Appendix 4

Rolling Stock Technology Assessment

December 2010

METROLINX
An agency of the Government of Ontario

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APPENDIX 4
ROLLING STOCK TECHNOLOGY ASSESSMENT

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EXECUTIVE SUMMARY

CONTEXT

Metrolinx operates a comprehensive transportation system of light rail transit, bus and commuter rail lines in the Greater Toronto and Hamilton Area (GTHA). The system includes the GO rail network which is an essential part of Metrolinx's service to the area commuters. GO Transit currently provides commuter rail service on seven corridors in the GTHA, using conventional diesel-electric locomotives and non-powered bi-level coaches in push-pull configuration.

In late 2008, Metrolinx published a Regional Transportation Plan – The Big Move – a multimodal vision for regional transportation to strengthen the economic, social and environmental sustainability of the Greater Toronto and Hamilton Area. The Big Move sets out a fast, frequent and expanded regional rapid transit network as a key element of the plan. The plan includes establishing Express Rail and Regional Rail services at speeds and frequencies that could be enhanced by system electrification.

ELECTRIFICATION STUDY

Metrolinx has initiated a study of the electrification of the entire GO Transit rail system as a future alternative to diesel trains now in service. The electrification study is examining how the future GO rail services will be powered – using electricity, enhanced diesel technology or other means – when these services are implemented in the future. The study will assess the benefits and costs of a full range of technology options, including enhanced diesel, electric and alternative technologies. The study will consider the existing GO Transit network, the proposed network expansions to St. Catharines, Kitchener/Waterloo, Allandale, Bloomington, Bowmanville, as well as the future Pearson Air Rail Link.

ROLLING STOCK TECHNOLOGY ASSESSMENT

The objective of this paper is to identify and assess a broad range of existing and future potential rolling stock and electrification system technologies that could be used to provide future GO rail services. Rolling stock technologies considered include:

- Diesel Locomotives
- Diesel Multiple Units
- Electric Locomotives
- Electric Multiple Units
- Dual-Mode Locomotives
- Dual-Mode Multiple Units
- Alternative Rolling Stock Technologies and Enhancements, including
    - Alternative Locomotive Fuels
    - Hybrid Drive Trains
    - Hydrogen Fuel Cell Drive Trains
    - Maglev
    - New System Concepts

In addition to describing and comparing the technical attributes of these technologies, the rolling stock technology assessment involved the use of four screening criteria to identify a "short list" of technologies for further assessment. The criteria used in the assessment include:

- Is the technology **proven**?
- Is the technology **commercially viable**?
- Is the technology **compatible with the reference case[1] infrastructure?**
- Is the technology **compatible with the reference case service levels**?

RECOMMENDATIONS

After examination of the candidate rolling stock technologies, it was concluded that a number of technology alternatives should be eliminated from further consideration based on the application of the four screening criteria.

Further, it is recommended that the following technologies be carried forward for more detailed assessment and analysis as part of the electrification study:

- Diesel Locomotives – Bi-Level
- Electric Locomotives – Bi-Level
- Electric Multiple Units – Bi-Level
- Dual-Mode Locomotives – Bi-Level

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[1] The "reference case" describes existing attributes and planned enhancements of GO's rolling stock, rail infrastructure and services levels – as a basis for identifying and comparing rolling stock technologies that could be used for future services.

1. INTRODUCTION

The Greater Toronto and Hamilton Area (GTHA) is in the midst of a transportation transformation as a result of a renewed public commitment to invest and grow regional transit. The Big Move - a compelling integrated, multi-modal vision for regional transportation adopted by Metrolinx in 2008, will strengthen the economic, social and environmental sustainability of the Greater Toronto and Hamilton Area and profoundly change how people and goods are transported within the region1. GO, a division of Metrolinx and the GTHA's principal inter-regional transit service, will play a decisive part in this transformation. The means by which GO's rail system grows and develops is therefore essential to realizing the ambitious vision of The Big Move and creating a GTHA that is shaped and supported by a world-leading regional transportation network.

Metrolinx (formerly the Greater Toronto Transportation Authority), the agency responsible for piloting this transformation, is commissioning this Study to examine how GO can best accomplish the goals of The Big Move over the next 25 years. The overriding purpose of the Study is to provide Metrolinx's Board of Directors with the information necessary to make an informed decision on whether to meet future service requirements by using conventional diesel powered trains or by utilizing trains powered by electricity, or alternate means. The Study will consider alternate technologies that may become viable in the short to medium term to inform the Board of Directors decision with regard to available technology options. The Study is to assess and identify an optimal technology, or combination of technologies, that would be able to attain the system performance goals identified in The Big Move and further enhance the quality, reliability and accessibility and environmental sustainability of commuter rail services in the GTHA.

The decision will have broad implications across the GTHA and presents a unique opportunity to take full advantage of the most advanced and state-of-the-art technologies and systems in addressing future requirements and provides an opportunity to be innovative and visionary in the development of alternative rail system concepts for GO.

All GO system corridors originate at Toronto Union Station and radiate out to the west, east, and north of Toronto. Including the planned expansions to Bowmanville, Peterborough, Niagara Falls, Kitchener, Waterloo, as well as the Pearson Air Rail Link the system is planned to expand to an ultimate network of over 560 route kilometres.

1.1. Purpose And Objective Of The Rolling Stock Technology Assessment

The objective of the assessment is to identify a broad range of existing and future potential rolling stock and electrification system technologies. Rolling stock options will be compared by technical factors and the following four screening criteria:

- Is the technology **proven**?
- Is the technology **commercially viable**?
- Is the technology **compatible with the reference case**[2] **infrastructure?**
- Is the technology **compatible with the reference case service levels**?

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[2] The "reference case" describes existing attributes and planned enhancements of GO's rolling stock, rail infrastructure and services levels – as a basis for identifying and comparing rolling stock technologies that could be used for future services.

Based on this evaluation, technologies clearly not suitable for GO network electrification will be removed from the study and eliminated from further consideration. The technologies suitable to application to the GO commuter rail corridors will be selected and advanced in the study for further evaluations.

Once the suitable technologies are identified, a comprehensive computer-aided train operation simulation and electrical system load-flow will be performed. This will take into account all relevant rolling stock performance characteristics, track alignment infrastructure data, operation data, and electrification system parameters. The results of this work will provide the necessary data for development of a conceptual system design and cost estimates.

1.2. Scope Of The Study

The electrification study will consider the existing GO Transit network, the proposed network expansions to St. Catharines, Kitchener/Waterloo, Allandale, Bloomington, Bowmanville, as well as the future Pearson Air Rail Link.

Technologies Considered

The rolling stock options being considered include the following technologies:

- Diesel Locomotives[3]
- Diesel Multiple Units[4]
- Electric Locomotives
- Electric Multiple Units
- Dual-Mode Locomotives[5]
- Dual-Mode Multiple Units
- Alternative Rolling Stock Technologies and Enhancements, including:
    - Alternative Locomotive Fuels
    - Hybrid Drive Trains
    - Hydrogen Fuel Cell Drive Trains
    - Maglev
    - New System Concepts

Document Definitions and Glossary of Terms are presented in Appendix A.

Sources Of Study Data

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[3] Throughout this report Diesel Locomotives will mean Diesel Electric Locomotives.

[4] Diesel Multiple Units can be Diesel-Electric, Diesel-Hydraulic, or Diesel-Mechanic.

[5] Dual-Mode Locomotives and Dual-Mode Multiple Units in this report refer to rolling stock with independent electric and diesel propulsion systems and capable of operation in electrified and non-electrified territories.

The study evaluations were based on data developed under separate efforts, including:

- Route Profiles, Speed Restrictions, and Passenger Locations, CANAC
- Operating Plan, CANAC

Numerous photographs are presented throughout the report to illustrate the various technology options and electrification systems in service today. Some photographs were taken by LTK employees, some were obtained from Wikipedia, The Free Encyclopaedia, and others are used with the express consent of the photographer.

1.3. Study Presentation

This report is presented in a single volume containing the main body of the report and Appendices. Further information on the electrification technologies can be found in a companion report entitled Power Supply and Distribution Systems Technology Assessment for Metrolinx GO System Electrification, being prepared in parallel under separate cover.

Service Environment

Current GO Transit commuter rail operations use diesel-powered locomotive-hauled coaches (LHC) to provide 180 trips and move approximately 155,000 passengers on a typical weekday. By the end of 2010, the fleet will be comprised of 57 diesel-electric locomotives, 443 unpowered bi-level coach cars, and 52 unpowered bi-level cab cars. An additional 19 coaches and 1 cab car will be delivered in 2011. To meet peak period and off-peak period service demand, GO operates relatively long 10- and 12-car consists. These use one locomotive, 9 or 11 coach cars, and one cab car. Peak service headways are approximately 15 minutes while off-peak headways are approximately 1 hour. GO experiences high peak-service load factors. About 95% of all riders are traveling to or from Toronto Union Station.

As the GTHA continues to expand both population and economic activity, GO foresees a significant growth in commuter rail services, primarily in the counter-peak and off-peak periods. Peak-hour service levels are limited by the maximum number of trains that can be accommodated at Union Station. The core arterials to Union Station must maintain and strengthen the current service model of high-capacity, high-service-frequency trains.

GO also anticipates an expansion of service area and trackage, where smaller, feeder trains may move a low-density population to GO’s core routes. Although there are obvious advantages in having homogeneous fleet, particularly with the GO’s current network, this diverse service may potentially be best served by a mixture of more than one rolling stock technology.

Service Corridors

The electrification study will consider the existing GO network, the proposed network expansions to St. Catharines, Kitchener/Waterloo, Allandale, Bloomington, Bowmanville, as well as the future Pearson Air Rail Link . These service corridors are detailed in Table 2-1.

Table 1-1 - Rail Corridors Considered for Electrification

Line	From	Via	To	Approximate Distance	
				(miles)	(km)
Lakeshore West	Toronto, Union Station	Hamilton Junction	Hamilton TH&B	39.9	64.2
			St. Catherines	71.2	114.6
Lakeshore East		Pickering	Bowmanville	43.1	69.3
Milton		Medowvale	Milton	31.2	50.2
Georgetown		Georgetown	Kitchener	62.6	100.7
Barrie		Barrie South	Allandale	63.0	101.4
Richmond Hill		Richmond Hill	Bloomington	28.5	45.9
Stouffville		Kennedy	Lincolnville	31.1	50.0
Pearson Air Link		Woodbine Racetrack	Lester B. Pearson Airport	18.4	29.6

The Table shows the lengths of each individual route of its own, meaning that, segments shared by two or more lines are reflected in each line. For example, both Lakeshore West lines, to Hamilton TH&B and to St. Catherines, include the length of the Union Station to Hamilton Junction segment.

Figure 1-1 provides a graphical schematic of the service corridors. This is referred to as the reference case as it will form the base for the service schedules and load-flow studies. The schematic provides significant detail about the current and future expansion of GO service and the number of available tracks by corridor.

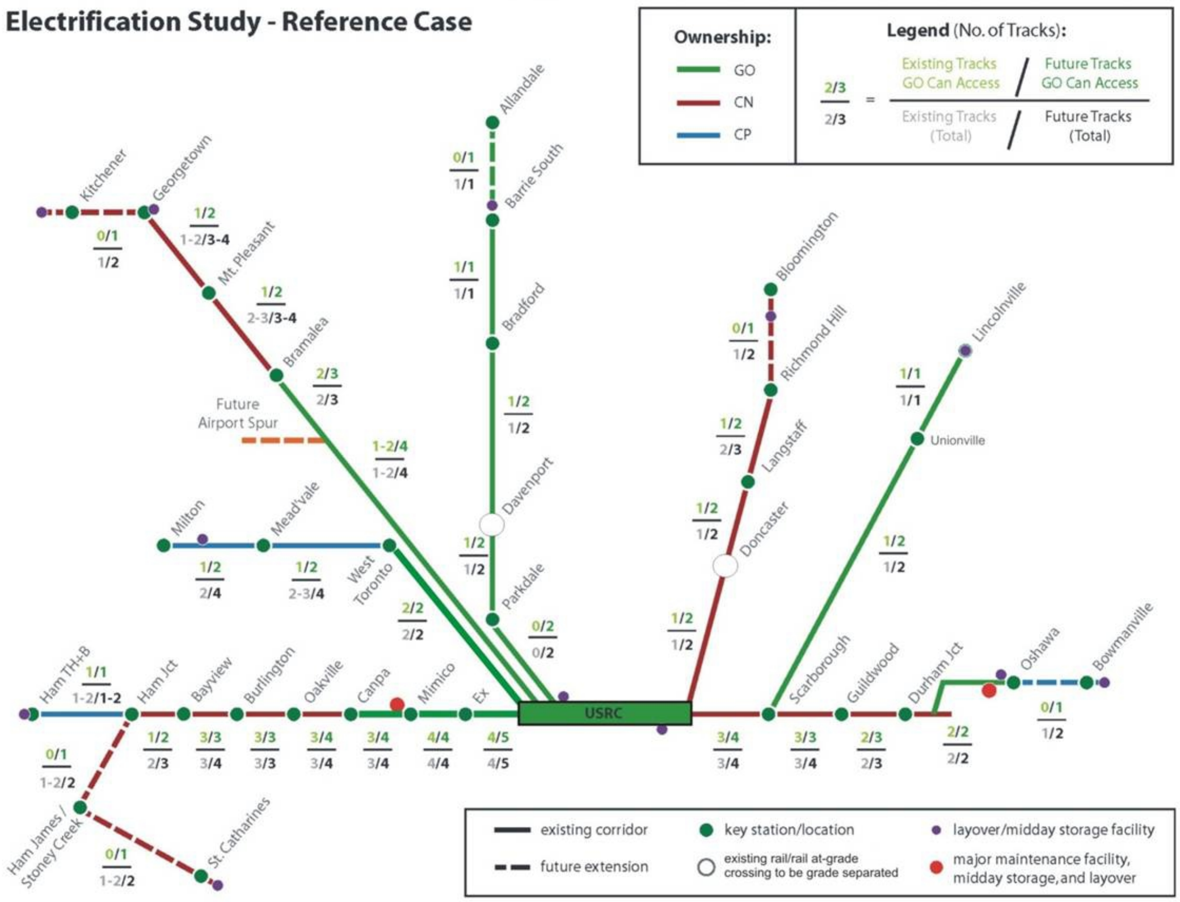

Figure 1-1 – System Map for Electrification Study

2. SHARED CORRIDOR USE

The GO trains currently share some corridors with daily Canadian National Railway Company (CN) and Canadian Pacific Railway (CP) freight trains and regularly scheduled VIA Rail Canada's (VIA) transcontinental passenger trains. The planned Air Rail Link (ARL) would interlace its own commuter rail trains with the GO trains along the Georgetown Line. The electrification study will accommodate these other services within the GO commuter schedule on shared corridors.

Because of shared corridor use, the minimum structural strength of any potential future GO commuter railcars may be an issue. This topic is more fully addressed in Section 3.10.6 below.

CN, CP and VIA trains are not planned to be electrified. The GO system infrastructure must potentially accommodate a mixed fleet of electrified and non-electrified rolling stock.

2.1. Union Station

Union Station is the center of the GO Transit commuter rail system. All commuter trains stop at Union Station as it has the highest number of passenger boardings and alightings within the system. Some trains continue through the station to complete their routes while others turn back to provide reverse service on one corridor. Union Station is the governing constraint on system capacity.

The current Union Station was opened in 1927 in the heart of Toronto. Since that time, significant construction has occurred near the Union Station foot print. The station platforms are now bounded between the station hall, Air Canada Centre, the CN Tower, the Metro Toronto Convention Centre Complex, the Rogers Centre, the Gardiner Expressway, and several other significant buildings. Several studies have considered ways to expand the number of platforms and station throughput capacity, but there are no easy answers. Figure 2-2 provides an aerial view of Union Station.

The station has 12 covered platforms and two open-air by-pass tracks. The station platforms are each 365 m (1,200 ft) long. All of the commuter railcars under consideration within this report are nominally 25.9 m (85 ft) long. Thus, Union Station platforms can accommodate the current one locomotive plus 12 cars.

East and west of the train shed are throat areas containing a complex series of lead tracks, switches, and crossovers to allow platform access. Throat layout and signaling constrains limit train-to-train headway and thus the station capacity. GO Transit is in the middle of a multi-year program to replace and upgrade the station throat switches and signal system. This program is providing incremental improvements.

Figure 2-2 – Aerial View of Union Station

2.2. Air Rail Link

The proposed ARL will connect Union Station with Pearson International Airport with dedicated-use commuter railcars. This service is anticipated to use single-level, self-propelled diesel-powered railcars known as diesel multiple units (DMU) in two-car consists. ARL service is proposed to depart every fifteen minutes between the hours of 6:00 am and 12:30 am, seven days a week.

The ARL service will be modeled within the electrification study to fully appreciate system schedule, track occupancy, and Union Station capacity. Union Station is anticipated to accommodate this level of service in addition to the GO service.

3. ROLLING STOCK TECHNOLOGY - IDENTIFICATION AND ASSESSMENT

3.1. General

The electrification study considered a range of rolling stock technologies with consideration given to the near-term, mid-term, and long-term implementation of any such transitional plan. The rolling stock study shall be fully integrated with the overall electrification study and will provide a decision mechanism to best provide Metrolinx's Board of Directors with the information necessary to make an informed decision regarding the benefits, costs impacts and overall feasibility of electrifying the GO commuter rail operations.

Technologies that will be considered in this study for addressing the GO commuter rail needs are diesel locomotives, electric locomotives, electric multiple unit (EMU) cars, DMU cars, or dual-mode rolling stock using conventional or selected alternative technologies and enhancements, such as alternative locomotive fuels, hybrid drive trains, hydrogen fuel cell drive trains, and Maglev. The sections below describe each candidate rolling stock technology in greater detail.

3.2. Diesel Locomotives

Diesel locomotives are self-sufficient units that combine a prime mover, traction motors, fuel tank, and operator controls to pull or push passenger cars over routes without additional wayside infrastructure to supply power, except for fuel filling stations within yards. Examples of modern diesel locomotives are presented in Appendix B.

GO currently uses diesel locomotives, shown in Figure 3-1, in push-pull configuration with Bombardier bi-level passenger coach and cab cars. The majority of locomotives are now MP40PH-3C locomotives, built by Motive Power Industries (MPI). GO still has a number of older F59PH units, built by Electro-Motive Diesel, Inc. between 1989 and 1990. The F59 locomotives provide reliable service and achieve moderate performance with an 8-to-10 car consists. GO is currently taking delivery of 27 new MP40 locomotives to replace the F59PH fleet. The new fleet will be 57 MP40 locomotives assuming that all F59 locomotives will be retired. The MP40 units have increased power and meet current Tier 2 emission level regulations.

Diesel LHC passenger trains are the standard technological approach for providing commuter service on non-electrified rail lines in North America. This approach has typically provided the lowest risk, lowest capital cost, quickest delivery and most flexible approach to commuter rail operators.

Figure 3-1 - GO Diesel Locomotive-Hauled Train (MP40PH-3C)

Environment Canada (EC) and the Ontario Ministry of Environment set railroad diesel engine exhaust gas emissions levels, traditionally following the United States Environmental Protection Agency (EPA). Emissions levels are referred to as Tiers, as they represent a progressive tightening of regulations. Emissions levels are defined by the model year and power of the engine and not the year of the rolling stock.

GO Transit has made a commitment to upgrade their existing fleet to meet Tier 4, whether through replacement or retrofit. This is a choice to exceed the minimum government standards and improve the GTHA regional air quality.

Diesel passenger locomotives are largely based on freight locomotive technology and benefit from the technical advances achieved for that much larger market. The modern diesel locomotive has seen a number of incremental improvements. Horsepower has increased and substantial progress is being made in meeting increased environmental requirements while retaining a high level of reliability and maintainability. It can be expected that these developments will continue, while maintaining technical compatibility with existing passenger coaches and operations.

Comparatively, diesel locomotives are the heaviest motive power units under consideration for GO. As a result, they generate relatively high wheel/rail forces. This leads to increased track and infrastructure maintenance costs, particularly as speeds increase.

High axle loads are not necessarily disadvantageous, as the tractive effort or drawbar force is influenced by the available adhesion level (friction between wheel and rail) and the total weight on drivers (driven axles). For low speed operations, especially at low to moderate adhesion levels, locomotives are adhesion-limited rather than horsepower-limited; the only ways to increase tractive effort are to modify friction through the use of sanders or to increase axle load. GO is reaching the practical limit of passenger consists with its current one-locomotive-and-12-cars consists in rush hour. To control travel times during periods of low to moderate adhesion levels, GO will need to consider adding a second locomotive to its long consists or operating shorter consists at increased frequency. However, any attempt to increase service frequency may conflict with Union Station throughput and capacity constraints.

Diesel locomotive performance parameters, such as power, acceleration and top speed, are relatively low when compared to electric propulsion. With GO’s typical configuration of one locomotive per train, train performance decreases with additional train length and weight, meaning that different train consists potentially require different scheduled running times for the same service pattern. GO cannot easily increase system capacity by simply increasing train lengths beyond 12 cars. Longer trains may require a second locomotive, or, more practically, shorter trains may be offered more often.

The self-sufficient nature of a diesel LHC allows it to operate on any system track at any time. Technologies that rely on off-car infrastructure to deliver power (electric locomotive, electric multiple units, each discussed below) are limited to only compatible tracks and to times when the off-car systems are functional. Diesel LHC consists may provide enhanced flexibility to work through unscheduled track and service issues.

Diesel locomotives can be combined with a variety of unpowered coach and cab cars. GO uses the Bombardier bi-level cars which are widely used through out North America. Other candidate cars include single-level, bi-level, multi-level, gallery, and double-deck designs. Each offers subtle differences in boarding options, interior arrangements, and passenger capacity. All represent proven technologies with decades of operating experience, known to be rugged, reliable and adaptable to a variety of operating environments and climatic conditions.

In general terms, a bi-level car (used here to generically refer to any design where passengers are stacked within the vertical car profile) has approximately 1.5 times the passenger carrying capacity of a single-level car. This can be critical for a constrained platform like Union Station. If train schedule and headway have been optimized, passenger capacity can be increased through longer trains. However, once the platform length has been matched, the only capacity variable left is to increase the number of passengers per car, namely by stacking passengers in a second seating level. Faced with similar capacity issues in the mid-1970's, GO Transit purchased the first bi-level commuter cars in North America.

GO's existing push-pull fleet, upgraded to Tier 4 emissions standards, will be considered as the baseline, reference technology because of its technology characteristics and its ability to meet Metrolinx's current capacity and performance goals. The diesel locomotive is capable of operating on any candidate expansion corridors and reaching the current track speeds. However, given the limitations of diesel locomotive performance, the ability of this option to deliver increased average train speeds and greater passenger capacity, particularly at Union Station, is minimal.

3.3. Diesel Multiple Units

DMUs are self-propelled, passenger-carrying vehicles that use one or more on-car diesel engines for power. This concept has been widely used in Canada and the United States in the past, but sees only limited use today. It is currently widely applied in Europe and Asia. The concept has regained some visibility in the United States with the recent reintroduction of United States Federal Railroad Administration (FRA)-compliant DMU cars. Examples of modern DMUs are presented in Appendix B.

DMUs, as shown in Figure 3-2, carry their complete propulsion system, including engines, fuel, exhaust treatment, and final drive equipment. This need to carry all of their equipment makes DMUs heavier than EMUs, but reduces the need for off-car infrastructure. Some DMUs use hydrodynamic or hydromechanic transmissions to directly drive the wheels with the engine while others, known as Diesel-Electric Multiple Units (DEMUs), use electric generators and traction motors in a manner similar to a diesel-electric locomotive.

Figure 3-2 - Example of a Single-Level DMU in Ottawa, Canada

Due to engine power output and packaging constraints, DMUs typically power about half the total axles within a train consist. This distributed tractive effort makes them tolerant of low adhesion conditions and moderately steep grades. Like EMUs, DMUs provide consistent performance as consists lengthen or shorten to meet ridership demand.

The combination of multiple engines and drive axles allow DMU consists to accelerate faster than diesel LHC consists. DMU performance is typically between that of EMUs and diesel LHC. Advances in transmission design make DMUs very controllable during low adhesion conditions and during starts on steep grades.

A DMU trainsets will have multiple, distributed diesel engines. This design feature typically allows at least one engine to fail without significantly affecting consist route performance – the train can still transport passengers over the route, maintaining a reasonable schedule. If a single engine failed on the current GO diesel LHC service, that trainset would stop and strand passengers until another trainset or locomotive could rescue it.

The North American DMU market is very limited and has been filled recently by smaller, niche manufacturers. Due to the recent business environment, there are currently no suppliers of FRA-compliant DMUs. Recent procurement efforts by Triangle Transit Authority (TTA), South Florida Regional Transit Authority (SFRTA), Tri-County Metropolitan Transportation District of Oregon (TriMet), New Jersey Transit (NJ Transit), Alaska Railroad (AKRR), Denver Regional Transportation District (RTD), and Sonoma Marin Area Rail Transit (SMART) have continued to attract interest from several candidate suppliers.

DMUs can be designed as single-level and bi-level. The North American and world DMU markets favour single-level due to car design and packaging issues as well as their ability to meet the ridership demands of their target service environment. Several bi-level DMU designs are operating in Denmark (with service into France, Belgium, and Germany) and Japan. Four true double-deck DMUs were sold in North America (three to SFRTA, one to AKRR), but that manufacturer has since ceased operations.

Several studies[6] have shown that DMUs are a practical alternative to diesel LHC up to train consist lengths of approximately four to six units. DMUs are not likely to directly replace current GO locomotive service, but could be used to extend or feed current routes, provide off-peak service, or replace locomotives in a high-service-frequency operating scenario where shorter, more frequent DMUs replace longer, less frequent LHC trains.

The practical limitations of DMU consist length can be highlighted quickly through consideration of their relative capital, operating, and maintenance costs as compared to equivalent capacity diesel LHC trains.

DMU consists can be considered to be comprised of all powered units. Total DMU costs rise with consist length as each DMU has an associated, moderate-magnitude capital, operating, and maintenance cost. A minimum DMU consist (one DMU) has a low total cost equal to the capital, operating, and maintenance cost of a single unit. A moderate length DMU consist (six DMUs) has a moderately high

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[6] The following titles are sited as reference studies on the relative costs of diesel LHC and DMU trainsets:

Parker, E.S., “Defining an Economic Niche for Hybrid DMUs in Commuter Rail," Fifth International Hydrail Conference, June, 2009

Parker, E.S., DiBrito, D.A., “Selecting the Proper Commuter Rail Vehicle Technology," 2007 APTA Rail Conference, June, 2007

Rader, C., “Economics of FRA-Compliant Diesel Multiple Units (DMUs),” 2003 APTA Rail Conference, June 2003.

Sislak, K, "Economics of Diesel Multiple Unit Operations," 1996 APTA Rapid Transit Conference, June, 1996.

Jacobs, D., Galbraith, A., "A Comparison of the Operating and Maintenance Costs of DMU and Locomotive-hauled Equipment for the MBTA," 1997 APTA Rapid Transit Conference, June 1997.

total cost equal to six times the single unit cost. A long DMU train (12 DMUs) has a very high total cost equal to 12 times the unit cost.

In contrast, a typical locomotive train consist is composed of one locomotive, several coach cars, and one cab car. The diesel locomotive has high capital, operating, and maintenance costs. Locomotive operating costs are fairly fixed over consist length – the total fuel burned is relatively steady, but the performance decreases as the train lengthens. Coach cars have relatively low capital, operating, and maintenance costs. Cab cars have slightly higher capital and maintenance costs than coaches. The minimum consist (one loco and one cab) yields a moderately low total cost (the sum of an expensive locomotive and a moderately low cost cab car). A moderate consist (one loco, five coaches, one cab) has a moderate total cost (one expensive locomotive plus six relatively inexpensive cars). The longest consist (one loco, 11 coaches, one cab) has a high total cost. As the LHC trains lengthen, the total costs increase by the unit cost of a coach car rather than the unit cost of a powered DMU.

The rough cost argument presented above illustrates that DMUs are competitive in short consists and impractical in long consists. The break-even point varies by service profile (distances between stops, maximum speed, profile) and by unit costs (mostly locomotive – rebuilt, new diesel, or new dual-mode). This point is typically four to five units for single-level DMUs and five to six units for double-deck DMUs.

A quick survey of world DMU service supports the short-DMU-consist argument. Almost all DMU applications use between one and four cars per consist. Several five-car DMU trainsets were found in service in China, Eastern Europe, and Venezuela. These trainsets use two powered cab cars and three unpowered coach cars. The powered cars have large engines that compromise the passenger volume in these vehicles. The trailer cars help make up some of the lost passenger volume and have significantly reduced unit costs. An alternative example is the Voyager Class 220, 221, and 222 DMUs operating in England. The Class 220 and 221 operate in four- and five-car consists, respectively. The Class 222 have been operated in eight- and nine-car consists, but have since been reconfigured to four- and five-car consists.

Figure 3-3 shows the relative total costs for diesel LHC and DMU as consist length increases.

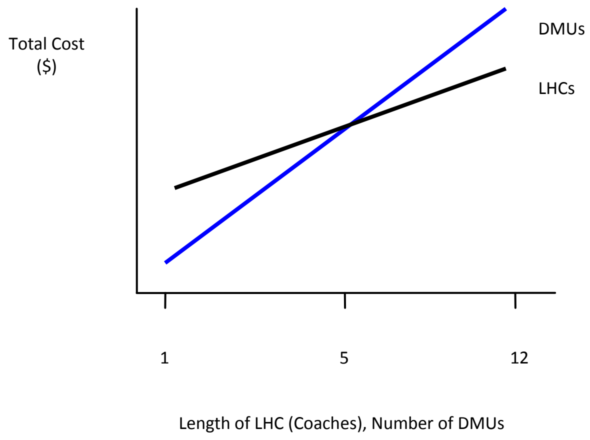

Figure 3-3 - Plot of Total (Cap + O&M) Cost vs. Length of Consist

Another way to consider costs is to normalize total costs to a cost-per-seat. The DMU cost-per-seat is almost constant as train length increases as each seat comes surrounded by a powered unit and requires nominally equal operating and maintenance support. A short LHC consist has a high cost-per-seat as that minimum consist must divide the locomotive costs over just a few seats. As the LHC consist grows longer, the locomotive costs can be distributed over more and more seats, bringing down the average cost-per-seat.

Figure 3-4 shows the relative, normalized cost per passenger seat for diesel LHC and DMU as consist length increases.

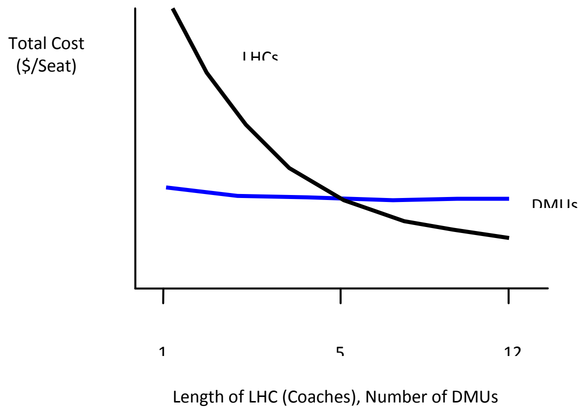

Figure 3-4 - Plot of Total (Cap + O&M) Cost per Passenger Seat vs. Length of Consist

Modern DMUs typically have enough power to pull a limited number of unpowered coach cars, similar to LHC service. These additional cars improve consist seating capacity while costing significantly less than DMUs to purchase, operate, or maintain. Consist performance will decrease with each additional unpowered coach car.

DMUs offer a good fit for GO's future feeder service. DMUs are efficient in small consists, servicing a low-density passenger base. Further, if two DMU routes merge as they travel toward a feeder station, it may be possible to adopt a European practice on some low density lines of coupling two small trainsets into a mid-sized consist to travel together under a single operator to Toronto Union Station. In reverse service, the DMUs can split into smaller consists. However, since there are many rules governing the forming of trains, such as trainline brake test, it may not be a practical operation for GO to perform on a daily basis. On the other hand, it should be noted that with the latest diesel locomotives design, multi-engines concept is available to allow shutting down of one or more engines for a smaller trainset.

3.4. Electric Locomotives

Electric locomotives do not carry an internal prime mover and instead rely on energy supplied by an off-car electrified traction power supply and distribution systems. For a given horsepower, an electric locomotive, shown in Figure 3-5, is considerably lighter than a diesel locomotive. Further, it is possible to achieve much higher overall horsepower in a similarly sized electric locomotive than in a diesel locomotive. The net effect is a benefit of higher overall train acceleration, speed and system capacity. Examples of modern electric locomotives are presented in Appendix C.

Figure 3-5 - Example of a High-Horsepower AC Electric Locomotive ALP-46

The strong but light electric locomotives suffer from adhesion limitations – the wheels are prone to spin on slippery rail. The locomotives are overpowered at low speeds and cannot realize the full benefit of their nominal horsepower ratings. The electric traction has its greatest benefit at the mid and high speeds, where it can help trains achieve the posted track speeds more quickly, recover from local slow downs and generally maintain posted speeds more consistently.

The locomotive could be designed to receive dc or ac power, either through an overhead contact system (OCS) and collected by a vehicle-borne pantograph or through a ground-level third rail system and collected by a suspension-mounted shoe. DC systems can directly feed the collected power into the traction motor controllers. AC systems require a large and heavy transformer and rectifier to change the input power into more usable power. DC-powered rolling stock is typically lighter and simpler. AC-powered rolling stock currently offers greater tractive efforts. Both types of electric locomotives are studied for GO network to the extent they are compatible with the electrification system proposed. Several locomotive models can accept both types of power.

Modern electric locomotives are highly efficient, although when the entire energy flow from a primary source to the locomotive wheels is considered, the overall efficiency is not markedly different from diesel locomotives. Electric locomotives provide two strong advantages. First, the electric locomotive can use any primary energy source – fossil, nuclear, hydro, wind or solar – while the diesel requires a high-grade fuel; and secondly, they have no local exhaust pipe emissions. Depending on the primary power source, electric locomotives may have remote exhaust pipe emissions (at the power plant).

Electric locomotives have the potential of regenerative braking, where the traction motors are used to convert braking energy back into electricity. This electricity can supply in-train loads, such as heating, ventilation and air conditioning (HVAC), lighting and low voltage power. Excess power can be fed back into the distribution system (OCS or third rail), if that system can accept and use the excess power. The power regenerated into the distribution system can power other trains on the system or can be fed back to the power utility for credit through net power metering. Regenerative braking is common in light rail and electrified commuter rail applications and has been documented to reduce system electrical usage by between 5% and 20%. Amtrak's North East Corridor, for one, uses net power metering. Recently, there have been significant advances in energy storage devices (batteries, ultra capacitors, flywheels) to collect such excess power when it's available, and to then feed it back into the system when it's needed. Some storage devices are designed to fit on cars and locomotives while others are designed to be installed on the wayside, beside the tracks.

The market for electric locomotives in North America is very small in comparison to that for diesel locomotives. In contrast, the European market for electric locomotives is robust. Development of North American electric locomotive technologies is, therefore, slower and depends largely on the incorporation of European developments. Several high-speed, high-horsepower units of European origin, such as the ALP-46 manufactured by Bombardier, have proven records in North American service. It should be noted that that most of the European electric locomotives are not FRA crashworthy compliant. The ALP46 and ALP45DP, discussed later in the report, are specifically made to meet the FRA crashworthiness standard.

Current North American operators of electric locomotives include Amtrak, NJ Transit, South Eastern Pennsylvania Transportation Authority (SEPTA), and Maryland Area Rail Commuter (MARC). NJ Transit operates the ALP46 with up to 12 bi-level cars in commuter service.

As with diesel locomotives, electric locomotives are compatible with single-level or bi-level coaches and cabs. Electric LHC could maintain the same per-train capacity as diesel LHC by using the same or similar bi-level cars as GO Transit currently uses.

3.5. Electric Multiple Units

EMUs are self-propelled electric vehicles that rely on energy provided by a traction power supply and distribution systems in the same manner as described above for the electric locomotive option. EMUs can be dc- or ac-powered; several models can accept both types of power. Examples of modern EMUs are shown in Appendix C.

Like the electric locomotives, the off-vehicle power is collected, conditioned, and used to power axle-mounted traction motors. Tractive effort is typically applied to every axle in the consist, providing high acceleration rates that are consistent across all possible consist lengths – each additional vehicle in the consist provides its own motive power. Traction motor torque is compatible with local axle loading, making the system very tolerant of low adhesion levels. EMU grade-climbing abilities are typically significantly better than diesel or electric LHC trainsets. All new EMUs are equipped with regenerative braking.

There are a limited number of dc-powered EMU cars available in North America. Nippon Sharyo has supplied both single-level and gallery car designs to Northern Indiana Commuter Transportation District (NICTD) and Chicago METRA. Bombardier has supplied single-level M-7 EMU cars to both the Long Island Rail Road (LIRR) and Metro-North Railroad (MNR) in New York. More common are dc-powered light rail and rapid transit vehicles. These vehicles are built to different structural and operational requirements than GO, but several carbuilders could blend technologies to offer competitive dc-powered EMUs.

Currently, North American ac-powered EMU cars are only available in single-level designs. Examples include NJ Transit’s Arrow III built by Budd Company/General Electric and rebuilt by ABB, SEPTA’s Silverliner IVs built by General Electric, MNR’s M-6 cars built by Morrison Knudsen, and Agence Métropolitaine de Transport’s (AMT) MR90 built by Bombardier, as shown in Figure 3-6. SEPTA’s Silverliner V built by Rotem and MNR’s M-8 built by Kawasaki are both in the early stages of delivery and testing. With less passenger capacity per vehicle than the current GO bi-level coaches, EMU train lengths will need to increase for an equivalent seating capacity per train or, more practically, shorter trains may be offered more often.

Studies have shown that EMUs are cost competitive with diesel locomotives and DMUs over short-to-moderate route lengths with high ridership and high service frequency. Like the DMU, EMU costs vary with consist length. However, EMU cost competitiveness is more strongly driven by service frequency and environment than by consist length. EMUs may be a candidate technology if GO wishes to increase service frequency in and out of Union Station by using many, moderately sized trains. However, any attempt to increase service frequency may conflict with Union Station throughput and capacity constraints.

Figure 3-6 - Example of a Single-Level AC-Powered EMU, Agence Métropolitaine de Transport's Deux Montagnes Line, Montreal, Canada

Modern EMUs would have enough power to pull a limited number of unpowered coach cars, similar to LHC service. These additional cars could improve consist seating capacity while costing significantly less than EMUs to purchase, operate, or maintain. Consist performance will decrease with each additional unpowered coach car. Only NICTD currently uses coach cars within their EMU service.

Caltrain, which serves the San Francisco Bay Area, has pursued similar electrification studies and has determined, partly due to platform length constraints, that Caltrain's preferred future fleet will be multi-level EMUs. These EMUs will receive power from a 25 kV ac OCS. Caltrain has worked with the FRA and has recently secured a waiver to allow the operation of proven, European design, non-FRA-compliant vehicles intermixed with its current diesel LHC fleet and limited freight. This waiver required years of technical review, including sophisticated computer simulations of train-to-train and train-to-highway vehicle collisions to argue that an equivalent level of passenger safety would be maintained between compliant and non-compliant rolling stock. Metrolinx should not underestimate the effort required to obtain their own approval, particularly since they are under jurisdiction of Transport Canada rather than the FRA.

Analyses have been performed, showing an effective crashworthy interface between a Caltrain locomotive and the proposed EMU. The European EMU design, shown in Figure 3-7, takes advantage of crash energy management features, such as engineered crush zones. It is believed that a 25 kV, European-derived multi-level EMU may be a feasible and commercially viable alternative for Metrolinx's consideration.

Figure 3-7 - Caltrain Plans to Use European-Designed Multi-Level AC-Powered EMUs

3.6. Dual-Mode Locomotives

A dual-mode locomotive can operate in electric propulsion mode when in electrified territory, but extend service into non-electrified regions by switching to an on-board diesel engine. This type of unit combines the prime mover, alternator and fuel system of a diesel locomotive with the power collection and power conditioning equipment of an electric locomotive. These systems feed a common traction control and propulsion system. The dual-mode locomotive concept could be useful to Metrolinx as it would maintain the service continuity of a "one seat ride" while the system is incrementally and/or partially electrified. Examples of modern dual-mode equipment are presented in Appendix D.

Three North American railroads – Amtrak, LIRR and MNR – presently operate dual-mode locomotives in daily service. These dual-mode locomotives are all diesel and 600 V dc capable. They are configured for third-rail power collection and cannot operate in electric mode under overhead ac electrification. Further, only the LIRR DM30AC locomotives have thermal ratings that allow them to operate continuously in electric mode; the Amtrak and MNR P32DM-AC locomotives have short-term ratings that limit their use to about 10 minutes of operation to and from the electrified tunnels of New York. These limitations stem from a very localized service environment restriction and associated locomotive design objectives.

There is currently one dual-mode locomotive under development for the North American market, the Bombardier ALP-45DP, as part of a joint procurement being undertaken by NJ Transit and Montreal's AMT. First units should be delivered for testing by the summer of 2011. The locomotive, a rendering of which is shown in Figure 3-8, will be able to operate from diesel power or under overhead ac electrification. Two Caterpillar 3512C HD diesel engines will power the unit in non-electrified territory. The electrical traction equipment is compatible with 25 kV, 60 Hz, 12.5 kV, 60 Hz, and 12 kV, 25 Hz electrification systems.

Figure 3-8 - Rendering of the Dual-Mode Locomotive ALP45DP

Since the dual-mode locomotive carries significant diesel and electric equipment, a compromise of volume and weight must be made. The unit will always carry extra weight as compared to a single-mode unit.

The dual-mode units typically have different power ratings in diesel and electric modes. The P32DM-AC is relatively weak in electric mode as this power is collected through a moderate voltage third-rail shoe; the P32DM-AC was designed to be primarily a diesel-powered unit. The ALP45DP will be very strong in electric mode as this was a design priority and power is collected from a high voltage source.

The ALP45DM is the only valid, near-term-available dual-mode locomotive considered for GO Transit within the rolling stock technology evaluation. In electric mode, the ALP45DP will deliver approximately 1.8 times the power of the current MP40s. This should support the current 12-car consists with improving run times. In diesel mode, the ALP45DP should be about equal to the MP40s with slightly less power but faster throttle response. This will provide nearly identical acceleration and schedule for the less used, typically lower speed, non-electrified territory.

3.7. Dual-Mode Multiple Units

Bombardier sells two models of single-level dual-mode multiple units (DMMUs) to Société Nationale des Chemins de fer Français (SNCF), the French national railroad. The DMMUs, shown in Figure 3-9, can operate under OCS power or from on-board diesel engines. The B 81500 series can be powered by 1,500 V dc while the B 82500 series can be powered by 25 kV ac. Examples of modern dual-mode equipment are presented in Appendix D.

The DMMUs suffer from the same space and weight constraints as mentioned for the dual-mode locomotives. To fit the additional equipment into the DMMU power car design, part of the traditional passenger volume is given to the propulsion equipment. Consists are configured as power car/trail car/trailer car/power car to balance propulsion performance with seating capacity.

Figure 3-9 - Example of Single-Level Dual-Mode MU operated by Société Nationale des Chemins de fer Français (SNCF)

The DMMUs carry a significant cost premium due to both their low manufacturing volume and the total amount of equipment that they must contain. As mentioned previously, DMUs may serve Metrolinx to provide off-peak and extension service but not likely replace the rolling stock in the core passenger corridors. Likewise, the DMMUs offer unique opportunities for operational flexibility and the "one seat" ride concept, but the combination of high capital cost and inefficiencies at high passenger capacity will not make DMMUs a good system-wide choice.

The current single-level DMMU models are compliant with European structural standards, but not with the FRA standards. They would not be directly applicable to the Metrolinx system without modification to the carbody structure or the interpretation of governing structural standards.

There are currently no bi-level DMMUs and no firm plans to produce such a vehicle. It would be relatively infeasible to package that much equipment and passenger volume into a single carbody without significant compromises in performance, capacity, and suspension loads.

4. ALTERNATIVE ROLLING STOCK TECHNOLOGIES AND ENHANCEMENTS

Several alternative technologies may be worth exploration for their specific applicability and benefits to Metrolinx.

4.1. Alternative Locomotive Fuels

The traditional diesel locomotive offers several opportunities for the integration of alternative technology without completely redesigning these proven workhorses. Several government and transit agencies are exploring the use of alternative fuels to meet environmental requirements. These include biodiesel, compressed natural gas (CNG), liquefied natural gas (LNG) and direct combustion of hydrogen. In general, this is being done without significant design changes to the locomotives. However, the alternative fuels have the following drawbacks:

- Biodiesel stores less energy per litre than petro-diesel, so that on-board storage capacities would need to be increased to compensate for more total fuel burned during a given locomotive trip cycle.
- Biodiesel is made from local, renewable, resources, but may not lower total carbon output, depending on harvesting and processing techniques.
- Biodiesel is typically blended with petro-diesel and this blend would need to change, potentially monthly, in cold climates such as Toronto.
- Engine manufacturers do not warrantee engines burning more than 5% to 20% biodiesel.
- CNG cannot typically be stored on rail cars in sufficient volume to support one day's operation.
- CNG and LNG are combustible substances and present a significant danger during a collision and may be a target for malicious acts.
- Natural gas (CNG or LNG) reduces carbon monoxide (CO) and particulate matter (PM) but increases oxides of Nitrogen (NO_x) as compared to diesel fuel.
- Direct combustion of hydrogen in an internal combustion engine is relatively inefficient.

CP, with the federal agency Natural Resources Canada, tested four locomotives between Calgary and Edmonton for four months during the winter of 2009/2010. The locomotives ran on biodiesel blend and the program evaluated the effect of the fuel on the engines in cold weather. Amtrak recently announced a partnership with the Oklahoma and Texas Departments of Transportation to test biodiesel fuel blend to power the Heartland Flyer, a daily passenger train between Oklahoma City, Oklahoma and Fort Worth, Texas. Biodiesel blend has also been tested by Eastern Washington Railroad, Iowa Interstate Railroad, and SFRTA in commuter service; however, most railroads have shown reluctance to use biodiesel.

In stationary locomotive engine tests, the biodiesel blend B20, which is 20 percent biodiesel and 80 percent petro-diesel, reduced hydrocarbons and carbon monoxide emissions by 10 percent each; particulate emissions, by 15 percent; and sulfate emissions, by 20 percent. Biodiesel can have negative impacts on valves and gaskets in older engines. Engines built or rebuilt since approximately 1998 avoid many of these problems as their gaskets and valves have been designed for biodiesel's chemistry and lower lubricity.

CNG cannot typically be stored on rail cars in sufficient volume to support one day's operation, as the range of CNG-fuelled main line locomotives is only 80-100 miles. Mid-day refueling can be considered, but this may delay locomotives and foul the system schedule. Due to LNG's higher energy density, LNG-fuelled locomotives have a range of up to 800 miles. In order to achieve this maximum LNG locomotive range, the fuel needs to be stored in an adjacent tank car. Further, natural gas presents a significant danger during a collision. Natural gas reduces CO and PM but increases NO_x as compared to diesel fuel.

CNG Locomotives are operated by at least two railroads. The Napa Valley Wine Train successfully retrofitted a diesel locomotive to run on compressed natural gas before 2002. This converted locomotive was upgraded to utilize a computer controlled fuel injection system in May 2008, and is now the Napa Valley Wine Train's primary locomotive. Ferrocarril Central Andino in Peru has run a CNG Locomotive on a freight line since 2005. CNG locomotives are usually diesel locomotives that have been converted to use compressed natural gas generators instead of diesel generators to generate the electricity that drives the motors of the train. Some CNG locomotives are able to fire their cylinders only when there is a demand for power, which, theoretically, gives them higher fuel efficiency than conventional diesel engines.

The Burlington Northern, now Burlington Northern Santa Fe (BNSF), converted two locomotives, #7149 and #7890, to operate on LNG. The demonstration locomotives, one of which is shown in Figure 3-10, operated successfully on commercial coal service between Wyoming and Wisconsin from 1991 to 1996 when the program closed as BNSF could not justify the costs of LNG in long-haul service. In the Los Angeles area, BNSF currently operates four LNG locomotives in regional and local service.

Figure 3-10 – Burlington Northern's LNG Powered Locomotive with Gas Tank

There are no known examples of locomotives being propelled by direct combustion of hydrogen. Hydrogen is not likely to be compatible with the traditional single large engine in a locomotive. Future studies may consider direct combustion in multiple small engines within a single locomotive.

To date, alternative fuels, besides limited trials with biodiesel, have not been used in daily commuter service.

4.2. Hybrid Drive Trains

Traditional drive systems produce energy that is immediately and fully directed to propelling the vehicle along the rails with no ability to store energy to buffer varying propulsion loads. Hybrid propulsion technology combines prime mover, energy storage, and traction drive elements into a coordinated system. Energy moves between these three elements as depicted in Figure 3-11 below:

Figure 3-11 – Energy Flow in Hybrid Drive Train

This basic architecture allows the prime mover to power the traction drive, the energy storage system, or both simultaneously. The traction drive can send excess braking energy to the energy storage for later use. The stored energy can power the traction drive to absorb transient loads or to supplement the prime mover and provide a burst of drive energy in excess of the nominal engine rating. The basic energy flow scheme can allow hybrids to be tuned for economy or for performance.

The hybrid drive train is a flexible concept. The prime mover could be diesel, biodiesel, natural gas, fuel cell (explained in Section 3.8.3), hydrogen combustion, or some other technology. The storage could be batteries, flywheel, ultra-capacitors, hydraulic pressure, chemical, or some other technology. The traction drive is also flexible, but likely to resemble a traditional light rail or EMU traction motor.

The energy flow relationships of hybrid propulsion systems are compatible with the requirements of commuter rail. Commuter rail operation involves using a large amount of energy for a few minutes to accelerate from a station, a small flow of energy to maintain speed between stations, followed by the need to remove a large amount of energy from the vehicles to slow for the next stop. Superimposed on this is a steady and not insignificant requirement of energy for HVAC and other auxiliary vehicle systems. If the energy that has to be removed during braking can be stored so that it can be used for the next acceleration, there is a significant potential saving in energy consumption.

On-board energy storage may support more uniform energy requirements of the trains which could reduce the design requirements for an electrification system or even for a diesel engine. Batteries have been considered for such application for a very long time, but are inefficient in terms of weight per energy stored, and incur a large cost for periodic replacement. Flywheel systems have been studied but involve significant additional weight which reduces energy saving capability. Recently, ultra-capacitors have come to the fore as a more effective form of energy storage. This approach appears to be promising, but is in an early stage of development.

Energy storage in such a heavy hybrid application is meant only for short-term, transient load variations. The systems may store several seconds or several minutes worth of energy – just enough to smooth out variations due to train accelerations or auxiliary equipment turning on or off.

Hybrids have higher internal energy conversion losses than do conventional drive systems, but regenerative braking and engine efficiencies more than overcome these losses.

Hybrid diesel electric switch engines have been developed and used with success in revenue service. General Electric is leveraging this experience to design a hybrid diesel electric mainline freight locomotive. It is conceptually possible that this locomotive could be adapted to a passenger application.

East Japan Railway Company (JR East) has built and operated a hybrid diesel multiple unit (HDMU) in demonstration service, shown in Figure 3-12. It is not considered a production design and does not meet the FRA requirements for commuter rail operations. It is a test bed that has been closely watched for possible future commercialization.

Figure 3-12 - JR East Test Platform for Hybrid and Fuel Cell Technologies

4.3. Hydrogen Fuel Cell Drive Trains

Fuel cells, in their most simplistic form, convert stored hydrogen gas into electric current and produce only water vapor as emissions. Several modular fuel cell units of significant energy output are nearing commercial viability. Fixed-location, institutional fuel cells currently have some advantages over mobile fuel cells in commercialization, robustness, and packaging. However, both technologies are progressing quickly.

Fuel cells have a strong advantage over batteries in that they effectively “recharge” by refilling the hydrogen tanks – a task of several minutes as compared to an electric battery recharge that could take three quarters of a day.

A vehicle could be designed to operate just from the available power of the fuel cell. However, fuel cells are good at providing steady power while a railcar drive system typically demands varying power. The fuel cell is a very good candidate for the prime mover within a hybrid drive train as described in Section 3.8.2.

The availability of commercial volumes of hydrogen gas is currently moderate as it is an easily obtained by-product of natural gas extraction. Electrolysis can be used to isolate hydrogen from water. Though this process is conventionally electricity-intensive, the Toronto area is in a relatively unique position of having excessive electrical power capacity in the overnight hours. Hydrogen could be harvested overnight using cheap electricity and then used to power commuter railcars during the day. Several universities in Ontario are working on advanced processes to facilitate the hydrogen supply, developing chemical and nanotechnology catalysts.

A significant drawback to on-board fuel cells is the need to store hydrogen on the vehicle. The hydrogen needs to be very highly pressurized to store sufficient volumes. This limits tank design and thus the ability to fit it in a railcar with other components. Small low-pressure gas leakage can be avoided through good design. Tank rupture protection during a collision can be challenging.

Since 2007 or earlier, Bombardier has had preliminary talks with the Ontario Ministry of Transport (MTO) as to the feasibility of hydrogen-powered commuter rail. Also, in March 2009, the University of Ontario Institute of Technology (UOIT) announced it has received a substantial grant for a two year research project to advance hydrogen fuel cell technologies for the automotive sector.

An experimental 250 kW fuel cell drive train freight switch engine has been developed and tested in the United States by a consortium lead by BNSF, shown in Figure 3-13. The progression to a fuel cell powered passenger locomotive is conceivable, in the long term.

Figure 3-13 - Experimental BNSF Fuel Cell Switch Engine

JR East in Japan has retrofitted its hybrid diesel multiple unit to be a hybrid fuel cell EMU. The vehicle continues to be tested and refined.

Advocacy groups have recently pushed for the development of fuel cell powered street cars in the United States. XCELLSIS, jointly owned by DaimlerChrysler, Ballard, and Ford, demonstrated the fuel cell engine technology in fuel cell buses and cars. Proterra has demonstrated a hydrogen fuel cell hybrid bus and expressed a willingness to apply its propulsion technology to steel-wheeled vehicles.

Fuel cells offer an opportunity to supply 40 to 100 kW of head end power (HEP) to current or future GO trains. HEP units supply conventional electric power to support lights, batteries, HVAC, controls, and other on-board auxiliary systems. Fuel cells of this capacity will be commercially viable in several years and could be placed on individual cars. This propulsion concept may be applicable to Metrolinx when developed, but is not expected to be commercially available in useable form for commuter rail application in the short to medium term[7].

Fuel cells also offer an opportunity to be located beside the railroad tracks or facilities and supplement or replace electricity drawn from the conventional power grid. Such power could easily support signalling and grade crossing circuits, or supplement maintenance yards. Stretching this concept, a network of distributed fuel cells could be connected to an OCS system to support traction power loads. By adding a local electrolysis station, such installations could absorb excess electrical power created by electric locomotives or EMUs during regenerative braking and feed the resultant hydrogen to a fuel cell to supplement system power during times of high load.

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[7] Future technology is defined as a technology where research and development work is complete, prototypes developed and testing advanced to the point where the technology is being commercially marketed and will be ready for production within 5 years. For the purposes of this Study, the short to medium term is 5-10 years.

5. ALTERNATIVE SYSTEM TECHNOLOGIES AND ENHANCEMENTS

5.1. Maglev

Magnetic levitation (maglev) technology uses magnets mounted on the vehicle or on the vehicle and guideway to levitate the vehicle several centimetres above the guideway and propel the vehicle along the system using the linear induction motor principle. Since there is no physical contact between the vehicle and the guideway, the maglev technology has the following attractive characteristics:

- High speed of operation, with commercial speeds of up to 500 km/h,
- No "rolling" resistance, leaving only air resistance and electromagnetic drag, potentially reducing energy losses associated with resistance against movement,
- Less noise than conventional trains at the same speed.

However, the maglev system requires specially built guideway and vehicles equipped with strong electromagnets. This requirement makes maglev systems very uneconomical for commuter rail application. Maglev technology is intended for high-speed intercity travel. For Metrolinx commuter operation with relatively close passenger stations, the maglev trains would not be able to accelerate to high speed before beginning to brake for the next station resulting in the maglev potential not being fully realized.

The only commercial maglev system in the world is the Shanghai Maglev Train operating from downtown Shanghai (Shanghai Metro) to the Pudong International Airport, shown in Figure 3-14. Construction began in 2001 and commercial operation began in 2004. The cost was $1.33 billon for a 30 km system with only two stations, which equates to approximately $60 million/km in today's dollars. Due to the high cost, the proprietary nature of the Transrapid Consortium's technology, concerns about safety, and radiation fears, maglev technology has not gained widespread acceptance. Even the plan to extend the maglev to Shanghai's other airport, Hongqiao with continuation to Hangzhou, has been suspended. Instead, a conventional subway line is being built to connect the two airports.

Figure 3-14 - Shanghai Maglev Train and Guideway

Although no actual figures are available, it is understood that energy costs per vehicle-km and per passenger-km are significantly higher than comparable steel-wheel-on-steel-rail technologies. This is due to the relative inefficiency of creating the strong levitation and propulsion magnetic fields required.

In addition, any switching operation to support merging or diverging movements at the junction of a mainline with a branch line requires the physical movement of a significant section of the maglev alignment. Route reset times require several minutes, versus less than 20 seconds for an existing GO junction. Maglev route reset times are too long to support the current frequency of service at major GO junctions, such as east and west of Toronto Union Station.

Due to the high cost of the system and its incompatibility with existing commuter, intercity, and freight operations, maglev is not considered suitable for Metrolinx electrification and will be removed from further consideration in this study.

5.2. New System Concepts

In order to eliminate the negative visual impacts of electrification and its need for poles and OCS wires, two new technologies have been developed for transit system applications:

- Inductive Power Transfer (IPT) system
- Ground-level power supply, also referred to as Alimentation Par Sol (APS)

Inductive Power Transfer System. The Inductive Power Transfer system features a continuous inductive cable loop installed underground which is supplied by a high current from a wayside supply. The high currents create strong magnetic fields and transfer power to the vehicle by inductive coupling to a pickup installed under the vehicle. The pickup is installed at close proximity to the track to maximize the efficiency of the mutual magnetic coupling. The collected power is conditioned in a carborne inverter for supply to traction motors.

Currently, the IPT system is offered by Bombardier and Conductix/Wampfler. In 2009, Bombardier demonstrated a catenary-free operation of a rail vehicle on its test track in Bautzen, Germany. Conductix/Wampfler applied the IPT system to monorail systems in industrial applications in 2004 at Mitsubishi Motors plant located in Adelaide, Australia and in 2005/2006 at KIA Motors plant located in Zilina, Slovakia.

Ground-Level Power Supply System. Ground-level power supply system consists of a contact strip installed between the rails. For safety reasons the strip is sectionalized and only the part of the strip directly under the vehicle is energized. Extensive power supply, switching, and control equipment is required to be installed under ground. At the time of preparation of this report, the APS system is offered only by Alstom, shown in Figure 3-15.

Figure 3-15 – In-Ground Power Supply System - Innorail

The Urban Community of Bordeaux in France was the first in the world to implement this technology, which has been in service since 2003. Since its launch, five other cities have selected this system. APS will be used on a part of the tram lines currently under construction in Orleans, Reims and Angers in France, as well as a part of the future line in Brasilia, Brazil. Dubai in the United Arab Emirates chose this system for its entire future tram line. The Qatar authorities are also examining the possibility of equipping some or all of their tramways with a catenary-free system.

Both Inductive Power and Ground-Level Power systems are designed for relatively low maximum speeds of 70 km/h, consistent with their intercity operation, as well as for moderately changing gradients. Both systems are available only in low voltage (750 volts) dc power systems. Either system, if applied to Metrolinx GO commuter network, would require a significant infrastructure rebuilding and would require high level of maintenance in the snowy Toronto winters. The IPT and APS systems are clearly inappropriate for the Toronto commuter, mainline, intercity, and freight rail network.

6. TECHNICAL FACTORS INFLUENCING ROLLING STOCK SHORT-LISTING

6.1. Compatibility with Reference Case Service Levels

Each technology discussed above offers a slightly different passenger capacity per car and potentially significantly different passenger capacity per train.

The diesel and electric LHC options rely on coach and cab cars to carry passengers. Single-level passenger cars typically have between 80 and 115 seats, depending on seating configuration and aisle width. To maintain an interior arrangement similar to current GO bi-level cars, the single-level coaches would seat less than 90 passengers. Bi-level cars (including gallery, multi-level and double-deck designs) typically seat between 125 and 170 passengers. Additional rush-hour passengers can be accommodated by standing in the aisles. Maximum standee capacity can be over 1.5 times the seated capacity.

The EMUs and DMUs discussed above were of single-level and bi-level designs. They must accommodate an operator's cab and some equipment lockers and chases within the carbody. Their typical passenger capacities, following modern ergonomics and design trends, are between 75 and 90 seats for a single-level and approximately 125 to 150 seats for a bi-level.

The alternative rolling stock technologies discussed above feature changes or enhancements to existing general locomotive or passenger car designs. The alternative technologies should not fundamentally change the interior layout and passenger capacity.

LHC train length in the GO operating scenarios will likely retain the current 12 car size, yielding between 960 and 1,944 seats. EMU train length could range between 2 and 14 cars, giving up to 1,260 seats. DMU trains would likely be kept to between 2 and 6 cars[8], or up to 540 seats.

Typical capacities of various rolling stock technologies are shown in Table 3-1.

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[8] It is certainly possible to operate 12 car DMU train. However, as already discussed, studies have shown that operation of DMU consists beyond 4-6 cars becomes uneconomical.

Table 3-1 – Typical Capacities of Various Rolling Stock Technologies

Technology	Maximum Seated Capacity		Average Daily Capacity with Moderate Standees		Maximum Crush Capacity	
	1 Car	12 Cars	1 Car	12 Cars	1 Car	12 Cars
Locomotive[9] Hauled Train, Bi-Level Coaches	162	1,944	200	2,400	310	3,720
Bi-Level Multiple Unit, EMU or DMU	125	1,500	150	1,800	290	3,480
Single-Level Multiple Unit, EMU or DMU	90	1,080	125	1,500	245	2,940

One must consider boarding and alighting times when considering total passenger capacity. Many wide doors help people move in and out of the vehicle, reducing station dwell times and increasing line capacity, but also reducing area of the car capable of mounting seats. Any multi-level configuration creates additional internal travel time to move from the seat to the door to detrain. Routes with many, closely spaced stops favour large doors and high standee capacities. Longer commuter routes favour comfortable seating with low standee accommodations.

6.2. Proven Technology/Commercial Viability

Locomotives, coaches, and single-level EMUs represent technologies that have been proven over decades of operation and have a variety of current product offerings. There is adequate competition, some of which are proven suppliers, and some of which are relatively inexperienced in this market.

DMUs have been in North American service for over 60 years, but have been out of mass production for the last 40. There are currently no FRA-compliant DMUs available for new purchase. A new DMU for GO would require the application and combination of proven components whose integration into a vehicle system has not yet been proven in revenue service.

Electric locomotives and potential bi-level EMUs represent a smaller competition base. EMUs, coaches, and diesel locomotives have adequate competition, some of which are proven suppliers, and some of which are relatively inexperienced in this market.

Dual-mode locomotives and DMMUs present a high technical risk and have the least competition from suppliers. The ALP45DM is nearing its first testing and delivery in North America but the DMMUs are a rare bread even in Europe.

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[9] Locomotive can be diesel, electric, or dual-mode hauling the existing Metrolinx bi-level cars.

6.3. Regulatory Requirements

The technologies identified in the preceding section should be adapted to Metrolinx to conform to Canadian regulatory requirements, recognizing that Transport Canada has ultimate regulatory authority with respect to railway vehicles on the GO network.

Transport Canada has recently indicated that they may be more flexible with the FRA structural strength requirements, which might open opportunities for GO to study a broader range of European and Asian EMUs and DMUs. Specifically, they stated their intent to require new GO vehicles to either:

- Meet FRA structure strength and crash worthiness for passenger cars, or
- Maintain temporal separation from freight and heavy rail passenger traffic, or
- Operate under some form of Positive Train Control (PTC) signalling system.

The regulations of the FRA and American Public Transit Association (APTA) provide guidance in terms of what vehicle technologies are appropriate for the GO network that also includes freight trains and intercity passenger trains. All of the technologies presented above can comply or be made to comply with FRA regulations for commuter rail vehicles, including safety, accessibility, and emissions. Improvements in crashworthiness are currently being evaluated by the FRA, and will be implemented on locomotive-hauled cab cars, as a test case, in the near future. The greatest challenge in satisfying FRA regulations has been complying with passenger accessibility standards.

6.4. Compatibility with Reference Case Infrastructure

All technologies require similar infrastructure at the track level. The use of multiple vehicles with powered axles, versus a single locomotive, may allow the track designer to increase track grades and shorten flyovers. Lower axle loads may allow lighter bridge construction; EMUs offer the lowest axle loads, followed by DMUs and then locomotives.

Electric propulsion, whether locomotive or EMU, requires a complete traction electrification system. This consists of traction power substations, an OCS or third rail, switching stations, paralleling stations and associated equipment. The traction electrification systems will be addressed under separate cover, but from a technology selection stand point, one must consider that different electrification systems have different cost and property acquisition implications.

Diesel technologies will require a fuelling facility. GO currently fuels its locomotives at a central maintenance facility, using a fixed fuel rack. This type of fuel rack is typically compatible with DMUs, or easily modified for their use. The alternative rolling stock technologies could require a completely new fuelling facility for compressed natural gas or hydrogen.

The current Metrolinx model of a centralized fuelling facility is very compatible with the system-wide diesel LHC rolling stock. If the electrification study favours a future fleet of mixed technologies such as electrified arterial service with diesel feeder service, then additional fuelling sites may be warranted. Non-centralized fuelling can be performed at several fixed facilities or through the use of fuel trucks.

6.5. Technology Comparison

A qualitative comparison of the rolling stock technologies considered for the GO network is presented in Table 3-3. It is assumed that factors, such as, route characteristics, run times, and driver aggressiveness are comparable in each case. All rolling stock shown with medium crashworthiness is assumed to meet FRA regulations for crashworthiness.

Table 3-3 – Summary Comparison of Rolling Stock Technical Criteria

Technology	**Diesel LHC Trains**	**Diesel Multiple Unit (DMU) Trains**	**Electric LHC Trains**	**Electric Multiple Unit (EMU) Trains**	**Dual-Mode Locomotives**	**Dual-Mode MUs**
Example Photograph						
Contribution to Improved Service						
Performance	Low	Low-Medium	Medium	High	Medium (Electric), Low (Diesel)	
Passenger Capacity per Train	High	Medium	High	Medium	Medium-High	Medium
Operational flexibility	High	High	Medium	Medium	High	High
Maintainability	High	Medium	Medium	High	Medium	High
Competitive Equipment Availability						
Proven Suppliers	Yes	Yes	Yes, European	Yes	No	One
Proven Equipment	Yes	Yes, non-FRA Compliant	Yes	Yes	Under Development	Yes
Adequate Competition	High	Low	Low	High	Low	Low
Infrastructure						
Technology-Specific Requirements	Fuelling Facility		Substations and OCS required throughout the system		Fuelling Facility, Substations and OCS in Electrified Territory Only	
Energy Consumption						
Onboard Fuel Consumption	High	Medium	None	None	High in Non-Electrified Territory	
Total Energy Consumption	High	Medium-High	Low	Medium	Medium-High	Medium-High
Safety						
Crashworthiness	High	Medium	High	Medium	Medium-High	Medium

Table 3-3 – Summary Comparison of Rolling Stock Technical Criteria (Continued)

Technology	**Alternative Rolling Stock Technologies**		
	CNG-Fuelled Locomotive	**Hybrid Drive Trains**	**Hydrogen Fuel Cell Drive Trains**
Example Photograph			
Contribution to Improved Service			
Performance	Low	Low-Medium	Low-Medium
Passenger Capacity per Train	High	Same or Lower than Before	Same or Lower than Before
Operational flexibility	High	High	Medium
Maintainability	Medium	Medium	Low
Competitive Equipment Availability			
Proven Suppliers	Yes	Few	Few
Proven Equipment	Yes, Limited Test Program	No, Under Development	No, Under Development
Adequate Competition	Yes	Low	Low
Infrastructure			
Technology-Specific Requirements	CNG or LNG Fuelling Facility	Fuelling Facility	Hydrogen Fuelling Facility
Energy Consumption			
Onboard Fuel Consumption	High	Medium	Medium
Total Energy Consumption	High	Medium	Medium
Safety			
Crashworthiness	Low	Same as Before	Same as Before

6.6. Potential Technologies To Be Considered For Metrolinx Electrification

GO is faced with the daunting task of potentially upgrading rolling stock technology on an existing and heavily used commuter rail system. The current system arterial corridors have a highly-peaked morning and afternoon rush hour demand of almost 2,000 passengers per train at 15 minute peak service frequency. About 95% of all passengers start or end travel at Union Station. Union Station is physically constrained as to the number of tracks and train-to-train headways must be held relatively high to allow the signalling system to maintain safety. The net result is that Union Station can only handle a limited number of trains at moderate headways. To maintain passenger flow, trains must remain relatively long – at approximately the current size of 12 cars, and have a high passenger capacity per railcar as displayed in the bi-level configurations.

Table 3-4 presents an at-a-glance summary of the rolling stock options considered in this study. Each technology is qualitatively ranked by the four screening criteria. To reduce the risk of new design development, potential GO Transit rolling stock should be proven in commuter rail service. Candidate rolling stock should also be commercially viable such that Go Transit can go out for bid in a competitive market place and select a manufacturer who is likely to support the product for years to come. Finally, the potential technologies should be compatible with both the reference case infrastructure and service level.

Reference case infrastructure and service level converge at Union Station to require moderately long, high-capacity trains to meet ridership levels within the fixed platform lengths. All single-level technologies fail to provide the desired service level within the maximum platform length. However, bi-level technologies, with their higher passenger capacity per car, do meet GO Transit's needs. The exception is bi-level DMUs – this technology could form 12-car trains to support the target ridership within the fixed platform length, but such long DMU trains become impractical as compared to other candidate rolling stock options.

The current diesel LHC trains, upgraded to Tier 4 emissions standards, should be carried forward into the electrification study as a baseline for system improvement.

Electric LHC, EMUs, and dual-mode LHC, all in a bi-level configuration, should be carried forward as well, as they each represent unique solutions to potentially reduce operating costs, improve service, and/or extend service into new territory.

Further study is not justified for DMUs, DMMUs, hybrid drive trains, or fuel cell drive trains at this time. Each technology has their niche applications. DMUs are suited to short trains and low ridership where they offer a system capital cost advantage. DMMUs and hybrid drives offer the opportunity to reduce operating costs and exhaust gas emissions but carry a high capital cost premium. Fuel cell technology is in its infancy for railroad applications and not expected to mature within the time frame of this study. In the GO arterial service, all of these technologies have prohibitively high costs per passenger and are unproven technologies.

This leaves the bi-level versions of the current diesel LHC, electric LHC, EMU and dual-mode LHC as the most viable arterial route candidate technologies. These options will be studied in detail in a life cycle analysis to determine the best long term solution for GO. Electrification requires a large capital cost that, in certain system loadings and duty cycles, can be reasonably offset by electric operational cost savings. Each technology will have unique fleet capital and maintenance costs. For example, electric locomotives may be able to use the existing coach and cab cars for the remainder of their service life.

However, the condition of these cars should be evaluated to determine their future and replacement or refurbishment costs.

The potential electrification of Union Station presents some unique challenges to provide a relatively continuous supply of traction power as trains navigate through the complex interlocking arrangements approaching the platforms. Recently, some concerns have been raised about the visual and environmental impact of an overhead catenary system in this area. An alternative would be to install a third rail system within the protected Union Station throat areas.

Third rail cannot cross over the two load-bearing rails. With Union Station's complex switch and crossover designs, the third rail could not be continuous. In a locomotive application, where all traction power is typically collected by one or two contact shoes on the locomotive, this could lead to many transitions between powered and unpowered operation. Each unpowered segment is an opportunity for the train to become stranded. A limited on-board energy storage capacity could help power through these transitions. EMU consists, with power collected at every car, could travel through these gaps better, as at least part of the train would be powered at all times.

It should also be noted that a 12-car train requires relatively high power demand during acceleration, and at the third rail low voltage, the high power demand results in high current. Such high current would be very difficult to pick up by a single locomotive current collector, and would essentially eliminate the electric locomotive and dual-mode locomotive technology options if the Union Station approaches must be third rail powered.

Table 3-4 – Summary Comparison of Rolling Stock Screening Criteria

	Technology Type	**Proven Technology**	**Commercially Viable**	**Compatible with Reference Case Infrastructure**	**Compatible with Reference Case Service Levels**
Single-level	Diesel LHC	Yes	Yes	Yes	No
	DMU	Yes	Yes	Yes	No
	Electric LHC	Yes	Yes	Yes	No
	EMU	Yes	Yes	Yes	No
	Dual Mode LHC	In development	Limited	Yes	No
	Dual Mode MU	Yes	Limited	Yes	No
Bi-level	Diesel LHC	Yes	Yes	Yes	Yes
	DMU	Limited	Limited	Yes	No
	Electric LHC	Yes	Yes	Yes	Yes
	EMU	Yes	Yes	Yes	Yes

	Dual Mode LHC	In development	Limited	Yes	Yes
	Dual Mode MU	No	No	Yes	Yes
	Biodiesel/ Natural Gas/ Hydrogen Fuel	Limited	No	Yes	Yes
	Hybrid	No	No	Yes	Yes
	Magnetic Concepts	No	No	No	No

6.7. Recommendations

The following rolling stock technologies are recommended to be carried forward for further system-wide analysis as they are proven technologies, commercially viable, and are compatible with the reference case:

- Diesel Locomotives – Bi-Level
- Electric Locomotives – Bi-Level
- Electric Multiple Units – Bi-Level
- Dual-Mode Locomotives – Bi-Level

Modern DIESEL Locomotives

A short list of modern diesel locomotives around the world is presented In Table A-1. The list is by no means comprehensive, and is intended to provide examples of currently operating commuter rail using diesel LHC and DMUs. Because so many styles of DMUs exist, they are noted in Table A-1 by propulsion type: diesel mechanical (DM), diesel hydraulic (DH), or diesel electric (DE); and by carbody structure: FRA-compliant (C) or non-FRA-compliant (NC).

Diesel equipment selection tends to be based on a few core models, modified slightly for individual operators. Table A-1 lists examples of the major equipment types, but does not intend to imply that equipment is exclusive to the named operator. For example, Caltrain is shown to operate MPI MP36 locomotives with Bombardier bi-level coach cars. There are thirteen properties in North America operating this same combination of equipment. Likewise, the Siemens DMU operated by First TransPennine Express appears as similar models used extensively throughout Europe.

Many countries have extensive diesel networks operating and have further plans to extend these systems in the future. In the following table, just one example per country is shown outside of North America.

Table A-1 – Modern Diesel Locomotives around the World

System	Dorion–Rigaud Line	
Operator	AMT	
Country	Canada	
Service	Commuter	
Rolling Stock	Diesel LHC, Bi-Level	
Speed/Headway	127 km/h/20 min	

System	Caltrain	
Operator	Peninsula Corridor Joint Powers Board	
Country	USA	
Service	Commuter	
Rolling Stock	Diesel LHC, Bi-Level	
Speed/Headway	127 km/h/5-15 min	

System	Raritan Valley Line	
Operator	NJ Transit	
Country	USA	
Service	Commuter	
Rolling Stock	Diesel LHC, Single-Level	
Speed/Headway	127 km/h/15 min	

System	O Train	
Operator	OC Transport	
Country	Canada	
Service	Commuter	
Rolling Stock	DMUs (DM, NC)	
Speed/Headway	120 km/h/15 min	

System	Westside Express Service (WES)	
Operator	Tri-County Metropolitan Transportation District of Oregon (TriMet)	
Country	USA	
Service	Commuter	
Rolling Stock	DMUs (DH, C)	
Speed/Headway	97 km/h/30 min	

System	Sprinter	
Operator	North County Transit District (NCTD)	
Country	USA	
Service	Commuter	
Rolling Stock	DMUs (DM, NC)	
Speed/Headway	89 km/h/30 min	

System	Capital MetroRail	
Operator	Capital Metropolitan Transportation Authority	
Country	USA	
Service	Commuter	
Rolling Stock	DMUs (DE, NC)	
Speed/Headway	97 km/h/35 min	

System	Tri-Rail	
Operator	South Florida Regional Transportation Authority (SFRTA)	
Country	USA	
Service	Commuter	
Rolling Stock	DMUs (DH, C), Diesel LHC	
Speed/Headway	127 km/h/20-40 min	

System	TransPennine	
Operator	First TransPennine Express	
Country	England	
Service	Commuter	
Rolling Stock	DMUs (DE, NC)	
Speed/Headway	160 km/h/15 min	

System	Gyeongbu Line	
Operator	Korail	
Country	South Korea	
Service	Commuter	
Rolling Stock	DMUs (DE, NC)	
Speed/Headway	150 km/h/45 min	

System	Transwa Prospector	
Operator	Transwa	
Country	Australia	
Service	Commuter	
Rolling Stock	DMUs (DH, NC)	
Speed/Headway	160 km/h/twice daily	

7. MODERN ELECTRIFICATION SYSTEMS

There are over 100,000 EMUs and Electric Locomotives operating around the world today. Figure B-1 shows the distribution of EMUs by continent. Europe and Asia operate the vast majority of EMUs, but several large North American transit agencies use them as well.

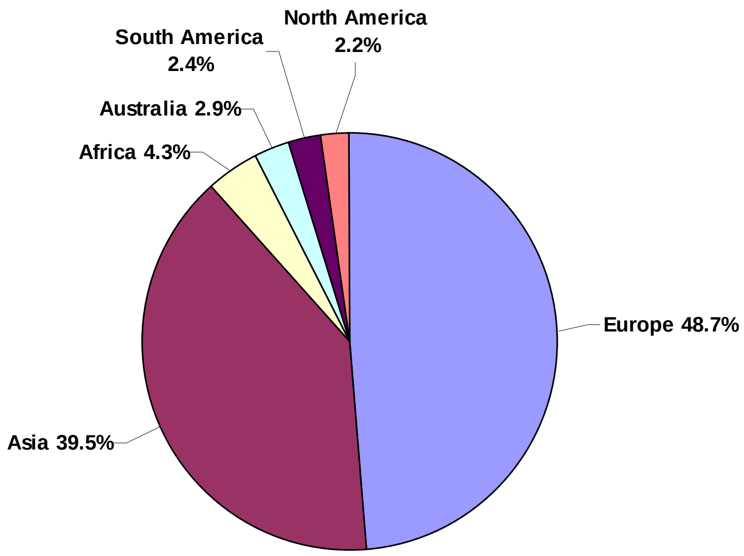

Figure B-1 - Distribution of the World's EMUs by Continent

A short list of modern electrification systems around the world is presented In Table B-1. The list is by no means comprehensive, and is intended to include examples of commuter, high-speed rail, and in some cases, freight electrification systems, already operating. All systems listed are operating at single-phase, using 25 kV electrification systems at commercial frequency of 60 Hz or 50 Hz, with source of power being provided by the local power utility companies.

Many countries have very extensive electrification networks operating and have further plans to extend their electrification systems in the future. In the following table, just one example per country is shown outside of North America.

__Table B-1 – Modern Electrification Systems around the World__

System	Deux Montagnes	
Operator	AMT	
Country	Canada	
Service	Commuter	
Rolling Stock	EMUs	
Speed/Headway	120 km/h/10-30 min	
Electrification	25 kV ac, 60 Hz	

System	Northend Electrification	
Operator	Amtrak	
Country	USA	
Service	High-Speed Rail & Commuter	
Rolling Stock	Power cars & trailers	
Speed/Headway	232 km/h/30-60 min	
Electrification	25 kV ac, 60 Hz	

System	North Jersey Coast Line	
Operator	NJ Transit	
Country	USA	
Service	Commuter	
Rolling Stock	Electric LHC & EMUs	
Speed/Headway	201 km/h/10 min	
Electrification	25 kV ac, 60 Hz	

System	West Coast Main Line	
Operator	Network Rail	
Country	England	
Service	Intercity/Commuter/ Freight	
Rolling Stock	Electric LHC & EMUs	
Speed/Headway	201 km/h/15-20 min	
Electrification	25 kV ac, 50 Hz	

<table>
<tr><td>System</td><td>TGV (Train à Grande Vitesse)</td><td rowspan="7"></td></tr>
<tr><td>Operator</td><td>French Railways (SNCF)</td></tr>
<tr><td>Country</td><td>France</td></tr>
<tr><td>Service</td><td>Intercity</td></tr>
<tr><td>Rolling Stock</td><td>Power cars & trailers</td></tr>
<tr><td>Speed/Headway</td><td>300 km/h/20-30 min</td></tr>
<tr><td>Electrification</td><td>25 kV ac, 50 Hz</td></tr>
</table>

<table>
<tr><td>System</td><td>Madrid-Sevilla Line</td><td rowspan="7"></td></tr>
<tr><td>Operator</td><td>Spanish Railway (RENFE)</td></tr>
<tr><td>Country</td><td>Spain</td></tr>
<tr><td>Service</td><td>Intercity</td></tr>
<tr><td>Rolling Stock</td><td>Power cars & trailers</td></tr>
<tr><td>Speed/Headway</td><td>300 km/h/30 min</td></tr>
<tr><td>Electrification</td><td>25 kV ac, 50 Hz</td></tr>
</table>

System	Elektrichka	
Operator	Russian Railways	
Country	Russia	
Service	Commuter	
Rolling Stock	EMUs	
Speed/Headway	100 km/h/10-30 min	
Electrification	25 kV ac, 50 Hz	

System	Mumbai Rajdhani Express	
Operator	Indian Railways (IR)	
Country	India	
Service	Intercity/Commuter	
Rolling Stock	Locomotive-Hauled Trains	
Speed/Headway	87 km/h/15 min average	
Electrification	25 kV ac, 50 Hz	

System	Shinkansen	
Operator	Japan Railways Group (JR)	
Country	Japan	
Service	Intercity	
Rolling Stock	EMUs	
Speed/Headway	320 km/h/3 min	
Electrification	25 kV ac, 50 Hz/60 Hz	

System	Guangshen Railway	
Operator	Guangshen Railway Company Limited	
Country	China	
Service	Intercity/Commuter/ Freight	
Rolling Stock	EMUs	
Speed/Headway	200 km/h/20-30 min	
Electrification	25 kV ac, 50 Hz	

System	Werribee Railway Line	
Operator	Australian Railways	
Country	Australia	
Service	Commuter	
Rolling Stock	EMUs	
Speed/Headway	115 km/h /5-20 min	
Electrification	25 kV ac, 50 Hz	

8. MODERN DUAL-MODE LOCOMOTIVES

A short list of modern dual-mode locomotives is presented In Table C-1. Dual-mode propulsion is receiving renewed interest from established transit agencies as they look to modernize their systems, reduce operating costs, and improve local environmental conditions. This technology offers the possibility of extreme operational flexibility and a “one seat ride” throughout a system – in both high density corridors and rural feeder service areas.

There are currently very few dual-mode options available. This equipment usually has a high capital cost, performance that varies with propulsion mode, and increased equipment weight and complexity.

The dual-mode equipment list focuses on those that operate on single-phase, 25 kV electrification systems at commercial frequency of 60 Hz or 50 Hz, with source of power being provided by the local power utility companies.

Table C-1 – Modern Dual-Mode Locomotives

System	Train de l’Est	
Operator	AMT	
Country	Canada	
Service	Commuter	
Rolling Stock	Dual-Mode Locomotive and Bi-Level Coaches	
Speed/Headway	127 km/h/30 min	
Propulsion	25 kV ac, 60 Hz, Dual Diesel Gen Sets	

System	Morristown Line	
Operator	NJ Transit	
Country	USA	
Service	Commuter	
Rolling Stock	Dual-Mode Locomotive and Bi-Level Coaches	
Speed/Headway	161 km/h/2-20 min	
Propulsion	25 kV ac, 60 Hz, 12.5 kV ac, 60 Hz, 12 kV ac, 25 Hz, Dual Diesel Gen Sets	

System	TER Champagne-Ardenne, TER Poitou-Charentes Lines	
Operator	Société Nationale des Chemins de fer Français (SNCF)	
Country	France	
Service	Commuter	
Rolling Stock	Diesel/Electric Dual-Mode MU	
Speed/Headway	160 km/h/15 min	
Propulsion	1.5 kV dc and 25 kV ac, 50 Hz, Diesel	

APPENDIX 4A: DOCUMENT DEFINITIONS AND GLOSSARY OF TERMS

Term	**Definition**
A	
Autotransformer-Fed System	Electrification system consisting of substations feeding along-track feeder and catenary systems. The feeder-to-catenary voltage is stepped-down to catenary-to-rail voltage at autotransformer stations and switching stations located along the system by the means of autotransformers. Since the feeder-to-catenary voltage is typically two to three times the catenary-to-rail voltage, longer substation spacing can be achieved than for a direct-fed system not using autotransformers.
Autotransformer Station	Station with one or more autotransformers used for transforming the feeder-to-catenary voltage to catenary-to-rail voltage. Autotransformer stations contain circuit breakers or switchgear line ups and effectively parallel the feeder and catenary circuits. Feeder and catenary paralleling achieves better current sharing between the conductors, lowers the effective impedance between substations and trains, and results in lower voltage drop.
C	
Cab Car	A passenger carrying railcar that also has a control stand from which a trained operator can control the propulsion and braking of the consist.
Catenary System	Overhead power distribution system providing traction power to electric locomotives and EMU cars.
Catenary System Supporting Structures	Poles, towers, bridges, or other stationary structures used for supporting a catenary system including foundations, anchors, guys, braces, and similar reinforcing attachments.

Term	Definition
Center-Fed System	Electrification system in which substations feed sections of catenary at their center to minimize catenary voltage drop. In the event that the center-fed system operates at commercial frequency, the system substations would have one or two single-phase traction power transformers connected phase-to-phase to the three-phase power utility network.
Conceptual Design	A generalized plan describing design requirements and used as a guide to preliminary design.
Coach Car	A passenger carrying railcar without an operator’s control cab. A coach car is typically more simple than a cab car.
Contact Wire	Conductor in contact with pantograph used by locomotives and EMU cars to collect train power requirements. The conductor is suspended from messenger or auxiliary messenger by the means of hangers and contact wire clamps.
Cross-bonds	Connections between impedance bonds to reduce effective resistance of the traction power return system and to return the currents back to the substation.
D	
Direct-Fed System	Electrification system consisting of substations feeding a catenary system.
Distribution	Delivery of power from transmission system to end-use customers at voltages greater than 110 V and less than 69 kV.
E	
Electric Multiple-Unit	A railroad car equipped with its own electrical propulsion system, braking system, and auxiliary devices.
Electric Traction	A means for propulsion of railroad vehicles whereby power is provided by electrical energy transmitted from a remote source through a traction power distribution system.

Term	Definition
Electrification System	Facilities and structures required to provide electrical power to the trains.
F	
Final Design	A design stage during which final specifications, contract drawings, schedules, and cost estimates are prepared for a specific construction project.
Fluctuation of Power Demand	Because of frequent train acceleration and deceleration, and due to sudden changes in track geometry, train power demand has a highly fluctuating pattern.
Fundamental Frequency Component	The fundamental frequency is the first harmonic.
G	
Grounded Equipment	Equipment connected to the conducting mass of the earth via ground rods, grounding grid, or both, to ensure an immediate discharge of electrical potential without danger.
H	
Harmonics	Voltages and currents at frequencies other than the fundamental system frequency. Harmonics are caused by non-linear circuit components such as diodes and thyristors.
Harmonic Distortion	Voltage and current waveform distortion due to the harmonic currents generated by non-linear equipment, such as thyristor-controlled equipment on board the rolling stock or in substations.
Head End Power	An on-train electrical power generation and distribution system to support lighting, heating, air conditioning, and other passenger convenience loads. Power is typically 480 V ac, 60 Hz, three phase. In LHC service, power is typically generated by one large unit on the locomotive. In EMU and DMU service, power is typically generated by one small unit per car.

Term	Definition
I	
Impedance Bond	An iron-core coil of low resistance and relatively high reactance used to confine signalling current to its own track circuit and to provide a continuous path for the traction return current around insulated joints to substation.
Insulated Gate Bi-polar Transistor (IGBT)	A semiconductor device acting as an electronic switch capable of switching current on and off with greater efficiency and lower harmonics than thyristor.
M	
Messenger Wire	Upper wire in a catenary system from which the contact wire is suspended by means of hangers.
Milepost	An identifier for a given location along a railroad line. Mileposts may or may not be located exactly one mile apart and may not be sequentially numbered.
Multiple-Unit	A railroad car equipped with its own propulsion system, braking system, and auxiliary devices.
P	
Pantograph	Locomotive or EMU collector of traction power from overhead catenary system.
Pantograph Head	Uppermost part of the pantograph fitted with the current collector which slides on the bottom of contact wire.
Paralleling Station	Stations containing circuit breakers or switchgear line ups used for paralleling of traction power distribution system circuits. Catenary paralleling achieves better current sharing between the conductors, lowers the effective impedance between substations and trains, and results in lower voltage drop.
Phase Break System	System consisting of on-board and wayside equipment enabling locomotives or EMU cars automatic, or “on the fly”, negotiation of phase breaks by ramping propulsion power down on approach and ramping propulsion power up upon crossing the phase break.

Term	Definition
Phase-to-Phase Connection	Traction power transformers of ac electrified rail systems operating at commercial frequency are connected between two conductors of the three-conductor power utility system. Such phase-to-phase connection results in unequal phase loading and causes a certain level of unbalance in the utility system.
Power Demand Analysis and Load-Flow Study	A computer-aided study using specially written computer program to calculate the combined performance of the traction power supply and traction power distribution systems with operating trains. The study results include catenary system voltages, catenary system currents, substation power demand requirements and substation energy consumption.
Power Factor	Ratio of useful (real) power to total (apparent) power. Power factor is dependent on the rolling stock propulsion system design. With conventional propulsion systems using thyristor-controlled rectifiers and dc traction motors, the power factor is low at low trains speeds and improves as the speed increases. Using modern IGBT-based propulsion systems with ac motors, a power factor close to unity can be maintained throughout the speed range.
Preliminary Design	A design stage at which specifications and drawings clearly show all major design elements and define requirements for final design. Design calculations are substantially complete, cost estimates are detailed to an extent compatible with the level of design, and a preliminary construction sequence schedules are prepared.
Prime Mover	The core source of tractive power on a non-electrified railcar. For a diesel locomotive, the prime mover is traditionally a single large diesel engine. More modern designs, including DMUs, tend to use several medium sized diesel engines to create the traction power. A fuel cell can also be a prime mover.

Term	Definition
S	
Simple Catenary System	A system of messenger wire supporting a contact wire by the means of hangers. The system is suitable for medium speed to high-speed applications.
Single Contact Wire System	A system of single contact wire without messenger or auxiliary messenger wire. The system is suitable for tramway system, yard, and shop applications.
Station Dwell Time	That amount of time during which a train is stopped to open and close doors and receive and/or discharge passengers.
Substation	Traction power supply facility. Typical traction power substation includes power utility interface equipment; disconnect switches, circuit breakers, traction power transformers, switchgear, control equipment, and auxiliary system. Special equipment, such as harmonic filtering and power factor control equipment may be installed in substations, as required.
Switching Station	Stations containing circuit breakers or switchgear line up used for switching section of distribution system during substation outage conditions and for paralleling distribution system circuits.
T	
Thyristor	A semiconductor device acting as an electronic switch capable of switching current on and off.
Track Circuit	An electrical circuit formed by the running rails of the track. The purpose of the track circuit is to detect the presence of rolling stock on a given section of track when the track circuit is short-circuited by wheels and axles.
Traction Electrification System	Traction power supply, traction power distribution, and traction power return systems.
Traction Motor	An electric motor that directly drives one or more axles to propel a railcar along the tracks.

Term	Definition
Traction Power Distribution System	Overhead catenary system, overhead trolley system or contact rail system. Each may be accompanied by along track overhead or underground feeders.
Traction Power Return System	Rails, impedance bonds, cross-bonds, earth, and in the case of ac electrification, also static wire.
Traction Power Supply System	Traction power substations located at predetermined spacing along the route.
Transmission	Delivery of power at a voltage of 69 kV or higher from generating plants across interconnected high voltage facilities to points where the power enters distribution system.
U	
Unbalance	Voltage and current unbalance occurs when a three-phase system supplies a phase-to-phase load. The utility system voltage and current unbalance can be limited by alternating substation transformer primary connections to different phases of the utility power system, e.g., A-B, B-C, C-A, A-B, and so on.
V	
Voltage Flicker	Mathematically, the voltage flicker is defined as a change in voltage divided by the voltage, and is usually expressed in percent.
A	
A	Ampere
AAR	Association of American Railroads
A, B, C	Designation of Three-Phases of Utility Power System
ac	Alternating Current
AMT	Agence Métropolitaine de Transport
APS	Alimentation Par Sol
APTA	American Public Transit Association

Term	Definition
AREMA	American Railway Engineering and Maintenance-of-Way Association
AT	Autotransformer
ATF	Autotransformer-Fed
ATS	Autotransformer Station
AW0	Empty Car Operating Weight, Filled with Consumables
AW1	AW0 Weight Plus Full Seated Passenger Load And Train Crew
AW2	AW1 Weight Plus Standees at 4 per square meter of Available Floor Space (One Passenger per 2.7 sq. ft.). Structural Mean Fatigue Load, Propulsion and Dynamic Braking Performance Load.
AW3	AW1 Weight Plus Standees at 6 per square meter of Available Floor Space (One Passenger per 1.8 sq. ft.). Friction Braking Performance Load.
AW4	Either 105% of AW3 or AW1 Weight Plus Standees at 8 per square meter of Available Floor Space (One Passenger per 1.35 sq. ft.). Structural Design Load, not Contemplated For Revenue Operation.
B	
BE	Braking Effort
C	
C	Capacitance
CEPA	Canadian Environmental Protection Act
CFM	Cubic Feet per Minute
CFR	Code of Federal Regulations (United States)
cmil	Circular mil
CN	Canadian National Railway

Term	Definition
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CP	Canadian Pacific Railway
CSA	Canadian Standards Association
CSI	Cab Signal Interference
D	
dB	Decibel
dBµV/m/MHz	Decibel microvolt per meter per Megahertz, Unit for Measurement of Electric Field Strength
dc	Direct Current
DEMU	Diesel-Electric Multiple Unit
DF	Direct-Fed
DMU	Diesel Multiple Unit
DMMU	Dual-Mode Multiple Unit
E	
EC	Environment Canada
EIS	Environmental Impact Statement
eff	Efficiency
EMF	Electromagnetic Fields
EMI	Electromagnetic Interference or Electromagnetic Induction
EMR	Electromagnetic Radiation
EMU	Electric Multiple Unit
EPA	Environmental Protection Agency (United States)

Term	**Definition**
ESI	Electrostatic Interference or Electrostatic Induction
F	
FRA	Federal Railroad Administration (United States)
G	
GTO	Gate-Turn-Off
g/bhp-h	Grams/Brake Horsepower-Hour
H	
HC	Hydrocarbons
HDMU	Hybrid Diesel Multiple Unit
HEP	Head End Power
hp	Horsepower
HV	High Voltage
HVAC	Heating, Ventilation and Air Conditioning
Hz	Hertz
I	
IEEE	The Institute of Electrical and Electronics Engineers, Inc.
IGBT	Insulated Gate Bi-Polar Transistor
IPT	Inductive Power Transfer
J	
j	Complex Number Operator
K	
k	kilo, 10^3

Term	**Definition**
kA	Kiloampere
kcmil	Kilo Circular Mil
kV	Kilovolt
kVA	Kilovolt-Ampere
kVAr	Kilovolt-Ampere Reactive
kW	Kilowatt
kWh	Kilowatt-Hour
kWh/ckm	Kilowatt-Hour per Car-Kilometre
kWh/cm	Kilowatt-Hour per Car-Mile
L	
L	Inductance
LHC	Locomotive-Hauled Coaches
LNG	Liquefied Natural Gas
LV	Low Voltage
M	
M	Mega, 10^6
µ	micro, 10^{-6}
m	mili, 10^{-3}
Maglev	Magnetic Levitation
MHz	Megahertz
MP	Milepost
MPI	Motive Power Industries
MU	Multiple-Unit

Term	**Definition**
MV	Medium Voltage
MVA	Megavolt-Ampere
MVAr	Megavolt Ampere Reactive
MW	Megawatt
MWh	Megawatt-Hour
N	
N. C.	Normally Closed
NMHC	Non-Methane Hydrocarbons
N. O.	Normally Opened
NO_x	Nitrogen Oxides
O	
OCS	Overhead Contact System
ONAN	Oil Natural Air Natural Transformer Cooling Method
P	
PCE	Pantograph Clearance Envelope
PM	Particulate Matter
PM10	Particulate Matter Less than 10 Microns in Diameter
PTC	Positive Train Control
p. u.	Per Unit
R	
R	Resistance
RLC	Resistive-Inductive-Capacitive
ROW	Right-of-Way

Term	Definition
RR	Railroad
S	
SWS	Switching Station
T	
T	Tesla, Transformer
TE	Tractive Effort
TES	Traction Electrification System
TPS	Traction Power Substation, Traction Power Supply
V	
V	Volt
V ac	Volts, Alternating Current
V dc	Volts, Direct Current
X	
X	Reactance
XFRM	Transformer
Z	
Z	Impedance

NOTE: Use hereafter of the terms “we”, “our” or similar means “Delcan/Arup Joint Venture team.”