Luxembourg tram system:

Catenary-free hybrid technology to reduce visual damage to the historical cityscape

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Abstract

Luxembourg is expanding public transportation networks as a measure against road congestion and air pollution associated with economic and population growth. As part of this, in 2017, a hybrid tram system with catenary-free technology has been reintroduced, which can be integrated into the historic district registered as a World Heritage Site. The hybrid system with on-board batteries allows the tram to operate 3.6km of catenary-free section by charging the batteries during operation on catenary sections and boarding at stations on catenary-free section. Similar technologies researched and developed by Japanese companies and institutions are still in test stage. Possible reasons for the delay for social implementation could be lower awareness on landscape protection, existence of numerous utility poles and overhead power lines, and pursuit of excessive quality for the hybrid system. Flexible and practical adoption of novel technologies is required to make a better society.

Key words

public transport, catenary-free tram, hybrid tram system, cityscape protection, smart city

1. Introduction

Luxembourg (officially Grand Duchy of Luxembourg) is the wealthiest among the OECD countries with GDP per capita of US$ 120,980 in 2019 (OECD, n.d.). The steel industry was the origin of the country's wealth and from 1860s until 1960s, the industry had been an important driving force of the economic growth of Luxembourg. Since 1960s, the government has started economic structural reform, with strong emphasis on finance sector. Currently, the Luxembourg is one of the largest financial centers, allowing the country to become the wealthiest country in the world. This economic success has aroused several economic and social problems. Among them, traffic congestion and accompanying air pollution are two of the largest ones.

Due to the economic success, the population has been growing rapidly. The housing construction has been outpaced by this population growth (OECD, 2020). This mismatch also leads to the higher housing prices. For example, owner-occupied housing price index has risen from 82.69 in 2010 to 121.91 in 2019 (Eurostat, 2020a). That is the increase of nearly 50% in ten years.

This rapid rising housing price has led to housing development in rural areas and the traffic congestions in and around the city center at peak times. The traffic congestion is one of the main reasons for the high CO_2 emissions per capita (14.8 tonnes in 2017) (OECD, n.d.).

Another issue facing the country is the size of the frontier workers (Eurofound, 2018), who live in the surrounding three countries (Germany, France and Belgium) and commute to workplaces in Luxembourg every day. The number of the frontier workers is more than 200,000 (Toussaint, 2019). Their main mode of commuting is private car, exacerbating traffic problems in the center.

In 2018, Luxembourg had the highest number of passenger cars per inhabitant in the EU, with 676 cars per 1000 inhabitants (Eurostat, 2020b). Approximately 60 % of these cars run on diesel fuel (Eurostat, 2020c).

A diesel engine uses, in principle, less fuel and produces less carbon dioxide than a petrol engine with the same power output. However, the engines produce higher levels of particulates which can penetrate deep into the lungs, causing irritation and potentially triggering asthma attacks (Leggett, 2018).

To cope with these road congestion and air pollution associated with economic and population growth, the successive governments of Luxembourg have been trying to promote modal shift and encouraging people to use public transport instead of private cars. One landmark policy implementation is the reintroduction in Luxembourg City of a tram system which was removed in 1960s. The reintroduction route passes through the historic district which was registered as a World Heritage Site in 1994. After the registration, the district has been gradually restricting vehicles, and landscape maintenance and pedestrian priority have been promoted. Therefore, when reintroducing the tram, the government put considerable time and effort to create a system that will protect and harmonize with the cityscape.

This paper reports on the hybrid tram with onboard battery to allow operation without catenary (overhead power line), which is one of the features of the reintroduced tram. At the same time, we will consider possible reasons for similar systems researched and developed in Japan not being implemented into the society.

2. Luxembourg Tram system

2.1 Manufacturer

The government of Luxembourg has adopted a tram system developed by CAF (Construcciones y Auxiliar de Ferocarriles), a Spanish company founded in 1892. The company's share of the tram market in Europe between 2013 and 2017 was about 3 % (Figure 1).

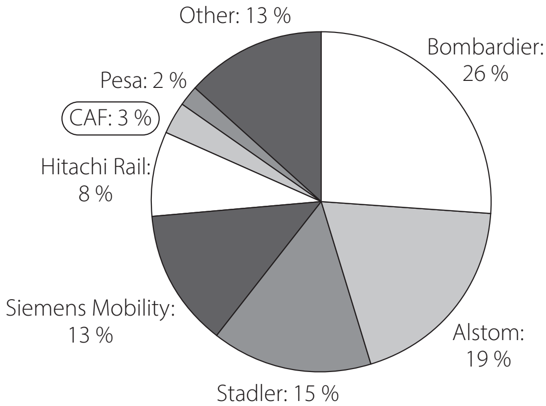

Figure 1: Market share of the rolling stock manufacturers in Europe between 2013 and 2017
Source: Statista (2020).

Despite its relatively small size compared to major companies like Bombardier or Alstom, CAF has delivered its tram systems to 39 cities worldwide. The main line of the tram is Urbos tram, which was introduced into the market in 2009 (CAF, 2019).

Hence, the company is a global company generating revenues from all over the world. Specifically, their revenue structure in terms of regions is as follows: 23 % in Britain, 12 % in the Netherlands, 12 % in Mexico, 12 % in Spain and 41 % in other countries.

As for train sales structure, Regional and commuter trains made up 56 % of train sales, while metros accounted for 24 %, trams and LRVs 13 %, high-speed trains 3 % and others 4 % (Burroughs, 2019).

2.2 Tram systems

The company manufactures various types of tram systems. One of the best-selling lines is Urbos series, with Urbos 3 being the latest trams which have been widely introduced in over 39 cities.

Urbos 3 series have two versions: Urbos 100 and Urbos 70. The former has 100 % low floor design while the latter has 70 % low floor design. For the car configurations, both versions are provided with 3-car, 5-car, 7-car sets. Urbos 100 has additional 9-car sets (CAF, n.d.-a).

2.3 Technology

The technology used in Urbos is called Greentech, which was originally developed by Trainelec, a group company of CAF and later merged with other group companies to become CAF Power & Automation (CAF, n.d.-b; Briginshaw, 2012). The Greentech technology is composed of Evodrive and Freedrive (CAF, n.d.-c).

2.3.1 Evodrive

Evodrive is an on-board system to maximize energy efficiency in rail transportation (CAF, n.d.-d). The system is based on ultracapacitors to recover the kinetic energy released on braking. This energy can be reused, improving the vehicle's energy efficiency. It has been specially designed for trams whose braking energy is difficult to return to the catenary.

The Evodrive energy storage systems are composed of a DC/DC converter, which manages the energy charge and discharge of the super capacitor, and an energy storage module, which stores the energy into the batteries and super capacitors. The super capacitors help improve the energy efficiency of the train by recovering the energy released during braking. Evodrive is especially suited for trams, where the recovery with a conventional traction system is low, since the energy cannot normally be returned to the overhead power wire. This permits approximately 35 % energy savings compared with a traditional system (Railway Technology, n.d.).

2.3.2 Freedrive

Freedrive is an on-board energy storage system that allows catenary-free operation (CAF, n.d.-e). This system is based on lithium-ion supercapacitors and batteries and has all the technological benefits of Evodrive. It is modular and easy to integrate in new and existing vehicles regardless of their manufacturers (Figures 2 and 3).

The advantages of the system are as follows:

- Allowing vehicles to operate in catenary-free sections.
- Over 10 km of autonomy with batteries in catenary-free mode.
- Ultra-fast charging process, less than 20 seconds are required
- Reduction in the level of visual intrusion and pollution in urban environments by totally or partially eliminating the catenary.
- Reduction in investment in infrastructure and its subsequent maintenance.

By adopting these advanced technologies and lightweight, eco-friendly materials, Urbos meets the most demanding eco-design requirements; reducing energy consumption, re-

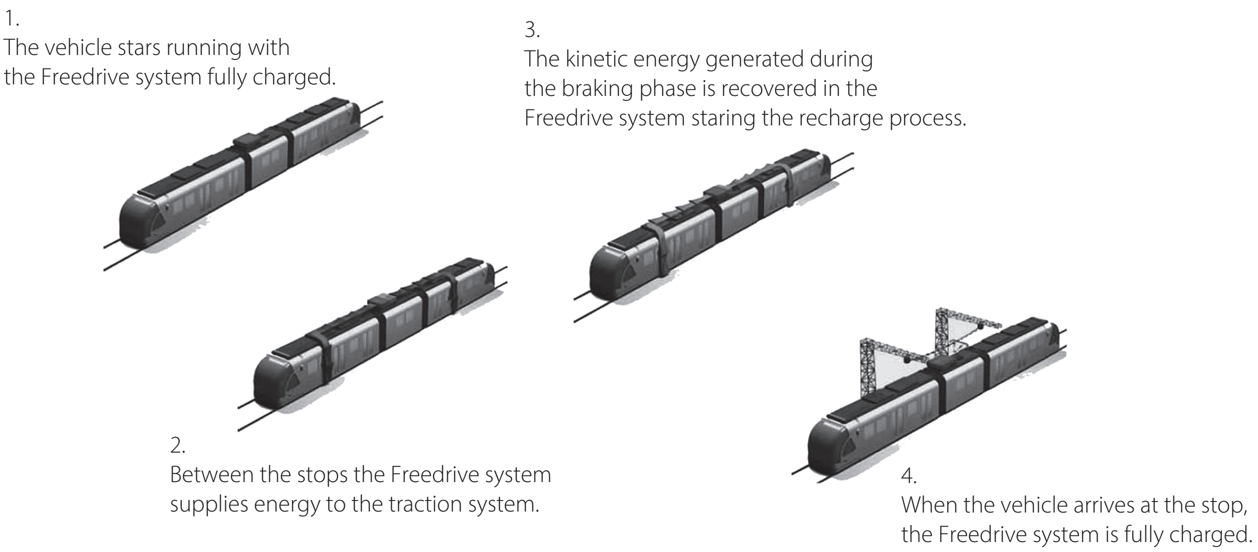

Figure 2: Schematics of Greentech
Source: CAF (n.d.-e).

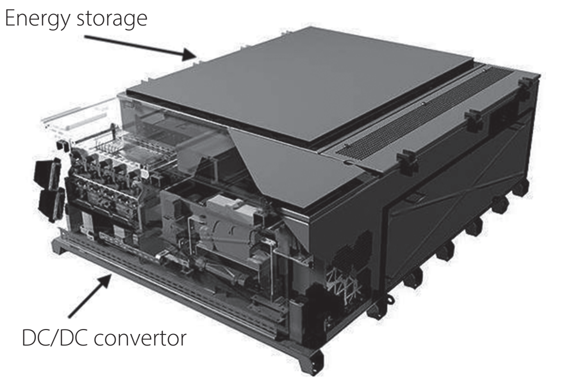

Figure 3: On-board system
Source: Railway Technology (n.d.).

ducing the visual impact and being integrated into the urban architecture (CAF, n.d.-f).

2.4 Luxembourg Tram route

Currently, the tram operates between a station at the north end of the historic district (Stäreplaz–Étoile) and a station near the exhibition facility (Luxexpo) at the east end of the business district. The construction for extending the line to the central station in the historic district has been completed in November, 2020 and the operation to the central station starts in December. The goal is to connect the airport (Findel Aeroport) with a station in the newly developed business district in the south (Cloche d'Or). Total length under the current plan is 16 km, with 3.6 km between Red Bridge and Central Station being catenary free section (Figures 4 to 6) (Shimauchi, 2020).

3. Situation in Japan

3.1 Tram system

In Japan, as in other countries, the abolition of trams has progressed since the 1960s due to the traffic motorization. As of 2013, 20 companies in 17 cities operate trams with total operating kilometers of 206 km. This is a significant reduction from those in 1932 when trams were operated in 65 cities by 82 companies with the total kilometers approximating 1,500 km (Ministry of Land, Infrastructure, Transport and Tourism, n.d.).

The resurgence of the interest in trams have been observed worldwide for various reasons, such as such as reducing the environmental burden, harmonizing with the cityscape, and creating a comfortable city to live in (Utsunomiya, 2009). However, in Japan, catenary-free system has not been introduced to the tram system, although the technology has already been developed by several companies (Yamauchi, 2013).

3.2 Similar technology

Since 1999, Railway Technical Research Institute has been conducting research and development on hybrid power-powered trains that use overhead wires and on-board battery storage system to optimize energy consumption through the effective use of regenerative energy. The first test vehicle was completed in 2003. The second test vehicle called Hi-tram was completed and tested from 2007 to 2009. Specifications of the battery module used for the tram is shown in Table 1.

The tests were conducted on tram track under severe winter condition in Sapporo and on railway track of JR Shikoku Yosan Line and Kotoku Line. The former tests proved

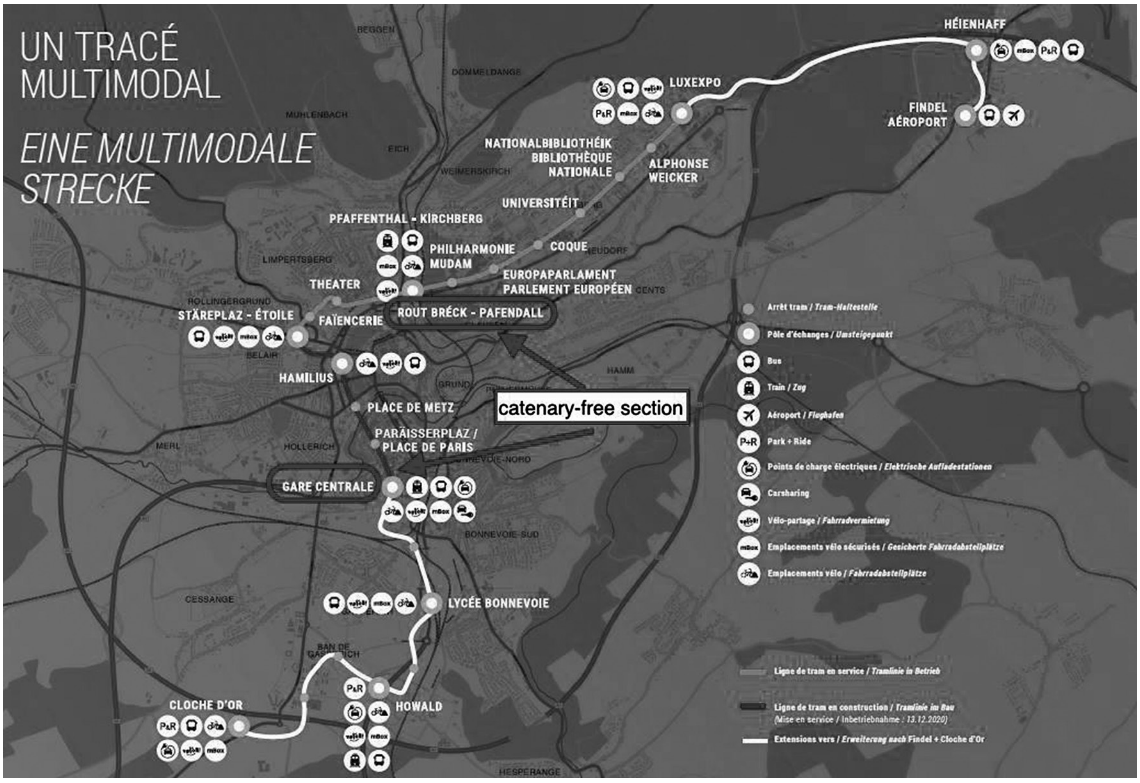

Figure 4: Tram line map
Source: Luxtram (n.d.).

Figure 5: Operation with catenary
Source: Luxtram (n.d.).

Figure 6: Catenary-free operation
Source: Hennebert (2020).

Table 1: Characteristics of Hi-tram battery module

Description	Specification
Module configuration	21S4P
Nominal capacity	1,000 Ah
Nominal energy stored	72,000 Wh
Nominal voltage	605 V
Weight	1,600 kg
Maximum charge/discharge	1,000 A

Source: Railway Technical Research Institute (n.d.).

the robustness of the system against the harsh condition and the latter proved a high-speed operation with up to 80 km per hour. The results have shown the feasibility of mutual direct operation between conventional railways (intercity railways) and urban railways (trams) and realization of low-floor tram trains, both of which could be key components for revitalizing local public transportation in the future (Ogasa, 2009; 2011; Railway Technical Research Institute, n.d.).

Kawasaki Heavy Industry developed an on-board battery driven LRV in 2007. 30 nickel-metal hydride battery cells are used to compose a battery module (Table 2). Trial runs were conducted in Sapporo in 2018, where the vehicle successfully operated more than 30 km without recharging. For opera-

Table 2: Characteristics of Kawasaki battery module

Description	Specification
Number of cells	30 cells
Rated capacity	150 Ah
Energy capacity	5,400 Wh
Nominal voltage	36 V
Weight	240 kg
Cooling system	forced-air
Maximum output (0.1 s)	161 kW
Maximum output (10 s)	96
Energy density	51 Wh/L

Source: Kawasaki Heavy Industry (2008).

Table 3: Characteristics of Toshiba battery module

Description	Specification
Module configuration	12S2P
Nominal capacity	40 Ah
Nominal energy stored	1,104 Wh
Nominal voltage	27.6 V
Weight	14 kg
Cooling system	forced-air
Nominal continuous charge/discharge current at 25 C	160 A
Peak charge/discharge current at 25 C	300 A

Source: Hirota (2016).

tional settings in busy city centers, the company envisions the distance would be shortened to 10 km due to traffic congestion and hence plans to establish charging facilities approximately at 10 km interval (Kawasaki Heavy Industry, 2008).

In 2015, Toshiba conducted an experiment of catenary-free tram operation by using a specially developed battery. Table 3 shows the characteristics of the battery module. The battery uses lithium titanium oxide to realize a long life of over 20,000 charge/discharge cycles, rapid charging, high input/output performance, excellent low-temperature performance, and maintaining a high level of safety. 20 modules and accompanying control unit were tested in 2015 on a tram line in Kagoshima. The result was satisfactory, with battery-driven operation exceeding 10 km (Hirota, 2016). However, since then the company decided to focus on railway and subway instead of tram for applying the battery system. Current applications in railways include a subway emergency running system, a hybrid propulsion system for a luxurious travel train for JR West, and European regional trains.

Hitachi Rail S.p.A, a group company of Hitachi, has developed an on-board energy storage system (OBESS). The system is composed of an energy storage unit, a battery thermal management system, a DC/DC converter and control unit, and a cooling control system. The system and battery modules are connected to optimize energy flow and allow trams to operate on catenary-free sections. Figure 7 shows energy flow management diagram (Romano et al., 2020).

One battery module uses 32 lithium-ion battery cells (8 series / hour parallel configuration). 20 battery modules are connected for the actual system. Main characteristics of the module are listed in Table 4.

These systems have performed at the level equivalent of or exceeding those of Urbos series. However, the technologies and systems developed by Japanese companies and institutions are still in long trial stage and not yet implemented into the market.

4. Conclusion

The concept of landscape pollution/protection is well established in Europe, which can be symbolized by the adop-

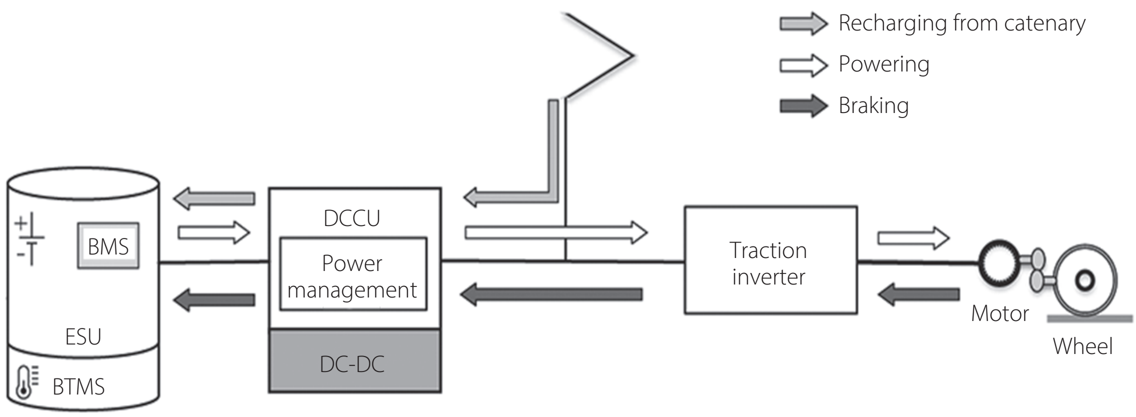

Figure 7: Energy flows managed by DCCU
Source: Romano et al. (2020).

Table 4: Characteristics of Hitachi battery module

Description	Specification
Module configuration	8S4P
Nominal capacity	92 Ah
Nominal energy stored	1,692.8 Wh
Nominal voltage	36.8 V
Weight	22 kg
Cooling system	liquid
Nominal continuous charge/discharge current at 25 C	400 A
Peak charge/discharge current at 25 C	800 A
Energy density	202 Wh/L

Source: Romano et al. (2020).

tion of the European Landscape Convention in 2000 (Hamin, 2002; Jones, 2007; Olwig, 2007; Jones and Stenseke, 2011; Sonkoly, 2017). Overhead trams are often operated in cities where trams have been used consistently since the 19th century or have been introduced shortly after World War II. However, in cities where trams are being reintroduced, catenary-free trams are preferred solutions to avoid landscape pollution (Yamauchi, 2013; Utsunomiya, 2009).

In Japan as well, research and development on catenary-free technology has been progressed parallel to European railcar companies. However, there are no catenary-free trams in Japan. One of the reasons for this delay in the introduction to the service could be lower awareness of landscape protection compared to European society (Toki, 2016). Another reason could be lower demand for catenary-free system since cities in Japan have excessive amount of utility poles overhead power lines, which does not require for considering the feasibility of the new system (Ministry of Land, Infrastructure, Transport and Tourism, n.d.).

In addition, the excessive quality of Japanese companies may be one of the causes (Kawahara et al., 2016; Shiokawa and Ishii, 2017). In the case of Luxembourg, the introduction of catenary-free technology is limited to historical districts registered as World Heritage Sites and to bridges where it is difficult to lay overhead lines. In other areas, it is powered by the overhead line, and the operation in the non-overhead line area is realized by quick charging at the stop station. Flexible adoption of such hybrid operations could avoid excessive quality of new technologies, leading to lower prices and faster social implementation.

Although there is currently no hybrid tram system in Japan, there are several railway lines which operate with hybrid or battery driven trains. These lines are Karasuyama line (20.4 km) in Tochigi, Oga line (26.4 km) in Akita, Kashii line (25.4 km) and a part of Wakamatsu line (10.8 km) in Fukuoka. Originally, these lines were non-electrified line and diesel trains were in operation. These developments suggest when a demand arises, a hybrid tram system will be introduced smoothly using technologies developed by Japanese companies. The introduction of the system requires a certain amount of investment. Currently, tram operators are struggling hard to attain and retain passengers. Financial supports by governments for tram operators are necessary to facilitate the introduction of the hybrid system. Catenary-free tram system will improve cityscape, with potentials for attracting more users, including tourists and residents. Also it will contribute to a greener and more sustainable society by promoting modal shift from private cars to public transport, a policy aim shared by many countries especially in those in Europe including Luxembourg.

References

Briginshaw, D. (2012). CAF merges specialist subsidiaries into one company. *International Railway Journal*. https://www.railjournal.com/financial/caf-merges-specialist-subsidiaries-into-one-company/ (Accessed on November 20, 2020).

Burroughs, D. (2019). CAF reports strong revenue growth. *International Railway Journal*. https://www.railjournal.com/financial/caf-reports-strong-revenue-growth/ (Accessed on November 20, 2020).

CAF (2019). Annual report 2018.

CAF (n.d.-a). There is an urbos for each type of the city. http://www.caf.net/en/productos-servicios/familia/urbos/descripcion/gama_urbos.php (Accessed November 10, 2020).

CAF (n.d.-b). Railway systems CAF power & automation. https://www.cafpower.com/en/company/caf-power-automation (Accessed November 10, 2020).

CAF (n.d.-c). Greentech, CAF's solution to the catenary-free tram. http://www.caf.net/en/ecocaf/nuevas-soluciones/tranvia-greentech.php (Accessed November 10, 2020).

CAF (n.d.-d). Evodrive: Energy efficiency-railway systems CAF power & automation. https://www.cafpower.com/en/systems/energy-storage-system-greentech/evodrive-energy-efficiency (Accessed November 10, 2020).

CAF (n.d.-e). Freedrive: Catenary-free running-railway systems CAF power & automation. https://www.cafpower.com/en/systems/energy-storage-system-greentech/freedrive-catenary-free-running (Accessed November 10, 2020).

CAF (n.d.-f). Sustainability: A clear commitment to energy efficiency. http://www.caf.net/en/productos-servicios/familia/urbos/descripcion/sostenibilidad.php (Accessed November 10, 2020).

Eurofound (2018). Frontier worker. Eurofound. https://www.eurofound.europa.eu/observatories/eurwork/industrial-relations-dictionary/frontier-worker (Accessed on September

2, 2020).
Eurostat (2020a). Owner-occupied housing price index (2015=100)—Annual data. https://ec.europa.eu/eurostat/databrowser/view/prc_hpi_ooa/default/table?lang=en (Accessed on September 2, 2020).
Eurostat (2020b). Passenger cars in the EU—Statistics explained. https://ec.europa.eu/eurostat/statistics-explained/index.php/Passenger_cars_in_the_EU#Highest_number_of_passenger_cars_per_inhabitant_in_Luxembourg (Accessed on August 29, 2020).
Eurostat. (2020c). Passenger cars, by type of motor energy—Eurostat. https://ec.europa.eu/eurostat/web/products-datasets/-/road_eqs_carpda (Accessed on September 9, 2020).
Hamin, E. M. (2002). Western European landscape protection western European approaches to landscape protection: A review of the literature. *Journal of Planning Literature*, Vol. 16, No. 3, 339-358.
Hirota, K. (2016). Battery energy storage systems for rolling stock using SciB lithium-ion battery. *Toshiba Review*, Vol. 71, No. 4, 16-19.
Jones, M. (2007). The European landscape convention and the question of public participation. *Landscape Research*, Vol. 32, No. 5, 613-633.
Jones, M. and Stenseke, M. (2011). The issue of public participation in the European landscape convention. In M. Jones and M. Stenseke, *The European landscape convention: Challenges of participation (*eds), 1-23. Landscape Series. Dordrecht: Springer Netherlands.
Kawahara, F, Hashimoto, Y., and Ouchi, N. (2016). A study on overshooting product performance: A quantitative analysis focusing on mirrorless interchangeable-lens cameras. *Abstracts of Annual Conference of Japan Society for Management Information 2016*, 61-64.
Kawasaki Heavy Industry (2008). Development of train system using gigacell. Kawasaki Heavy Industry Environment and Society Report 2008.
Leggett, T. (2018). Air pollution: Are diesel cars always the biggest health hazard?" BBC News. https://www.bbc.com/news/science-environment-42666596 (Accessed on September 2, 2020).
Hennebert, J. M. (2020). Le tram n'incarnera pas, seul, la mobilité de demain. Luxembourger Wort, November 24, 2020, https://www.wort.lu/fr/luxembourg/le-tram-n-incarnera-pas-seul-la-mobilite-de-demain-5fbbdcb2de135b9236441f66 (Accessed on December 15, 2020).
Luxtram (n.d.). Un tracé multimodal. http://www.luxtram.lu/fr/la-ligne/un-trace-multimodal/ (Accessed on December 15, 2020).
Luxtram (n.d.). Galerie d'images." http://www.luxtram.lu/fr/documentation/galerie-dimages/ (Accessed on December 15, 2020).
Ministry of Land, Infrastructure, Transport and Tourism (n.d.). Changes in the number of utility poles. https://www.mlit.go.jp/road/road/traffic/chicyuka/chi_13_03.html (Accessed on November 30, 2020).
Ministry of Land, Infrastructure, Transport and Tourism (n.d.). LRT introduction support measures. https://www.mlit.go.jp/road/sisaku/lrt/lrt_index.html (Accessed on November 30, 2020).
OECD (n.d.). Luxembourg—OECD Data. http://data.oecd.org/luxembourg.htm (Accessed on September 2, 2020).
OECD (2020). OECD economic surveys: Luxembourg 2019. https://www.oecd-ilibrary.org/economics/oecd-economic-surveys-luxembourg-2019_424839c1-en (Accessed on September 2, 2020).
Ogasa, M. (2009). Catenary free technology: 'Hi-Tram' as contact-wire/battery hybrid LRV. *Proceedings of the Transportation and Logistics Conference 2009*, 57-60.
Ogasa, M. (2011). Extension of battery-onboard rail electric vehicles. *Yuasa Technical Report*, Vol. 8, No. 1, 1-15.
Olwig, K. R. (2007). The practice of landscape 'conventions' and the just landscape: The case of the European landscape convention. *Landscape Research*, Vol. 32, No. 5, 579-594.
Toussaint, T. (2019). 200,000 cross-border workers in Luxembourg, RTL. https://today.rtl.lu/news/luxembourg/a/1398145.html (Accessed on September 9, 2020).
Railway Technical Research Institute (n.d.). Research and development of catenary-battery hybrid LRV. https://www.rtri.or.jp/rd/division/rd42/rd4210/rd42100102.html (Accessed on December 9, 2020).
Railway Technology (n.d.). Greentech by trainelec—Railway technology. https://www.railway-technology.com/contractors/electrification/trainelec1/ (Accessed on November 20, 2020).
Romano, D., Grimaldi, F. P., De Vita, F. D., Della Corte, M., Rota, V., Schiavo, R., Improta, V., and Cascone, B. (2020). Catenary-free streetcar with on-board li-Ion battery system. *Hitachi Review*, Vol. 69, No. 6, 780-787.
Shimauchi, T. (2020). Reinventing public transport system in Luxembourg and its implications for foreign tourists. *Journal of Global Tourism Research*, Vol. 5, No. 2, 161-166.
Shiokawa, H. and Ishii, N. (2017). Issues for excessive quality cost reduction. *Proceedings of Annual Conference of the Information Systems Society in Japan*, 13, d11.
Sonkoly, G. (2017). The history of historic urban landscape. In G. Sonkoly, *Historical urban landscape* (ed.), 9-76. Cham: Springer International Publishing.
Statista (2020). Market share of leading rolling stock manufacturers in Europe 2017. https://www.statista.com/statistics/1099183/market-share-leading-rolling-stock-

manufacturers-europe/ (Accessed on November 20, 2020).
Toki, H. (2016). Landscape awareness and landscape policy in Japan. Doctoral dissertation of Doshisha University. https://doshisha.repo.nii.ac.jp/index.php?active_action=repository_view_main_item_detail&page_id=13&block_id=100&item_id=1303&item_no=1 (Accessed on November 30, 2020).
Utsunomiya, K. (2009). LRT in the world and challenges to address in Japan. *IATSS Review*, Vol. 34, No. 2, 155-162.
Yamauchi, M. (2013). The shift from tramways to LRT and application of new technologies. *IATSS Review*, Vol. 37, No. 3, 215-223.

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