel-cell / battery or fuel-cell/ultracap/supercap buses) o Trolleybuses (where the source of power is not, for the most part, on board the bus) o All electric buses (that have a single source of electric power such as batteries or fuel cell)
Powertrain configurations: - There are two main types of hybrid buses, series and parallel configuration, with several variations: o Parallel hybrid o Mild parallel hybrid o Power-split or series-parallel hybrid o Series hybrid o Plug-in hybrid electric bus o Fuel cell, electric hybrid
Electric buses use various means to recharge their on-board power supply: - Conduction charge at the depot (plug-in); - Induction charge when parked or at bus stops during service; - Rapid conduction charge at bus stops during service; - Exchange of batteries when parked; - Hydrogen refuelling at depot.

As can be easily inferred, one can no longer compare purchase prices and a few options (such as adding air conditioning or not) to distinguish from one offer to the next; such task has become much more complicated and fleet managers are generally ill-equipped for the job.

In addition to comparing vehicles, the important and costly modifications often required to the infrastructures and practices of the organisation are no longer mere incidentals. They include:

TABLE 3 Impact of Bus Technology Choices on other Organizational Components

Infrastructures:
- Maintenance:
  ○ Ceiling heights
  ○ Safety equipment (air sensors an fire fighting, for example)
  ○ Lift capacity
  ○ Washers
- Refueling:
  ○ Storage
  ○ Compression (gas)
  ○ Liquefaction
  ○ Gasification
  ○ Safety
  ○ Battery room
  ○ Power supply
  ○ Battery chargers
- Road
  ○ Overpass
  ○ Stops
  ○ Wiring
  ○ Power supply
  ○ Energy banks (induction)

Training and skill sets mix: - Drivers - Mechanics - Electricians - Fire fighters and first responders
Others infrastructure / equipment: - Bus barns or other overnight facilities - Tools - On-road repair / recovery
Practices: - Planning and scheduling - Bus rotations - Number of busses required

3 The Solution

There is little doubt in anyone's mind that fleet truly dedicated to optimizing their operations and minimizing their carbon footprint require a more holistic approach than the one used in the past.

Lifecycle Cost Analysis and Emission Calculations are the most advanced and helpful tools in our arsenal to help fleet managers make the best possible choices. But even these tools cannot provide much help without the accurate information that can only be provided by fully characterising the duty cycles at work in the system.

3.1 STEP 1: Procuring Accurate Data

Up to very recently, procuring accurate data was time consuming, relatively complicated in terms of the quantity and type of equipment required on-board vehicles and therefore costly.

Figure 1: Typical Data Collection Installation on-board a city bus

New data logging technology developed by FleetCarma greatly simplifies the installation and reduces the cost of collecting accurate data. A simple module is plugged into any vehicle's available OBD-II / J1939 port with (or without) the use of an adaptor and relays key information about the vehicle via cellular network. Furthermore, this information can be synchronized with the the geo-location of the vehicle in real time while it performs its standard duty. While a little more expensive than the base installation (without modem and GPS), the full installation saves the maintenance crew the time required to unplug and upload the information on a daily or weekly basis.

Compact data logger clips in OBD-II port

J1939 Adapter

Modem monitors vehicle location (GPS) and uploads data through cell network

Figure 2: Data Collection Hardware, FleetCarma

CrossChasm's FleetCarma data logger clips into the standard port available onboard most buses to measure fuel usage & track vehicle location. Custom J1939 adapters are also available to ensure the loggers are consistent with all heavy-duty vehicles models, including plug-in electrics and hybrids. Data can be automatically (and wirelessly) uploaded to FleetCarma's database.

In addition to proving accurate input to the lifecycle cost analysis process, FleetCarma brings considerable added benefit through a web portal viewable by anyone in client organization with proper login credentials.

This web portal supplies information regarding the following real-world analytics:

- Distance traveled
- MPG
- Fuel usage
- Driving behaviour
- Idle statistics
- Utilization data
- Tailpipe and upstream emissions

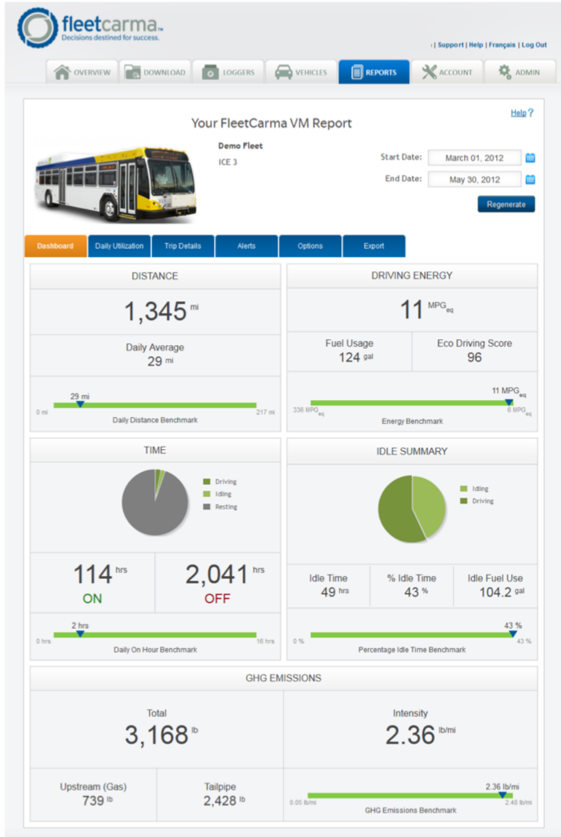


Figure 3: FleetCarma Analytics on its Web Portal.

This objective trip statistics of duration, distance traveled and fuel usage are downloadable and exportable in Excel and PDF formats.

GPS data analysis on vehicle location is also available and provides an assessment of which vehicles & routes would be good "fits" for specific propulsion systems, of fleet-wide charging / refueling points. The data is exportable to Google maps for ease of visualization.

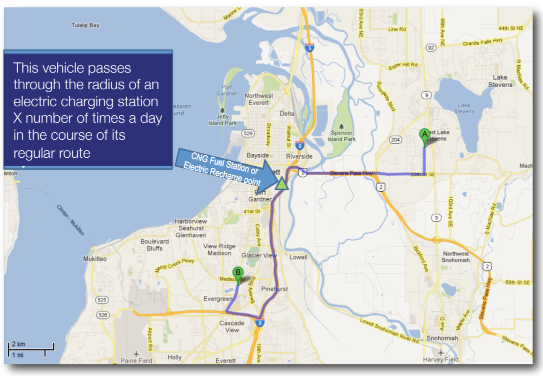


Figure 4: Sample output from Web Portal.

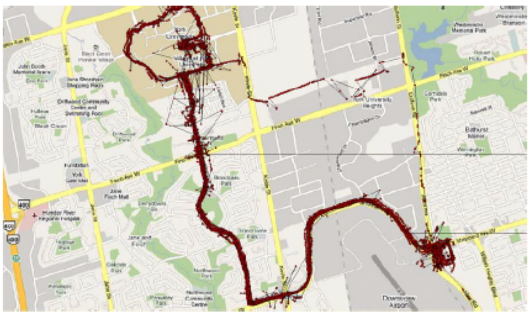
Once the challenge of characterising duty cycles for an urban transit system (or any other ground transportation fleet) has been overcome, it is possible to rely on a more *empirical* method of propulsion technology selection.

3.2 STEP 2: Forecasting Fuel Consumption

In order to predict fuel usage in a reliable way, it is necessary to build and validate predictive models for the whole range of duty cycles experienced by the target fleet. Such models simulate fuel consumption for alternative propulsion vehicles (CNG / Diesel Hybrid / Electric) to quantify potential savings by route and calculations across the entire fleet.

The pilot project conducted at the Toronto Transit Commission (TTC), the largest urban transit fleet in Canada, illustrates our methods best. It is important to point out that this optimisation project **did not** involve the reconfiguration of the routes designed by TTC planners. It simply assumed that such routes had already been optimized for service delivery purposes.

For the purposes of this project, GPS results were used to identify which route was being repeated for each day.



Date	2010-02-02
TTC Route Travelled	106 York University
Time of Record(hour)	12.5
Distance Travelled(km)	241.9
Total Number of Stop	1748.0
Total Travel Time (hour)	8.6
Total Stop Time(hour)	4.0
Average Speed (kph)	19.3
Average Number of Stop (/km)	7.2

Figure 5: TTC Data for Analysis.

In selecting routes, we ensured that "Most Urban", "Average", and "Least Urban" routes were captured, including "stem_to" and "stem_from" components of the duty cycles for comprehensive analysis.

In our route samples, Diesel-Electric Hybrid Buses consumption ranged from 43 to 62 L/100km of diesel fuel on different routes.

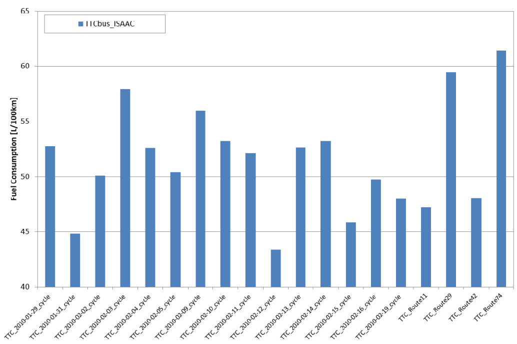


Figure 6: TTC Fuel Consumption Data.

An analytical model was developed to enable fleet operators to estimate fuel consumption based upon drive cycle characteristics. This analytical model approach was then compared to a simulation based approach which was developed for this project. The analytical model approach had on average <u>over</u> 10% error between the predicted fuel consumption and the actual fuel consumption for a given route. The simulation based approach on the other hand had <u>less than</u> 3% error on average.

By expanding this high fidelity vehicle modeling based approach to different vehicle powertrain configurations, CrossChasm was able to accurately predict how different technologies would perform on different "real-life" TTC routes as well as how they would perform on "standard" drive cycles.

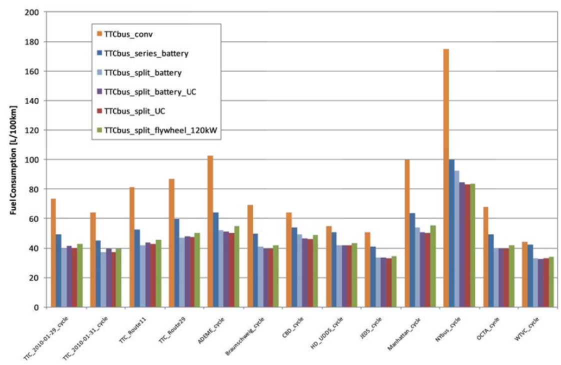


Figure 7: High Fidelity Simulated Fuel Consumption of Different Bus Powertrain Types on Different "Real-life" TTC Routes and some "Industry Standard" Drive Cycles

The results clearly demonstrate that different drive cycles have a substantial impact on a vehicle's fuel consumption.

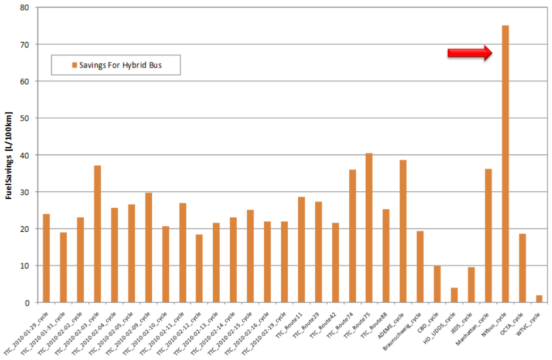


Figure 8: Fuel Savings of Hybrid Bus vs. Diesel Bus on Different "Real-Life" TTC Routes and on "Industry Standard" Drive Cycles

Switching to hybrid buses can yield immense fuel savings on certain routes while they can be negligible on other routes.

The most important lesson to be retained here is the importance of doing data acquisition on the routes of interest prior to making any predictive calculations.

Taking someone else's information and assuming that it applies to the case at hand is a recipe for disaster. Not using data gathered directly on the fleet under investigation guarantees that fuel consumption numbers will either be too low or too high. This error can often completely skew the results of an analysis.

In the case of a large transit fleet, this can easily lead to bad decisions costing hundreds of millions of dollars more than if proper data logging and simulations had been performed prior to the decision process.

3.3 STEP 3: Identifying other costs

Albeit important, the cost of fuel is but one component that must be considered in the process of optimizing a fleet. Newer technologies (than the incumbent diesel bus) are notoriously more expensive to purchase and often require other changes with either positive, or negative impact on the overall cost of running a fleet.

These "other costs" can be critical to the selection of a bus propulsion technology, and, at the very least, the following items must be taken into consideration:

VEHICLE ACQUISITION COST

- Base price for buses
- Warranty conditions
- Share of price covered by outside agency (may vary from one technology to the other)

INFRASTRUCTURE MODIFICATIONS

- Buildings
  - Garage doors
  - Washing facilities
  - Roof clearance
  - Battery room (for lead-acid batteries only)
  - Additional spare parts space
  - Safety / Leak detection equipment
- Equipment
  - Lifts
  - Battery conditioner
  - Others (ex. battery handling)
- Stations and other assets
  - Transit way stations
  - Bus stop shelters
  - Private property compensation
  - Others

OPERATING DATA

- Energy storage life expectancy (years)
- Fuel prices (current and forecasted)

MAINTENANCE COSTS

- Energy Storage replacement (per bus)
- Non-scheduled energy storage system replacement (per bus)
- Annual preventive maintenance (power pack)
- Energy Storage System disposal costs (per bus)
- Power Inverter Module (PIM)
- Power train (Incl: turbocompressor)
  - Engine replacement
  - Transmission replacement
  - Preventive maintenance (annual)
- Starter
- Frame, steering and suspension (annual per bus)
- Annual brake maintenance (per bus)
- Others
- Other Transit System specific cost

SPARE PARTS COSTS (Fleet)

- Additional inventory required
- Annual carrying cost of inventory

NON-RECURRING SOFT COSTS

- HPS Project - feasibility study
- HPS Project management
- Preventive maintenance - Reprogramming
- Training
  - Maintenance employees
    - Number of employees to train
    - Applicable rate
    - Time required (hours)
  - Drivers
    - Number to train
    - Applicable rate (in CAD)
    - Time required (hours)
  - Others
    - Number to train
    - Applicable rate (in CAD)

Time required (hours)

Modifications to service plan
Modifications to long-term planning
Tooling (ex. Energy storage system servicing)
Advertising & promotion

INDIRECT BENEFITS
Increase in ridership (in %)
Average fare
Current ridership
Resulting increase in revenues

A full evaluation of the impact of implementing new technologies may require other studies to be conducted in order to obtain accurate input on these various items. For example, depending on the state and age of existing facilities, it may be wise to consider building new ones, especially when it is operationally difficult or costly to accommodate the coexistence of conventional diesel buses and newer technologies (such as CNG or Hydrogen Fuel Cell) within the same maintenance garages while transiting to that new technology.

3.4 STEP 6: Using TLC BU$™

The first total lifecycle cost estimating model developed by MARCON (http://www.marcon.qc.ca) was used in the context of a benchmark project that examined the possibility of converting the Canadian urban transportation bus fleet to use hydrogen fuel cell power in electric buses[1].

Later on, MARCON's assignments with several Canadian urban transporters such as the Société des transports de Montréal, OC Transpo (Ottawa), and the Société de transport de l'Outaouais (Gatineau) allowed us to perfect the model called Total Life Cycle Bus or TLC BU$™. Further work performed for the Canadian Urban Transportation Association lead to a simplified version of the model (TLC BU$ Lite™) that could be used (without our help) by subscribers in making a first, more superficial evaluation, without incurring great costs.

While duty cycle data used in such evaluations can be provided by third parties (independent laboratories, bus manufacturers, etc.), fleet managers are reminded that the accuracy of the conclusions is always dependant on the accuracy of the input provided by such third parties. We therefore highly recommend the use of the FleetCarma data collection and analysis services (http://www.fleetcarma.com/en/Home/EVM) as a first step in the evaluation process.

The CrossChasm Technologies team has a proven track record, a combined 30 years of expertise and 11 industry awards. FleetCarma characterizes each route in a fleet inexpensively, accurately, reliably and rapidly, taking the "*approximation*" out of the lifecycle cost evaluation process.

4 Sample results

In the capital of Canada, Ottawa, TLC BU$™ was used to compare several alternate propulsion options for the purchase of 226 buses (12 m.). The value of such an acquisition ranged from 90M$ to 140M$ for the vehicles alone. Although bio-diesel, hydrogen fuel cell and hythane buses were considered, we will use only the results for conventional diesel, compressed natural gas (CNG) and diesel-electric hybrid (DEH) buses in this presentation.

Capital investment costs are the easiest to determine, assuming the information is accessible for infrastructure components. In addition to the cost of the vehicles, modifications and additions to the operator's maintenance and garaging facilities are required in some cases (doors, gas detectors, ventilation systems, battery recycling room, etc.). In this case, road installations (bus stop shelters, overpasses, …) also required changes, as DEH and CNG buses tend to be higher than conventional diesel buses.

Table 2: Capital Investment Costs at OC Transpo

	DIESEL	CNG	DEH
Capital Investment Costs			
Bus acquisition	90 108 581	95 366 244	139 816 714
Building and Infrastructure cost	0	50 207 748	1 763 264
Other soft, non-recurring costs	0	692 074	955 283
Total capital costs:	**90 108 581**	**146 266 066**	**142 535 262**

Fuel costs are not so easily determined. Buses in Canadian urban transit systems remain in service for an 18-year period. In addition to fuel consumption, the price of various energy sources must be forecasted for almost two decades. While the price of electricity is fairly stable in Canada and 10-year contracts can be signed for natural gas supply, the price of diesel fuel for such a long period is difficult to pin down and one must rely of institutions such as the International Energy Agency whose track record in such matters is no better and no worse than anyone else.

As a result of the calculations performed at a time that predates the crash of natural gas prices in North America, the fuel costs for each option over the 18 year lifetime of the 226 buses were:

Table 3: Forecasted Fuel Costs at OC Transpo	
Diesel (fleet average)	$161.2M
Diesel (low speed/high stop)	$223.8M
CNG (general allocation)	$112.1M
DEH (low speed/high stop allocation)	$163.4M

This data demonstrates clearly that if DEH buses are not allocated to routes where they can perform in an optimal manner, they will not save their owner anything and may, in cases even cost more in fuel than their conventional counterparts. The TTC, for example, experienced only 5% reduction in fuel cost with their DEH buses fleet because they do not make proper allocation of this technology on their routes, claiming union contract constraints to act in such manner.

At today's market price for natural gas, the advantage of CNG buses would clearly improve.

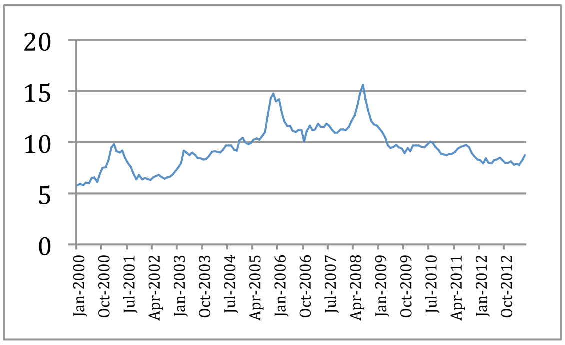


Figure 6: NG historical commercial prices in NA
(in USD per thousand cubic feet)

When other operating costs were added to the analysis and all costs were discounted the net present value, the final tally yielded two sets of results based on bus allocations.

Table 4: Lifecycle costs at OC Transpo Average Fleet Allocation	DIESEL	CNG
Capital Investment Costs		
Bus acquisition	90,108,581	95,366,244
Building and infrastructure cost	0	50,207,748
Other soft, non-recurring costs	0	692,074
Total capital costs:	**90,108,581**	**146,266,066**
Operating Costs		
O&M cost (excluding fuel)	192,698,598	193,902,965
Fuel cost	161,193,810	112,051,396
Electricity (compressor)	0	6,293,399
Total operating costs:	**353,892,408**	**312,247,760**
Non-Discounted Total Cost	**444,000,989**	**458,513,826**
Discounted Total Cost	**302,108,366**	**333,267,256**

Table 5 : Lifecycle costs at OC Transpo Low Speed / Frequent Stops	DIESEL	DEH
Capital Investment Costs		
Bus acquisition	90,108,581	139,816,714
Building and infrastructure cost	0	1,763,264
Other soft, non-recurring costs	0	955,283
Total capital costs:	**90,108,581**	**142,535,262**
Operating Costs		
O&M cost (excluding fuel)	246,834,752	182,890,809
Fuel cost	223,774,936	163,361,122
Battery replacement cost	0	25,481,952
Other costs	0	5,078,268
Total operating costs:	**470,609,689**	**376,812,151**
Non discounted Total Cost	**560,718,269**	**519,347,413**
Discounted Total Cost	**373,459,512**	**365,250,148**

Fleet operators made this bus allocation decision (DEH buses on optimal routes and CNG buses on average routes) because they were not prepared to modify their current procedures for CNG buses where they would for DEH buses. In most fleet, new busses are allocated first to "*high stops/low speed*" routes and, as they aged, allocated to less strenuous duty cycles.

5 Learnings and Conclusions

Over and above lifecycle costs, a full analysis must take the following into consideration:

- Technical performance of propulsion technology to date
- Environmental performance
- Transit system's history with various technologies
- Climatic conditions

In short, according to our experience comparing various technologies in the field and considering all the (rational) factors fleet managers must deal with, energy efficiency of various options alone does not justify the adoption of an alternate bus propulsion technology.

A much broader analysis must be conducted to determine where electric and hybrid electric buses perform best.

Generally speaking, and from an energy efficiency standpoint alone, electric hybrid vehicles perform best on routes with more stops per kilometre and lower average speed.

That being said, no pragmatic technology purchase decision by a transit fleet should be done without first establishing the drive cycles of the feet's current and projected routes and then performing validated fuel consumption simulations on those exact route drive cycles for different powertrain technologies.

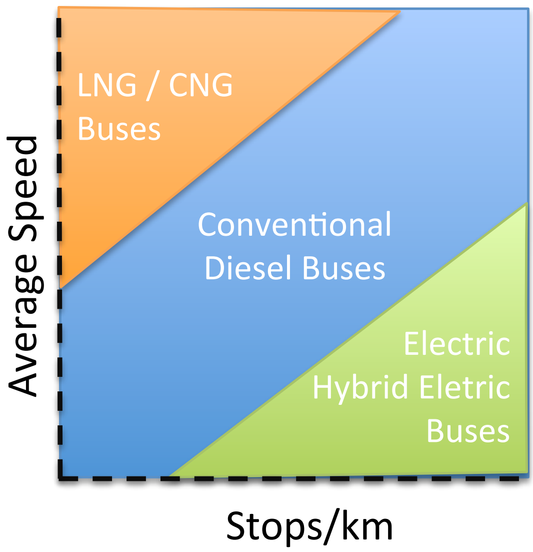


Figure 9: Optimal Range for three bus propulsion technologies.

While results based on average speed and stops/km tend to favor different technologies based on the graph in Figure 9, MARCON and CrossChasm believe it should be mandatory for transit fleets who are subsidized by public funds to perform a thorough investigation of where how different vehicle technologies will perform on their routes, prior to new purchases implementing. Past projects have demonstrated that the cost of such a pragmatic approach is usually orders of magnitude smaller than the cost of not making the optimal decision.

In fact, each technology performs best under a certain set of circumstances that include many more factors discussed earlier than this simple representation. Only in fleet data acquisition can truly capture the circumstances affecting a given route.

Each bus propulsion system can nevertheless contribute to optimizing the fleet by improving its energy efficiency and minimizing its overall costs.

The 360-degree analysis performed on behalf of several clients and the business case used in this article demonstrate the relevance of electric bus technologies in the portfolio of vehicles that comprise a transit fleet as long as there is a sufficient number of vehicles in such a fleet to justify the investments required in adapting the facilities to their use.

Acknowledgments

The authors would like to acknowledge their numerous clients for giving them the opportunity to develop their skills and knowledge.

References

[1] Pierre Ducharme and MARCON, *Transforming the future: Moving Toward Fuel Cell-Powered Fleets In Canadian Urban Transit Systems*, NRCan Publication, M38-24/1-2005 and 0-662-68749-3.

[2] Matthew Stevens, Jen Bauman, Chris Mendes – CrossChasm Tech and Ray Minato, Larry Zhou – Inertia Engineering, *Maximizing the benefit of hybrid buses*, Report to the Toronto Transit Commission, 2010.

[3] Matthew Stevens & Simon Ouellette, *Hybrid Buses: Real-World meets Simulations*, EMC Publication of EV2010 & 2011 Proceedings, 2010-2011.

[4] Pierre Ducharme and William Bugyra, CNG Bus Option Evaluation for the City of Ottawa, Report to OC Transpo, 2007.

Authors

Pierre Ducharme is the president and co-founder of MARCON Management Consultants Inc., a consulting firm specialising in transportation and energy. Pierre is the main architect of TLC BU$™, the total lifecycle cost evaluation model described in this presentation. Pierre studied at the Royal Military College of Canada in Quantitative Methods of Management, at Université du Québec in Montréal (in Business Administration and at McGill University where he obtained his D. Mgt.

Pierre provides advice to fleet managers regarding optimal fleet configurations as well as strategic advice to government in energy efficiency program design. He is the author of Canada's second largest province's Public Transportation Electrification Strategy (2012).