Feasibility of Alternative Power Supply Systems for the LUAS BXD

20 April 2012

1. INTRODUCTION

1.1 Purpose of the document

An Bord Pleanala as part of its deliberations to determine whether the LUAS City Broombridge (BXD) project should be granted consent to proceed, has employed SYSTRA in order to examine the feasibility of employing an alternative to the Overhead Contact System (OCS)[1].

An alternative traction system is envisaged for portions of the BXD line that would run in visually sensitive areas of the city centre of Dublin: from St. Stephen's Green to the north end of O'Connell Street (about 1.7 km). Alternatives have been examined in terms of technical feasibility. Additionally, we have provided elements regarding industrial availability and cost. The terms of reference drawn up by An Bord Pleanála are provided in Appendix 1.

The objective of this work is to provide the Board with further information, clarification and assistance on the subject - independent of the project developer - to facilitate its decision regarding employment of an alternative system to OCS on the LUAS BXD.

1.2 SYSTRA

SYSTRA is a world-leading engineering consultancy specialising in urban and rail transport. We work on all stages of transportation projects, from master plans and feasibility studies up to project execution and technical assistance for operations and maintenance. SYSTRA is involved in transport projects around the world, and boasts numerous references working with light rail systems.

SYSTRA has been involved in the implementation of alternative power sources for light rail systems in Dubai, Qatar, Rheims and Bordeaux.

1.3 Evaluation criteria

In this document we evaluate and compare the available alternative technologies, and we identify to what extent they would be applicable to the LUAS BXD requirements. The following points are explored.

System reliability

The reliability of each system is examined, taking into account the specific conditions of the BXD line, in particular shared running and climate conditions.

Suitability (and safety) for the proposed level of shared running

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[1] OCS can also be referred to as "overhead line" or "catenary". We use both the terms "OCS" and "catenary" throughout this document.

We will evaluate the suitability of each system for the proposed level of shared running with cars, buses, bicycles, etc.

Ability to cope with adverse weather conditions

Specific attention is paid to the ability of systems to deal with adverse weather conditions such as heavy rain and snow.

Energy considerations

Energy considerations are examined with regards to the technical characteristics of each possible solution.

Retrofitting on existing fleets of trams

We evaluate the technical possibility of retrofitting existing fleets of trams.

Capital and operational costs

We estimate capital and operational costs associated with the alternative system(s), as compared to OCS.

Industrial capacity

We examine industrial capacity for delivery of each possible solution. In addition, attention is paid to the constraints that the choice of each solution will impose for the future: dependence on a single provider or not, degree of deployment of the system in other LR networks...

Prior deployment

An Bord Pleanála has suggested that the main focus should be for a system that has already been proven on an existing in-service tramway.

1.4 Reference documents

As part of its consideration, SYSTRA has referenced a suite of selected documents, drawings and information including EIS documents and oral hearing submissions (see full list attached as Appendix 2 to this report) provided by An Bord Pleanála.

1.5 Visit on site

In addition to the above documents, SYSTRA representatives visited the offices and met with representatives of An Bord Pleanála, visited the LUAS depot at Sandyford (accompanied by a representative of An Bord Pleanála) and inspected the subject area of the report and existing LUAS running arrangements during a visit to Dublin on the 7th and 8th March 2012.

2. KEY FEATURES OF THE SECTION OF THE BXD LINE UNDER STUDY

In order to be able to assess the technical feasibility of an OCS-free power supply in the section of the BXD line between St. Stephen's Green and the north end of O'Connell Street, the key features of this section must be understood and analyzed, especially those which may have an impact on the potential technical solution.

The compliance of the various technical solutions to the requirements identified here is assessed in chapter 4 of the current document.

2.1 Gradient and distance between stations

Gradient and distance between stations are of particular concern for some OCS-free power supply systems.

In the case of the section under study, the maximum distance between two adjacent stations is about 480 m (between the Dawson and the Westmoreland stations), and the maximum gradient is less than 1.5% (between St. Stephen's Green and Dawson).

Both values are low enough that they will not pose particular problems for any of the OCS-free power supply solutions evaluated.

2.2 Running environment

Two key characteristics of the BXD running environment between St. Stephen's Green and the north end of O'Connell Street are the following:

- Along most of the section, the tramway shares its track bed with road traffic.
- Some of the alignment sections are narrow (from façade to façade); as such, bulky equipment will need to be accommodated in underground technical rooms.

These two features lead us to identify two requirements:

- Any equipment installed in the track bed must be able to withstand heavy road traffic, without adding potential hazard to road users.
- Space requirements for equipment to be installed along the line should be kept as low as possible.

Example of section with both heavy traffic and tight space for the new line

2.3 Impact of road traffic on tramway operation

The sharing of the track with road traffic along most of the section under scrutiny has an obvious potential impact on tramway operation, as trams risk to get stuck in traffic.

In addition to that, we learnt from RPA during our visit in Dublin that the level of priority given to trams at intersections is decided by the city council. Current policy is to provide limited priority to trams during peak hours in order to avoid blocking road traffic running perpendicular to the tram route.

These two factors mean that tram operation is likely to be impacted upon by traffic, such that trams will have to stop and start several times between two stations.

Therefore, the OCS-free power supply solution must be able to handle a situation in which trams may be forced to stop and start multiple times between any two stations, without risk that trams may be left stranded without power in the middle of dense traffic.

3. OVERVIEW OF THE CATENARY-FREE SYSTEMS AVAILABLE ON THE MARKET

The purpose of this section is to provide a high-level understanding of the various solutions currently proposed by tramway providers to ensure the supply of power without an overhead catenary.

These systems can be classified in two main different categories:

- Systems based on on-board energy storage
- Systems based on a continuous power supply from the track bed

For each of these concepts, various solutions are proposed by rolling stock manufacturers. The following paragraphs provide an overview of the main technical and operational features of the available systems.

3.1 Systems based on on-board energy storage

The three following solutions all rely on an on-board energy storage device which supplies the tram while it runs on sections without an overhead catenary.

3.1.1 CAF Super Capacitor system

3.1.1.1 Operating principle

The system proposed by CAF is based on a Rapid Charge Accumulator, branded ACR by CAF, which stores energy in super capacitors[2] to feed the tram.

There are two situations in which the ACR is charged:

- A partial charge when regenerative braking is used
- A complete charge when the tram is stopped at a station that precedes an OCS-free section

Stations are equipped with a short section of overhead rigid catenary, and the tram raises its pantograph when it stops in stations.

The power stored in the ACR is used in two situations:

- On the section fitted with OCS: during the acceleration phase to reduce the current peak drained from the OCS

[2] Super capacitors are particularly high-bandwidth energy storage devices. They can store large amounts of energy very quickly and can also release energy very quickly. A battery, on the other hand, takes more time to store energy and releases it more slowly.

- On the OCS-free section: to feed the train during its whole trip until the next station

3.1.1.2 Key features

The super capacitors (also called "super caps") used to store energy are the key component of ACR.

The benefit of using super caps is to make it possible to transfer a great deal of power in a short period of time. The super capacitors are charged during the dwell time which should last between 20 and 30 seconds, depending on the length and gradient between stations.

3.1.1.3 Life expectancy

The super capacitors are under high stress because they go through permanent charge-discharge cycles.

They require a temperature control system (dedicated air conditioning unit) in order to avoid operation under high temperature that would be detrimental to their life expectancy.

Manufacturers indicate that their life expectancy is estimated to be from 7 to 10 years, depending on the actual mission profile of the OCS-free sections.

3.1.1.4 Use of batteries

In order to cope with some particular configurations (exceptional distance between two stations, trams equipped with powerful air conditioning or heating), the super capacitors may be associated with batteries.

The batteries contain more energy than super capacitors, but the maximum current acceptable at a time is much lower, so the charge/discharge cycle takes place on a longer time scale. The batteries are charged when the trams run on sections equipped with OCS, and slowly discharged on the OCS-free sections.

3.1.2 Siemens Super Capacitor system Sitras MES / Sitras HES

3.1.2.1 Operating principles

The operating principles of the Siemens solution are identical to those described above for the CAF solution, i.e. the tram is powered by on-board energy storage device(s) when running on OCS-free sections.

3.1.2.2 Specificity of Sitras MES / Sitras HES

Siemens proposes in its standard solution a mix of batteries and super capacitors.

The batteries supply the constant background load, whereas the super capacitors supply the power peaks and store the energy produced by regenerative braking.

3.1.3 On-board battery by Alstom

3.1.3.1 Operating principles

The solution proposed by Alstom and Saft for the tramway in Nice, France, relies on on-board energy storage as well.

In this case, energy is stored in Nickel Metal Hydrure (Ni-MH) batteries when the tram runs on sections equipped with OCS, and this energy is used on OCS-free sections.

3.1.3.2 Key features

The distance that can be covered while running on an OCS-free section with this solution depends on the battery capacity and the length of the preceding OCS section where the batteries are charged beforehand.

The solution implemented in Nice covers two sections for a total length of about 900 m.

On these sections located in the historical centre of the city, the tram crosses pedestrian areas at low speed.

It has to be noted that operation on batteries reduces the achievable rate of acceleration, the maximum speed and possibly the commercial speed.

3.2 Systems based on a continuous power supply

3.2.1 APS by Alstom

3.2.1.1 Operating principles

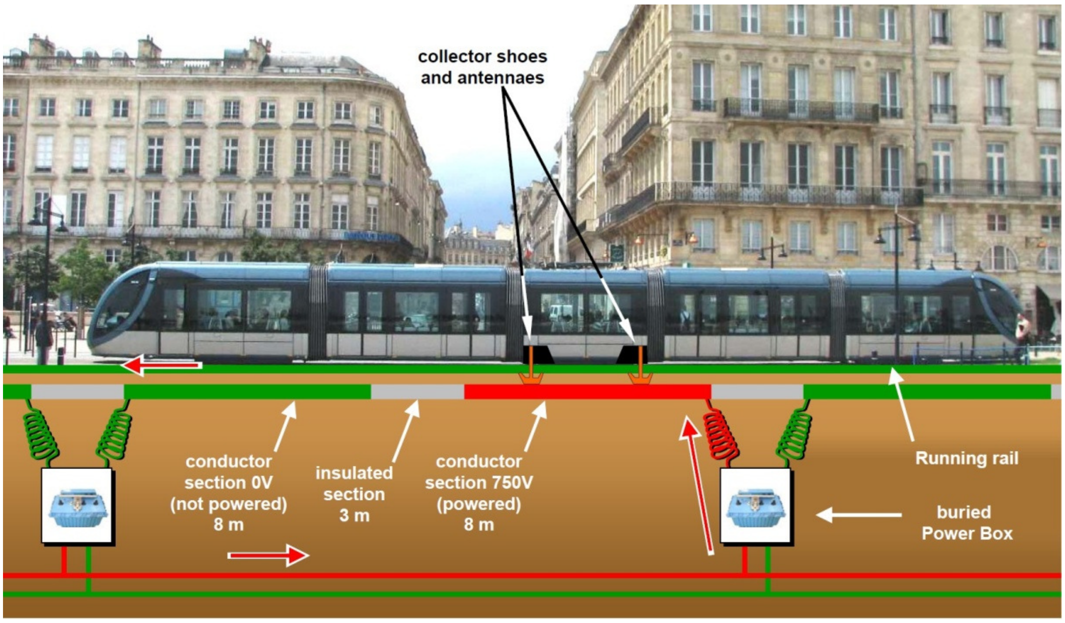
Alstom's APS system is based on traction power supplied to the vehicle by a power rail located between the running rails. The rolling stock uses a current collector shoe to obtain power via physical contact between the collector shoe and the track-embedded power supply rail.

The power supply rail is divided into 8 m long segments separated by 3 m long insulation segments.

The rail is fed with 750 V DC from "power boxes" embedded in the track.

Segments of power supply rail are only activated when they are completely covered by a tram vehicle.

This principle ensures a live rail is never accessible to pedestrians. Loops embedded in the track bed detect the presence of a vehicle via a coded radio signal emitted by the trams. This energy-distribution principle through segmentation is illustrated in the figure below.



When there is no vehicle over a given section, the rail is electrically connected to the return-current circuit (0 V) to avoid any unwanted powering up of the APS rail.

APS allows for catenary-free sections of any length, or even on the whole line.

Transitions between APS sections and catenary-equipped sections require that the tram come to a full stop. Practically, the transition is made within stations so that dwell time can be taken advantage of in order to minimise the impact of the transition time.

3.2.1.2 Specific features

The maximum operating speed on APS sections is 50 km/h, while an Alstom Citadis vehicle can operate at 70 km/h with overhead catenary.

In order to mitigate local failure of the system, the vehicles are equipped with batteries. These batteries enable trams to cross failed sections of up to 50 meters.

3.2.2 Tramwave by Ansaldo

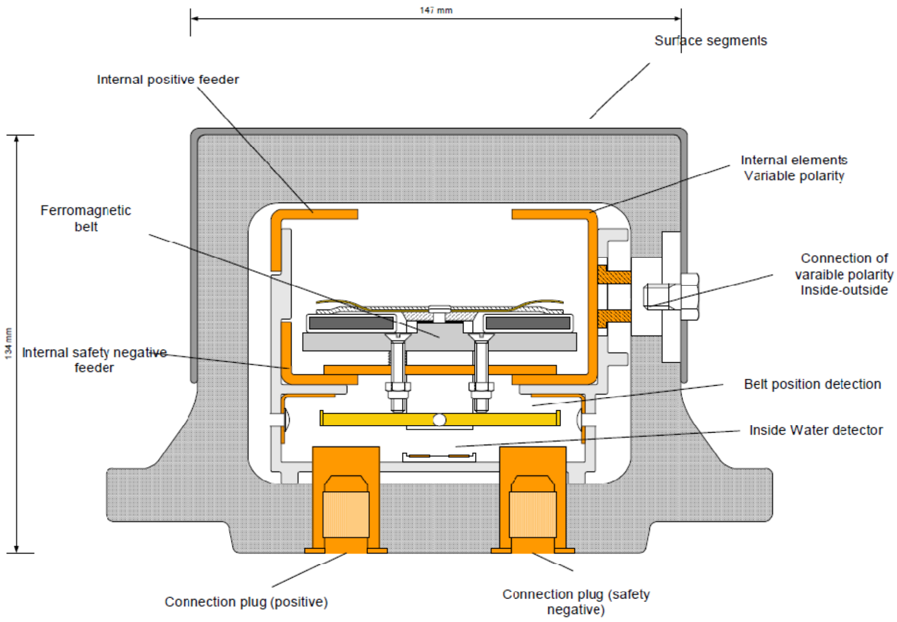
3.2.2.1 Operating principle of the Tramwave system

The Tramwave system provides trams with a continuous 750 DC power supply thanks to modules embedded in the track between the running rails.

The power is collected through a collector shoe. For safety reasons, only the modules located beneath the tramway collector shoe are powered up, so the hot part is never accessible to the pedestrians.

The powering up of the sections under the collector shoe is ensured by a relatively simple electromechanical solution: the collector shoe contains a powerful permanent magnet which lifts a metallic belt contained in the track-embedded module. When this belt is positioned in the upward position, contact is ensured between the 750 V DC feeder running along the Tramwave module ("internal positive feeder" on the upper left of the drawing below) and the "internal elements variable polarity" (on the upper right of the drawing) and the metallic surface segment on the top of the module. The part labelled as "internal elements variable polarity" is permanently connected to the "surface segment" (top of the drawing), so the "surface segment" is brought to 750 V DC potential.

The Module Section



Tramwave power rail cross section (© Ansaldo)

When the belt is positioned in the downward position, the part labelled "Internal elements variable polarity" is connected to the "Internal safety negative feeder" through the lower part of the belt and thus the metallic surface segment is connected to the negative feeder. The negative feeder is connected to the 0 V pole of the substation (as well as the running rail).

The safety of the Tramwave system is based on the fail safe principle: in the event the metallic belt remains stuck in the upward position after the collector shoe has left the zone, the lower part of the belt will fall due to its own weight and connect the metallic surface segment to the internal safety negative feeder. At this point, there is a short circuit between the positive and the negative feeder, leading the high speed circuit breaker to trip immediately.

The Tramwave modules are supervised from the operating control centre (OCC): the operator can monitor the electrical status of each section.

In addition, the presence of water inside the module is detected by a dedicated captor and the corresponding alarm sent to the OCC.

An on-board battery can carry the tram along a section in which the track bed modules malfunction.

On a recent bid, Ansaldo proposed on-board super capacitors to improve energetic efficiency. These super capacitors have a much lower capacity than those proposed on CAF and Siemens solution because they are not the primary source of power.

3.2.2.2 Operation of the collector shoe

The collector shoe contains the permanent magnets which lift the belt in the platform-embedded module.

For safety reasons, these magnets are made up of several magnets and are arranged in a way such that they repulse each other (S-N N-S S-N), but they are kept together by the structure of the collector shoe. In the event of a breakage of the collector shoe, the magnets will repulse each other. Each magnet taken individually is not strong enough to lift the belt, so a broken collector shoe cannot lead to a powered module by leaving loose magnets.

The collector shoe is maintained in the upward position by a spring. In order to lower it, a hydraulic system has to compensate the force of the spring.

The force of the spring is greater than the force of the magnet, so any failure of the hydraulic system would release the collector shoe to the upward position, thus setting the rail to 0 V.

3.2.3 Primove by Bombardier

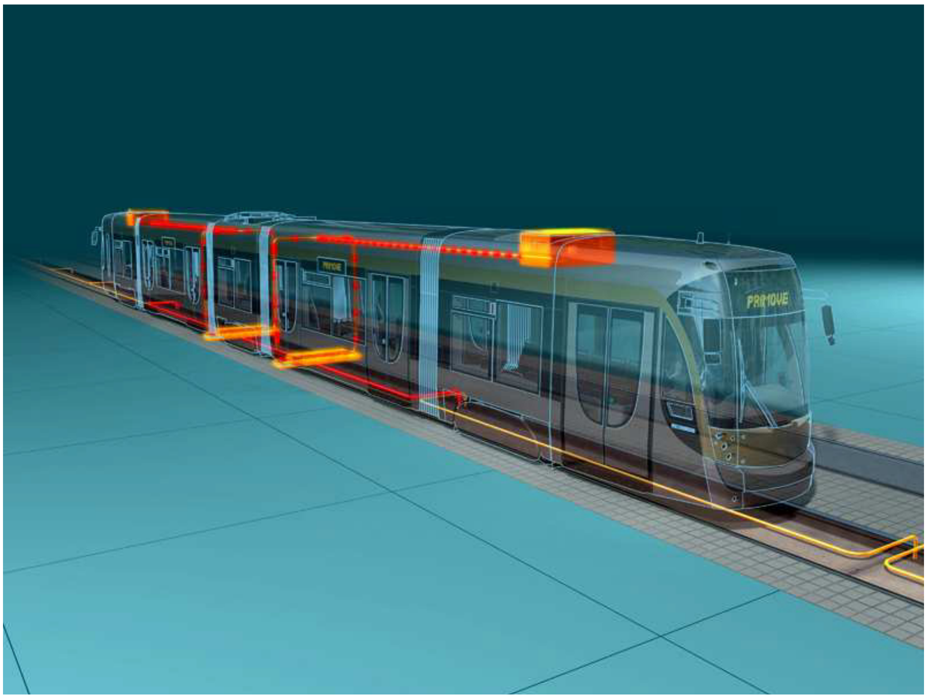
3.2.3.1 Operating principle

Bombardier's Primove solution provides continuous power to the tram thanks to induction loops embedded in the trackbed and coils installed under the frame of the tram.

Power is transmitted, without any physical contact, through the electromagnetic flux produced by the embedded loop.

The coils embedded in the track bed are powered on only when the tram is running over them to avoid unnecessary electromagnetic emission.

The tram is detected via the coded radio signals that it emits and which are received by the trackside equipment.



Bombardier's Primove system (© Bombardier Transportation)

3.2.3.2 *Specific features*

Although Bombardier has not revealed extensive technical details on the Primove solution, some specific technical features are known.

The amount of power the induction loops are able to transfer is less than the power transmitted with an OCS, so the Primove solution cannot deliver the power peak required to maintain constant acceleration of the tram above 20 km/h. In order to solve that problem, the tram is equipped with super capacitors which provide the required boost needed during the second part of the acceleration phase.

These super capacitors, presented as an improvement of the basic Primove solution, are in fact a mandatory feature.

The loops embedded in the track bed must be covered by a plate made of a material which does not contain any metal because metal is conductive and would shield the electromagnetic flux.

4. ANALYSIS OF FITNESS FOR PURPOSE

In this chapter we evaluate the fitness for purpose of each of the technological solutions described above. The evaluation criteria are defined in function of both the constraints linked to the BXD extension and the brief provided by An Bord Pleanála (principally reliability) and reproduced in Appendix 1.

The analysis begins, for each technology, with the constraint and criteria of the highest importance to proceed further with criteria of lesser importance. In the event one of the technologies does not comply with one of the mandatory requirements, making it unsuitable for the BXD line, the analysis is not be pursued further with the criteria of lesser importance.

4.1 Suitability of CAF super capacitor system

4.1.1 Fitness for shared running

4.1.1.1 Mechanical aspects

This solution based on super capacitors does not require the installation of any specific equipment in the track bed along the catenary-free section.

In other words, the track bed will be identical to the track bed implemented along the section fitted with catenary, so the super cap solution is compatible with shared running from a mechanical point of view.

4.1.1.2 Running in congested traffic

Shared running along the busiest streets of the city centre means a potential risk of having a tram stuck in traffic, requiring several stops and starts between two stations.

The super cap solution is based on the principle that the tram carries its own on-board power supply. This supply is sized to be able to cover the longest distance between stations and includes a margin to be able to face an unscheduled stop between two stations.

In congested traffic, the maximum number of unscheduled stops between stations cannot be predicted; neither can their duration (when the tram is stopped, ventilation, lighting, and other ancillary equipment keep on draining down the supply).

It seems unlikely that the on-board supply could be sized such as to ***guarantee*** that there would be no risk of trams running out of power (and thus getting stuck) between stations.

Moreover, sizing the super cap supply such that it could handle some predefined scenario of congested traffic would lead to a significant increase in both its size and weight.

Since a train which has run out of power has no possibility of moving without being rescued by another tram or vehicle, such an event would have a significant impact both on tram operation and road traffic.

4.1.2 Conclusion

The combination of shared running (and thus the likelihood of having to handle congestion) and a super cap on-board power supply system leads to an unquantifiable risk of having trains stranded in the middle of the city centre.

This major drawback leads us to conclude that, based on currently available information, the super cap solution is not suitable for the BXD line.

4.2 Suitability of Siemens super capacitor and battery system

From a functional and technical point of view, the solution proposed by Siemens is very similar to the CAF solution, so the arguments discussed above will be quickly summarised below.

4.2.1 Fitness for shared running

4.2.1.1 Mechanical aspects

The solution based on a super capacitor does not require the installation of any specific equipment in the track bed along the catenary-free section, so the track bed will be identical to the one implemented on sections fitted with OCS.

4.2.1.2 Running in congested traffic

The energy stored in the super capacitors and batteries is limited, and – given the shared running that is planned for this section of the BXD line – it cannot be sized to cope with all possible scenarios in terms of unscheduled stops and starts.

4.2.2 Conclusion

The combination of shared running (and thus the likelihood of having to handle congestion) and a super cap on-board power supply system leads to an unquantifiable risk of having trains stranded in the middle of the city centre.

This major drawback leads us to conclude that, based on currently available information, the super cap / battery solution is not suitable for the BXD line.

4.3 Suitability of Alstom battery system

4.3.1 Fitness of shared running

4.3.1.1 Mechanical aspects

The solution based on batteries does not require the installation of any specific equipment in the track bed along the catenary free section.

As already mentioned for the super capacitor based solution, the track bed will be identical to the track bed implemented along the section fitted with catenary, so the super cap solution is compatible with shared running from a mechanical point of view.

4.3.1.2 Running in congested traffic

The battery solution has two major drawbacks when it has to run in congested traffic:

- The quantity of available energy is limited, and therefore so is the number of unscheduled stops and starts that the tram can withstand between two stations.
- The maximum current which can be delivered by the batteries is lower than the current delivered by the OCS or super caps; thus the rate of acceleration that the tram can achieve is limited.

4.3.2 Level of deployment

Alstom has deployed its battery solution only in Nice.

4.3.3 Conclusion

The Alstom solution based on batteries is not designed for shared running, and would present a high risk of having trams stranded between two stations after multiple unscheduled stops.

Thus, at the time of this writing, we consider that the Alstom battery solution is not suitable for the BXD application.

4.4 Suitability of Bombardier Primove System

4.4.1 Fitness of shared running

4.4.1.1 Mechanical aspects

The Primove system requires the installation of embedded electrical loops between the running rails.

These loops shall be covered by a 40 mm layer of nonconductive material such as resin, asphalt base course or non-reinforced concrete.

Bombardier has not provided information regarding the long-term resistance of this arrangement under road traffic.

Moreover, Bombardier does propose that the Primove track-embedded equipment not be implanted in intersections.

These aspects lead us to consider that there are currently no satisfactory technical solutions available to meet the requirement related to heavy road traffic running over the Primove embedded loop.

4.4.1.2 Running in congested traffic

The Primove system provides a continuous power supply, which makes it possible for trams to stop and start as many times as necessary, as long as they stop over induction loops.

According to Bombardier, at low speeds (below 18 km/h), the acceleration performance supplied by Primove is identical to that provided by an OCS; thus congested traffic and repeated stops and starts are not a concern.

4.4.2 Level of deployment

At this time, the Primove system is not implemented in commercial service.

In addition to the Bautzen test track installed in Bombardier premises, an 800 m long pilot section has been installed and tested in Augsburg, Germany.

This pilot section did not carry any passenger and was segregated from road traffic and protected by fences.

4.4.3 Conclusion

The Primove System is able to face congested traffic by withstanding frequent stops and starts, but, for the moment, in its current design, it does not appear to be able to withstand the load associated with shared running, as foreseen on the BXD line.

Moreover, although the Primove System has been proposed by Bombardier in some of its bids, it cannot be considered as a proven in use system.

For these reasons, we consider that, at the time of this writing, the Primove solution is not suitable for the BXD line.

4.5 Suitability of Alstom APS system

4.5.1 Fitness for shared running

4.5.1.1 Mechanical aspects

The APS solution requires the installation of a power rail between the running rails, embedded in the track bed.

In the BXD context, the power rail must be able to withstand continuous road traffic for years, without damage.

On French projects, APS is mainly installed on segregated running sections, except for road intersections where road traffic crosses the rail.

As part of its certification process, the first version of the APS system went through an endurance test to simulate the effect of urban traffic (over 700,000 cycles with 7-ton pressure wheels).

View of the endurance test plant (© Innorail)

Despite this test and certification process, the first version of APS installed in Bordeaux in 2003 suffered damage at road intersections. It is worth mentioning that in this previous design, the APS rail was directly embedded in asphalt.

Following this experience, Alstom revised its design to embed the APS rail in a concrete plinth to increase its resistance to road traffic. This improvement ended up being satisfactory in Bordeaux.

The latest design of APS (APS 2) now includes a reinforced power rail, still embedded in a concrete plinth. Alstom claims that it can withstand 13.5 ton axle loads.

For Dubai, Alstom's design is foreseen to withstand road crossings with more than 100 buses a day.

4.5.1.2 Running in congested traffic

The APS power rail continuously provides the same amount of power as an overhead catenary, so running in congested traffic is not a concern for a tram fed by APS.

4.5.2 Resistance to weather conditions

4.5.2.1 Flooding

The APS power rail, like any power rail, cannot operate when it is covered by water, because such a situation would lead to current leak when the rail is powered up, and thus tripping of the circuit breaker protecting the traction power circuit.

Flooding of the track bed is an exceptional situation which should be prevented by an appropriate drainage arrangement embedded in the track.

Regarding the protection of the embedded power box, the latest APS design is based on an IP 68 rated box, which means, according to standard EN 60529, it can remain immersed in 1 metre of water for 15 days.

4.5.2.2 Snow and ice

On December 28th, 2006, relatively light snow falls in Bordeaux lead to the interruption of tram service on sections equipped with APS.

The layer of snow between the collector shoe and the power rail prevented proper contact and thus the feeding of the tram.

In the morning of December 29th, 2006, the snow melted during the day and then froze during the night, forming a layer of ice on the power rail, making it even more difficult for the maintenance teams to clean it. On January 24, 2007, operation was interrupted again for the same reason.

The tram operator in Bordeaux did not have specific tools or equipment for removing snow or ice from the power rail, because snow is usually not a concern with Bordeaux's relatively mild climate.

Since this episode, new equipment and practices have emerged to solve the issues related to snowfall and cleaning of the power rail in general:

- A railroad truck specifically designed for cleaning the groove of the running rail and the APS power rail is now available on the market
- Alstom now proposes the installation of heavy duty brushes in front of the collector shoe
- Specific maintenance procedures have been implemented in Rheims (in operation since April 2011), where snow fall is more significant than in Bordeaux. These include:

- Use of glycol to prevent icing of the APS rail
- Continuous operation of a tram when snow falls are foreseen to prevent the snow from sticking to the APS rail
- Ban of applying salt on the streets at a distance of less than 50 cm from the track bed, as salt water leads to current leaks and triggers the tripping of the circuit breaker

Although these measures improve the availability of APS, it is to be noted they are not an absolute mitigation of the risk related to snowfall. Recently, on February 5th 2012, in Bordeaux and February 8th 2012, in Rheims, operation was interrupted for several hours because of snow falls that prevented APS from functioning correctly.

4.5.3 Impact of APS technology on electric distribution scheme

The arrangement of the traction sub-stations is identical for APS and for regular OCS.

4.5.4 Feasibility of fleet retrofitting

APS is currently installed in other cities on Citadis 402 and Citadis 302 trams. The current LUAS fleet is made up of Citadis 401 (Red Line) and Citadis 402 (Green Line).

The retrofit of existing trams to install the on-board APS equipment would require the following modifications:

- Installation of collector shoes
- Installation of roof-mounted batteries
- Installation of antennae under the frame
- Modification of the traction circuit

The Red Line depot has been used in the past to retrofit Citadis 301 trams to become Citadis 401 trams. The necessary equipment is thus available so that the retrofit activity may be carried out in the Red Line depot.

4.5.5 Safety considerations

The electrical safety of the APS system has been demonstrated and reaches Safety Integrity Level 4.[3]

[3] The allocation of safety integrity levels is specified in standard EN 50126. The safety integrity level varies from 0 to 4, where 4 is the highest level of safety integrity.

The French authority for the safety of guided transportation issues each year a report dealing with tramway safety. Since the opening in Bordeaux of the first tramway line equipped with APS in 2003, the impact of the APS power rail on pedestrian or cyclist safety has never been identified as a concern.

4.5.6 Energy efficiency

For safety reasons, regenerative breaking is not possible when running with the APS system, thus energy efficiency is degraded by 15% to 20%.

The cost associated with this increase in the power consumption is difficult to estimate accurately at this stage. In order to carry out this estimate, many assumptions must be made; each of them introduces potential uncertainty in the result.

The main assumptions concern power consumption with regenerative braking and the cost of electricity.

The following table identifies the parameters we took into account for this rough estimate.[4]

cost per MW.h (€)	60
power consumption without regenerative braking (kW.h/tram.km)	13.5
power consumption with regenerative braking (kW.h/tram.km)	11.3
power consumption due to absence of regenerative braking (kW.h/tram.km)	2.3
duration of peak hour (h)	4
headway during peak hours (min)	5
duration of off-peak hour (h)	16
headway during off-peak hours (min)	10
length of the APS section (km)	1.7
number of runs per day	288
distance run per day (km)	478
number of km run per year (tram.km)	174,499
power consumption by year due to absence of regenerative braking (kW.h)	392,623
additionnal cost due to absence of regenerative braking (€)	23,557

The annual additional cost due to the absence of regenerative braking remains relatively low according the calculation above. This is mainly due to the moderate length of the section to be potentially equipped with catenary free system.

[4] The cost of a MW.h is of course highly variable. The energy consumption per tram.km is the result of a simulation of the running of a 43-metre Citadis 402 tram carried out by Systra on a recent project.

Alstom is currently working on improving energy efficiency by introducing on-board super caps. This solution is more efficient than reinjection of power in the OCS (the classical approach to energy regeneration), because it does not require the presence of another tram on the same section to use this power. On the other hand, the retrofit of existing trams to install on-board super caps appears to involve heavy works which would likely require reinforcement of the tram carshell.

4.5.7 Level of deployment

The APS system is currently deployed in revenue service in the following cities:

- Bordeaux (since 2003)
- Angers (since 2010)
- Rheims (since 2011)

It should be noted that on the French projects, the trams run most of the time on segregated rights-of-way, except at road intersections.

In addition to the projects mentioned above, Alstom has been awarded contracts to implement APS in the following cities:

- Orléans (2006)
- Dubai (2008)
- Brasilia (2009)
- Tours (2010)

4.5.8 Conclusion

The APS solution appears to properly address the constraints specific to the BXD line, by offering:

- Continuous feeding, to cope with unscheduled stops between stations
- A design which takes into account the mechanical stress caused by road traffic
- A high level of safety
- The possibility of retrofitting the existing fleet of Citadis 402

It also meets the requirement for a proven system.

The implementation of the APS system for the BXD line is not prevented by any major technical impossibility and appears feasible to us.

The risk associated with snow fall and ice can be mitigated by proper maintenance and operation procedures, but cannot be completely suppressed as recent experience in Rheims has shown: operation has been interrupted by ice and snow falls several times during the winter of 2011/2012.

4.6 Suitability of Ansaldo Tramwave system

4.6.1 Fitness for shared running

4.6.1.1 Mechanical aspects

The power rail embedded in the track between the running rails will have to withstand road traffic on the shared running zones.

The Tramwave power rail (originally branded Stream by Ansaldo) has been designed to withstand road traffic and shared running, as it was originally planned to be implemented for buses running in lanes shared with other traffic

View of a Stream power rail on via Mizzoni, Trieste (© L. Fascia)

In Trieste, the embedded power rail has been installed in 2000 to feed electric buses. Although these buses are no longer in service, the power rail has been left in the road bed ever since.

According to Ansaldo, this power rail does not show traces of fatigue or cracks.

4.6.1.2 Running in congested traffic

The Tramwave power rail continuously provides the same amount of power as an overhead catenary, so running in congested traffic is not a concern for a tram fed by Tramwave.

4.6.2 Impact on electric distribution scheme

The arrangement of the traction sub-stations is identical for Tramwave and for regular OCS.

4.6.3 Resistance to weather conditions

4.6.3.1 Flooding

As already explained for the APS power rail, the Tramwave power rail cannot operate when it is covered by water, because such a situation would lead to current leaks when the rail is powered up, and thus tripping of the circuit breaker protecting the traction power circuit.

Flooding of the trackbed is an exceptional situation which should be prevented by an appropriate drainage arrangement embedded in the track.

The Tramwave equipment embedded in the track bed is designed and tested to be watertight.

4.6.3.2 Snow and ice

Snow and ice stuck on the power rail prevent proper contact with the collector shoe and thus may disrupt operation.

The Tramwave system has not yet faced this type of problem because of the mild climate of the location where it has been implemented, but it is likely it would suffer the same kind of operational issue as APS has when exposed to snow and ice.

The solutions adopted for the APS (brush mounted on the tram and specific maintenance vehicle) could likely be adopted for the Tramwave solution.

4.6.4 Feasibility of fleet retrofitting

Tramwave is currently installed on Sirio Tram produced by Ansaldo, and a retrofit of tramways manufactured by another company has never been carried out before.

When contacted about this topic, Ansaldo's representative confirmed the potential interest of the company in such an operation and did not expect any technical impossibility.

He made it clear that in any case the possibility of a retrofit must be confirmed by thorough study of the mechanical and electrical arrangement of the Citadis 402.

The retrofit of existing trams to install the on-board Tramwave equipment would require the following modifications:

- Installation of collector shoe
- Installation of roof super capacitors
- Modification of the on-board traction circuit

The weight of the super capacitor is expected to be lower than the weight of the battery required for the APS solution, so the modification of the Citadis 402 appears technically feasible.

4.6.5 Safety considerations

The Tramwave solution has been recently granted Safety Integrity Level 4 certification by RINA[5] for the 3 km pilot line in Napoli. The previous system (Stream) has been assessed by TUV[6] in 1997.

The risk of pedestrians tripping is mitigated by the flatness of the power rail which is perfectly embedded.

The risk of cyclist sliding on the bare metal surface is similar to the risk of sliding on the top of the running rail, without the risk of having a bicycle wheel trapped in the rail groove.

4.6.6 Energy efficiency

The Tramwave system allows regenerative braking and current injection back to the power rail, in the same way as it is done on sections fitted with OCS.

The overall energy efficiency of the Tramwave system is even in theory slightly higher than the OCS because the copper cables included in the power rail box provide better conductivity than an OCS, although the benefit in terms of energy consumption is minor.

4.6.7 Level of deployment

The Tramwave system has not been deployed as part of a commercial project yet.

The references claimed by Ansaldo so far are the following:

- Implementation of the Stream system in Trieste from 2000 to 2002
- 400 m of test track installed at Ansaldo premises in Napoli
- Pilot line in Napoli on semi segregated running since April 2011

4.6.8 Conclusion

The Tramwave solution appears to properly address some of the constraints specific to the BXD line, by offering:

- Continuous feeding, to cope with unscheduled stops between stations
- A design which takes into account the mechanical stress caused by road traffic

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[5] RINA is an Italian company, member of the IACS (International Association of Classification Societies).
[6] TUV is an Italian testing, inspection and certification entity.

- A high level of safety
- The possibility of retrofitting the existing fleet of Citadis 402

On the other hand, this solution does not properly satisfy two criteria identified by An Board Pleanála:

- There is no guarantee of its performance in circumstances of significant ice and snow fall
- It cannot be considered as fully proven since it has not been implemented as part of a commercial in-service project

The implementation of the Tramwave system for the BXD line is not prevented by any major technical impossibility and appears feasible to us.

The risk associated with snow fall and ice could be mitigated by proper operation and maintenance procedure but cannot be completely suppressed.

In addition, the technical risk associated with a non-proven system cannot be quantified despite the thorough testing performed by Ansaldo so far.

4.7 Conclusion

The paragraphs above analysed the suitability for BXD of the various catenary-free systems available on the market.

The catenary-free solutions which rely on on-board energy storage cannot guarantee the tram will be able to start after many stops and starts in heavy traffic.

For this reason, we consider that the solutions proposed by CAF (Super Capacitor), Siemens (Super Capacitor associated with batteries) and Alstom (Batteries) are not suitable for BXD.

The three remaining solutions under scrutiny have in common their reliance on a continuous supply of power which makes it possible for the tram to stop and start as many times as needed, thus avoiding the risk that trams may find themselves unable to start when stopped in the street due to traffic.

Amongst these three solutions, we have a major concern regarding the mechanical strength of the cover of the embedded loop in the current design proposed by Bombardier for its Primove system.

Moreover, given the constraints associated with electromagnetic flows, it appears doubtful a solution will be easily found to make Primove suitable for shared running and heavy traffic.

For this reason, we consider that, at its current stage of development, Primove is not suitable for BXD.

Alstom's APS system meets most of the requirements identified for BXD; its design addresses operation in congested traffic, mechanical resistance to heavy traffic, high level of safety.

The retrofit of the Citadis 402 fleet currently run on the Green Line is technically feasible.

The requirement for a proven system is also met, with APS deployed in Bordeaux, Rheims, Angers and Tours.

The vulnerability of the embedded power to heavy snow or ice cannot be denied, but operation procedure and technical features have been developed to mitigate this weakness.

The Tramwave solution proposed by Ansaldo, despite long and thorough testing and the implementation of a pilot line in Naples, cannot yet be considered as a proven system.

On the other hand, the design proposed by Ansaldo meets most of the operational and technical requirement identified for BXD: its design addresses operation in congested traffic, mechanical resistance to heavy traffic, high level of safety.

Based on the available information, the retrofit of the Citadis 402 to implement the on-board Tramwave component appears technically feasible to us.

In conclusion, the market does not yet offer a technical solution that would be perfectly adapted to all of the constraints of the LUAS BXD.

Nonetheless, we consider that two viable solutions, Alstom's APS and Ansaldo's Tramwave, meeting the main requirements are available on the market.

Beyond technical feasibility, contractual feasibility must also be determined.

5. INDUSTRIAL CAPACITY

5.1 Situation of Alstom

From a technical point of view, the capacity of Alstom to retrofit Citadis 402 trams is obvious and should not be a concern.

APS has not been developed to be sold as a standalone product, however, but rather to provide Alstom a competitive advantage when selling trams. We do not have information that would indicate whether Alstom would be interested in carrying out a retrofit.

The French authority in charge of ensuring fair competition among bidders in public tenders has obliged Alstom to publish a thorough description of the interface between the track-side APS equipment and the on-board APS equipment, in order to make it possible for other manufacturers to propose trams which are compatible with the APS infrastructure.

Following this publication, CAF was able to propose APS-compatible trams as part of its bid for Bordeaux's fleet extension in 2011.

5.2 Situation of Ansaldo

Although we suspect that it would be technically possible to retrofit Citadis 402 trams with on-board Tramwave equipment, this assumption would need to be confirmed by Ansaldo.

Once again, we do not have information regarding the interest that Ansaldo may or may not ultimately have for carrying out such a retrofit operation.

Tramwave is also a proprietary solution, covered by patents, and despite the simplicity of the on-board equipment, another tram manufacturer would not be allowed to provide Tramwave-compatible vehicles, except if this has been agreed upon beforehand with Ansaldo at the time the BXD section is installed.

5.3 Conclusion

The retrofit of Citadis 402 trams for use with a catenary-free system appears feasible to us from a technical perspective. We do not know, however, whether the manufacturers would be interested in carrying out such a retrofit.

The only approach to mitigate the long-term risk of monopoly for the procurement of new trams is to reach a contractual arrangement to this effect with the initial manufacturer.

Such an agreement would oblige the manufacturer to supply any future tram suppliers with the components which ensure compatibility with the catenary-free infrastructure or to provide a detailed description of the interface between the trackside and the on-board equipment so that other manufacturers may design trams that are compatible with the proprietary infrastructure.

6. EXTENT OF THE RETROFIT

6.1 Operational requirement and context

The LUAS BXD project includes an interconnection with the existing Red Line, whereas currently no connection exists between the Green and Red Lines. This interconnection is planned to be implemented when the Green Line extension crosses the Red Line in O'Connell Street and in Marlborough Street.

The existing tram fleet of the Green Line will be used on the extended Green Line.

In addition, RPA wants the Red Line fleet to be able to run on the Green Line and vice versa.

6.2 Technical consequences

The interconnection of the two lines has deep consequences because transitions between a section fitted with OCS and an OCS-free section is usually made at station.

In other words, it means that the connection between the Red Line and the Green Line on O'Connell Street near the GPO would require retrofitting the Red Line up to the next station before the connection, to install OCS free power infrastructure in addition to the existing OCS.

The existing Green Line fleet (Citadis 402) must be retrofitted to be able to run on the extension fitted with OCS-free power supply.

The current requirement for Red Line trams (Citadis 401) to be able to run on the Green Line would necessitate the retrofit of the entre Red Line fleet, as well

6.3 Conclusion

The retrofitting of the existing Green Line fleet is a necessity and cannot be avoided. Despite its cost, the retrofit of the Citadis 402 appears feasible.

The requirement for interoperability between the Red and the Green Line fleets has a major impact on rolling stock (retrofit of 40 Citadis 401) and installation of a few hundred meters of OCS-free power supply infrastructure on the Red Line.

The technical feasibility of the retrofit of the Citadis 401 is not guaranteed at this stage, and would likely require deeper works than the retrofit of Citadis 402.

The benefit of the interoperability of the Red and Green Line is not obvious to us. During our visit, we learnt that both depots have equivalent capabilities, so there is reduced need to transfer trams from one line to the other on a regular basis.

Given the huge expected costs and reduced benefits, we do not consider it is worth implementing the full interoperability of the two lines.

A cheaper alternative to consider is to maintain the interconnection of the tracks between the two lines, without implementing the continuity of the power supply. In the event the operator wishes to transfer a Red Line tram to the Green Line depot, this tram could be towed when running over the OCS free section.

7. INVESTMENT AND OPERATING COSTS

Following the technical analyses carried out above, the cost aspects will be addressed for the two solutions which have been considered as potentially suitable for BXD line: Alstom's APS and Ansaldo Tramwave.

The information is available to SYSTRA based on past and recent involvement in bids and cooperation with operation companies.

Whilst such information cannot be site specific and has to a certain extent been generalised due to commercial sensitivities they are however based on SYSTRA's recent practical and considerable knowledge and experience in the field.

Regarding the operation scheme, *Luas Broombridge St. Stephen's Green to Broombridge (Line BXD) Environmental Impact Statement (Book 1)* states on page 109 §7.4 that the duration of the trip is expected to be 24 minutes, and the foreseen headway is 3 minutes.

From these operation parameters, we deduct the minimal theoretical tram fleet should be 16 trams (8 trams running in each direction at each given time). Since some additional trams are usually needed to provide operational flexibility, we assume 18 new trams will be purchased.

7.1 Investment costs

The investment costs provided below are based on recent contracts or bids. These costs have to be considered cautiously, keeping in mind the high variability of the prices proposed by the tramway providers from one project to another.

We have observed that, depending on the level of competition and the desire of a provider to get a first reference for a new solution, the price may vary by +/- 25%.

7.1.1 Alstom APS

The APS system is made of on-board equipment and track side equipment.

To this date, on-board equipment has always been delivered on new trams.

The cost of this on-board equipment *delivered on a new tram* is estimated to be around 300,000 €, in addition to the basic cost of the tram.

A retrofit of in-service trams to install on-board APS equipment has never been performed, so we lack references.

Nonetheless, given the specificity of the operation, we can estimate the retrofit of a Citadis 402 will add an extra 100,000 € approximately to the price of the on-board APS equipment.

In the case of a Citadis 401, more extensive modifications may be needed; we cannot estimate the cost of such an operation.

The cost of the APS track side equipment is estimated to be 1,850,000 €/km.

The overall additional cost for APS implementation is estimated to be about 19,000,000 €.

For price breakdown, refer below to 7.2.3

7.1.2 Ansaldo Tramwave

Ansaldo's Tramwave system in not yet installed anywhere. On the other hand, Ansaldo has participated in some tenders but no price was officially communicated.

Despite this lack of information, we estimate that capital costs of the Tramwave on-board and track-side equipment should be of the same order of magnitude as the costs related to Alstom's APS system.

Given the specificity of a retrofit operation carried out by Ansaldo on the Citadis 402 trams, involving significant redesign activities, we expect that the cost of retrofit will be higher than that of the equivalent retrofit made by Alstom with its APS system.

Nevertheless, we do not know the amount Ansaldo could ask for this retrofit. In particular, manufacturers may be willing to offer a competitive price if the contract is considered to be important.

7.2 Operation and maintenance costs

7.2.1 Alstom APS

The trackside APS equipment requires some maintenance effort, especially the power boxes embedded in the track bed.

The maintenance effort for the fixed APS equipment is estimated to cost 75,000 €/year/km.

In addition, the current design of APS is not compatible with regenerative braking, so the power consumption will be increased by 15% to 20% on the section equipped with APS.

As the calculation carried out in §4.5.6 showed, the annual cost associated with the relative reduction in energy efficiency is roughly 25,000 €.

7.2.2 Ansaldo Tramwave

The Ansaldo Tramwave is not yet in revenue service, so there is no information available regarding the operation and maintenance cost.

Ansaldo Tramwave allows regenerative breaking, so energy consumption will not be increased as compared to OCS.

7.2.3 Cost Summary

The following table summarizes the additional investment and operating and maintenance (O&M) cost associated with the implementation of APS (as compared to an OCS-only system).

This table is based on the estimated unit costs provided above and the hypothesis that only BXD line will be equipped with APS (not retrofit of the red line fleet).

According to these hypotheses:

- 1.66 km of tracks shall be equipped with APS
- 26 trams shall be retrofitted
- 18 new trams shall be purchased (estimate based on 24 minutes trip and 3 minutes headway)

Investment cost	€
APS infrastructure	3,071,000
Cost of fitting APS equipment on new Trams	5,400,000
Cost of retrofit	10,400,000
Total	18,871,000
Yearly O&M costs	€
Additional power supply cost	25,000
APS maintenance cost	124,500
Total	149,500

APPENDIX 1 - TERMS OF REFERENCE FOR REPORT ON ALTERNATIVE POWER SUPPLY SYSTEMS

Objective

Examine the feasibility, primarily from a technical and economic perspective, of employing an alternative to the Overhead Cable System (OCS) proposed in the draft Railway Order, in the visually sensitive areas of Dublin city centre.

Considerations

The sensitive area for the purpose of the study is from St. Stephen's Green to the north end of O'Connell Street, including Dawson Street, College Green, O'Connell Bridge and the GPO. The south-bound leg of the one-way system (Parnell Street to College Street) is not considered sensitive.

The author should become familiar with the existing LUAS systems as already serve Dublin Region, and how the BXD line will integrate with same, and also longer term transport plans for the region.

The study should focus only on systems that are developed and commercially available. Systems employed in cities such as Bordeaux, but also more recently in Nice, Reims, Orleans and Angers should be included for consideration (and any other relevant locations).

Up to date information on such systems should be gathered, including consultation with system providers and operators, where possible. Up to date cost estimates should be used.

The report should identify the most relevant technology/ technologies applicable to the LUAS BXD requirements, and consider the potential for use on LUAS BXD, including:

- System Reliability
- Suitability for the proposed level of shared running (with cars buses etc.) and implications for reliability/ traffic management
- Ability to cope with adverse weather conditions, e.g. snow/ice or heavy rainfall (and possible implications for the roads authority or the environment if new response procedures are required)
- Safety implications for cyclists in a shared running environment
- Energy considerations
- Necessity and extent of retrofitting on existing fleets of trams
- Likely cost differential (both capital and operational) that an alternative to OCS would mean for the overall project.

APPENDIX 2 - REFERENCE DOCUMENTS

Title of the document
Greater Dublin Area - Draft Transport Strategy 2011-2030 - 2030 vision
Inspector report for case 29N.NA0004 by B. Wyse
Luas Broombridge Oral Hearing - Proof of evidence - Overhead Conductor System (OCS) by Paolo Carbone
Luas Broombridge Oral Hearing - Proof of evidence - Construction and Operational Traffic Management by Eoin Gillard
Dublin Chamber of Commerce - Submission to An Bord Pleanala - RPA Railway Order for Luas Broombridge (dated 13th August 2010)
Letter: Construction operation and maintenance of a light railway system from St Stephen's Green to Broombridge, Dublin, by Alan McArdle (dated 3rd February, 2012)
Luas Broombridge Oral Hearing - Dublin City Council - Opening Address by Gerard Meehan B.L. (dated 20 May 2011)
Luas Broombridge (Line BXD): presentation for Enginers Ireland (dated 21 February 2012)
Development of Luas & the Next Phase of implementation - Luas Broombridge: presentation by Michael Sheedy and Jim Kilfeather (dated 21 February 2012)
Line BXD Power Description by RPA, rev 01 (dated 6 march 2012)
Kylemore Ess Equipment Layout reference by Ansaldo CZ-AXX-600-EM-0078, revision Z04 dated 30/06/04
Line BXD -Structures- Substation- Broadstone reference BXD-SS-29-E-0, no revision, no date
O'Connell BXD, Broadstone Single Line Diagram, reference A-BXD-0000-PS-0002, revision A01, dated 10/05/2011
Overhead Contact System Traction Power System Distribution Single Line Diagram reference A-BXD-000-PS-003, revision A01, dated 13/05/2011
St Stephens Green Ess Equipment Layout by Ansaldo, reference CZ-XBX-600EM-0122 revision Z03, dated 20/05/04
St Stephens Green Substation Single Line Diagram, reference A-BXD-0000-PS-0001 Revision A01 dated 10/05/11
Broombridge Line and Depot Single Line Diagram, reference A-BXD-0000-PS-0004 revision A01, dated 07/05/11
Substation Relocation Works Equipment & Cable Routing Layout, reference T-MN-7178B-PS-01001 revision T01 dated February 2010
Railway Works, Line BXD - Alignment Details - Cathal Brugha St. Dominick LWR reference BXD-R0-29-C-D, dated June 2010
Railway Works, Line BXD - Alignment Details - Eden Quay to Cathal Brugha St. reference BXD-R0-29-B-C, dated June 2010
Railway Works, Line BXD - Alignment Details - Grafton Street to Eden Quay reference

Title of the document
BXD-R0-29-A-B dated June 2010
Railway Works, Line BXD - Alignment Details - St Stephen's Green West to Grafton Street, reference BXD-R0-29-0-A dated June 2010
Draft Typical Cross Section - Double Track Embedded Shared by RPA (not dated, no author)
Draft Typical Cross Section - Double Track segregated Option 1 by RPA (not dated, no author)
Luas Broombridge (Line BXD): Environmental Impact Statement (book 1 of 5)
Luas Broombridge (Line BXD): Environmental Impact Statement (book 2 of 5) Area 29 St Stephen's Green to former Broadstone railway cutting
Luas Broombridge (Line BXD): Environmental Impact Statement (book 4 of 5): Maps
An Board Pleanala: Functions of the Board (extract of a web site)
Planning & Policy: Zoning Objectives dated April 2010
Overall map of Dublin showing the Heavy Commuter Line, the Existing Tram Line and the proposed BXD (drawn by hand, no reference)
Defining Dublin's Historic Core: Realising the Potential of the City Centre and its Georgian Squares for Citizens, Business and Visitors by Geraldine Walsh, Stephen Coyne and Graham Hickey (2010)
Tram System in Bordeaux: Report on the tram System and underground Power Supply for Dublin City Business Association by Brendan Finn, dated 7th December 2007
A spatial Vision for Dublin (April 2009) by Hendrik W van der Kamp