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# Review of the AC Overhead Wires, the DC Third Rail and the DC Fourth Rail Transit Lines: Issues and Challenges

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**ABSTRACT** This paper focuses on transits available around the world. AC voltage transits and DC voltage transit are reviewed and compared. Emphasis is given to differences, advantages and disadvantages of voltage supplies and traction types. First, differences between bus rapid transit (BRT), metro, light rail transit (LRT) and light metro are covered, with special attention to statistical of annual passengers per year, an attribute that defines the type of railway transit. Mention is also made to the history of DC and AC overhead wires, other traction preferences for metro transit and highlighted differences between the third rail and fourth rail traction. Malaysian transit systems are then discussed, with special attention to LRT Kelana Jaya line, world's third DC transit that employs the fourth rail traction. The discussion have produced relevant statistical data that this paper is in part aimed at summarizing and at comparing with what accomplished on the same subject within the third rail traction framework. The increased in LRT Kelana Jaya line annual passengers per year is a proof of success for the fourth rail technology.

**INDEX TERMS** AC voltage, DC voltage, fourth rail, LRT, metro, overhead wires, rapid transit, stray current, third rail and transit.

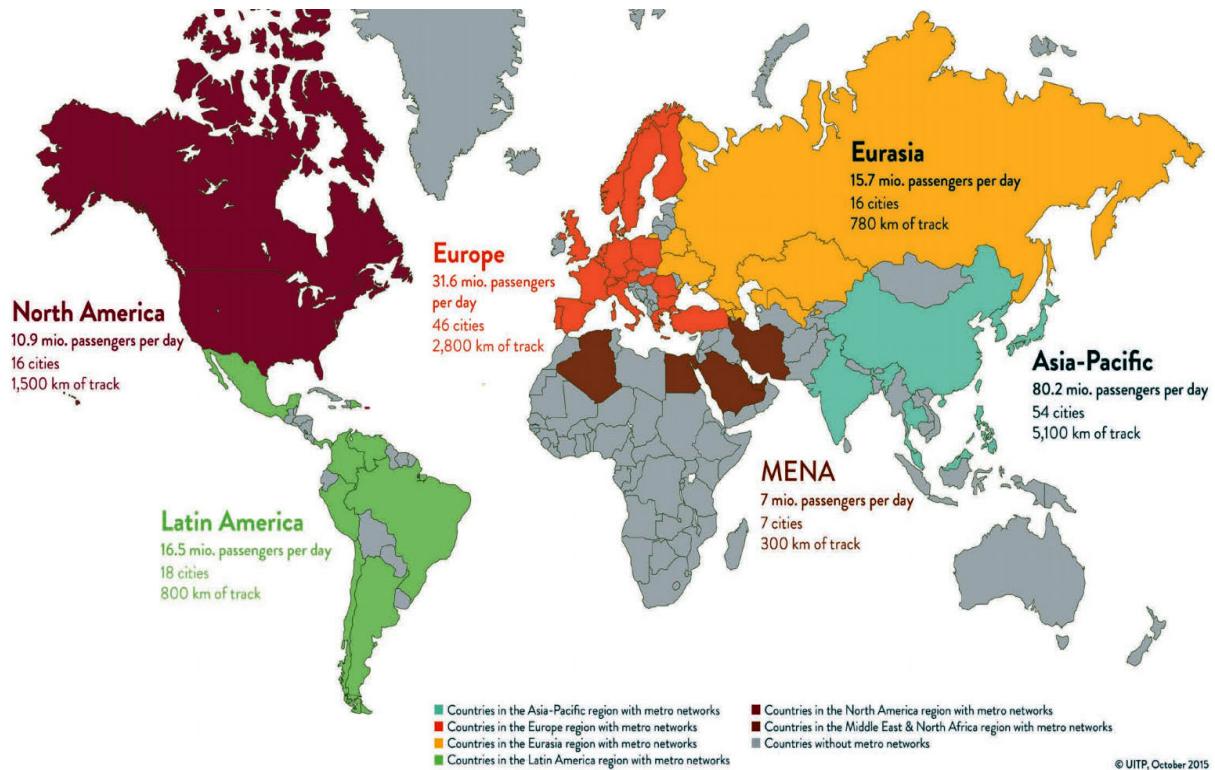
## I. INTRODUCTION

Transit is regard as a sound public transportation system and was born as a reliever to ease the pressure on city streets [1]–[3]. This pressure arose as a result of the excessive sprawling of urban areas that led to the escalating population of the urban dwellers and in due course transformed into an automobile dominated area. This excessive dependency on autos caused the sheer number of vehicles on city roads each day to skyrocket just carrying a single person each on their daily commute to work. When added to the delivery lorries and vans, service vehicles, and buses and taxis out there driving each day, this easily leads to a massive gridlock. This contributes to rising tensions, more fuel use, higher amounts of air pollution, and slower commuting times [1], [4]. Thus,

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as voiced out by the former Secretary-General of the United Nation [5] back in 2012, he raised the urgency for developing more sustainable urban transit systems that can address these issues. Sustainable urban transit systems have to be able to coordinate seamless movement within and between cities, which in turn is essential for urban functionality and prosperity. Metro, bus rapid transit (BRT) and light rail transit (LRT) are presumed to be such systems.

Metro, mass rapid transit (MRT), underground, subway or rapid rail [6]; similar systems but different names depending on what country you are in, is a railway usually in an urban area with high passenger capacities and frequent travel. Furthermore, as it usually a full grade separation from other traffic [2], [6] be it from roads or rail, thereupon it is acknowledged for its speed and decreased journey time. For example, getting from Leicester Square to Convent Garden by London Underground takes only 20 seconds, one-third of



**FIGURE 1.** Light Rail Transit around the world (2015) [15].

the equivalent taxi travel [7]. Moreover, the London Underground may be the oldest urban rapid transit system [8] in the world but it is certainly not the only one of its kind. As yet there are almost 180 rapid transit systems in 178 cities from 56 countries. Nevertheless, the London Underground has made it to the list of the ten largest rapid transit systems in the world [9].

The rapid transit which is also known as heavy rail so as to set it off from light rail transit, requires heavier investment [1] and is implemented as the preferable option for large cities where demand justifies the high capital cost [6]. A preference only arises when one mode offers a higher quality service such as fewer transfers, higher frequency [1] and reduced time of travel. However, in cases of medium-size urban areas, this investment may have limited practical value, to the extent that the public sector may end up with a long-term debt that can affect investment in more pressing policy areas. As a consequence, a more economical mode of transit is preferable such as rapid bus or light rail transit [10].

Rapid bus and light rail transit are more or less the same when compared with each other. Both transit systems operate on dedicated roadways or railways [11]. While rapid bus transit construction may cost much less than a light rail transit [1], [12] but in a city where space is at a premium it would be unlikely that the city administration would give over entire chunks of street to one category of bus. Light rail transit on the other hand also moves at street level and has an exclusive right-of-way. It emerged as a reinvigoration or

an upgraded version of a tram or streetcar. It has a higher capacity than a single tramcar as it operates with multiple unit trains. Another point is its speed ranges from a slightly improved tram system to a system that is essentially rapid transit but with some level crossings. Nonetheless the cost of building and operating light rail transit is considerably higher than the cost of rapid bus transit but much lower than the rapid transit [1], [12]. Yet still it is wise to reconsider this option as it offers lower local air pollution impact and possibly smoother rides for urban travellers [1] as shown in Table 1.

## II. LIGHT RAIL TRANSIT AROUND THE WORLD

Light rail transit (LRT) has re-emerged as an alternative form of public transportation after the world realised its potential. LRT was a prominent contributor to the reconstruction of Japan during the early post period after World War II [3], [4], [13], [14]. This transit system contributed to Japan's rapid economic growth and social mobility. Nowadays, LRT systems are in operation in 388 cities, the majority of which are in Europe (206) and Eurasia (93), followed by Asia (41) and North America (36) [15].

Fig. 1 shows an illustration of LRT operations around the world. To date, LRT carries approximately 13.6 billion passengers every year (45 million daily), which carries 3 % the total public transportation passengers worldwide. One example is Budapest, the capital city of Hungary, which despite having a  $525.2 \text{ km}^2$  total land area is the tenth largest

### LRT SYSTEMS WITH HIGHEST NUMBER OF ANNUAL PASSENGERS (MILLIONS)

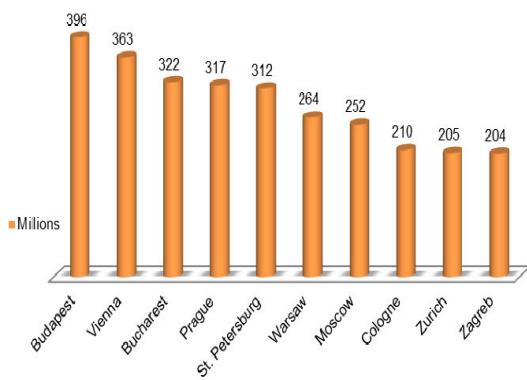


FIGURE 2. Cities with the highest number of LRT annual passengers [15].

### BUSIEST LRT NETWORKS

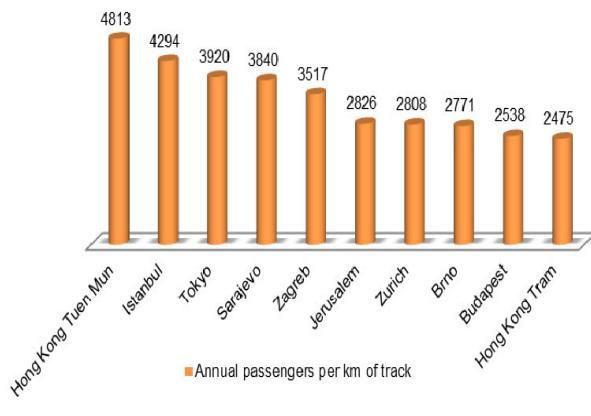


FIGURE 3. Busiest LRT networks around the world [15].

city in the European Union and has the highest annual number of LRT passengers as shown in Fig. 2.

This is followed by Vienna, Austria with 363 million passengers per year; a slight difference of 8 % and Zagreb is positioned tenth with 204 million passengers per year despite having a slightly higher total land area than Budapest ( $641 \text{ km}^2$ ).

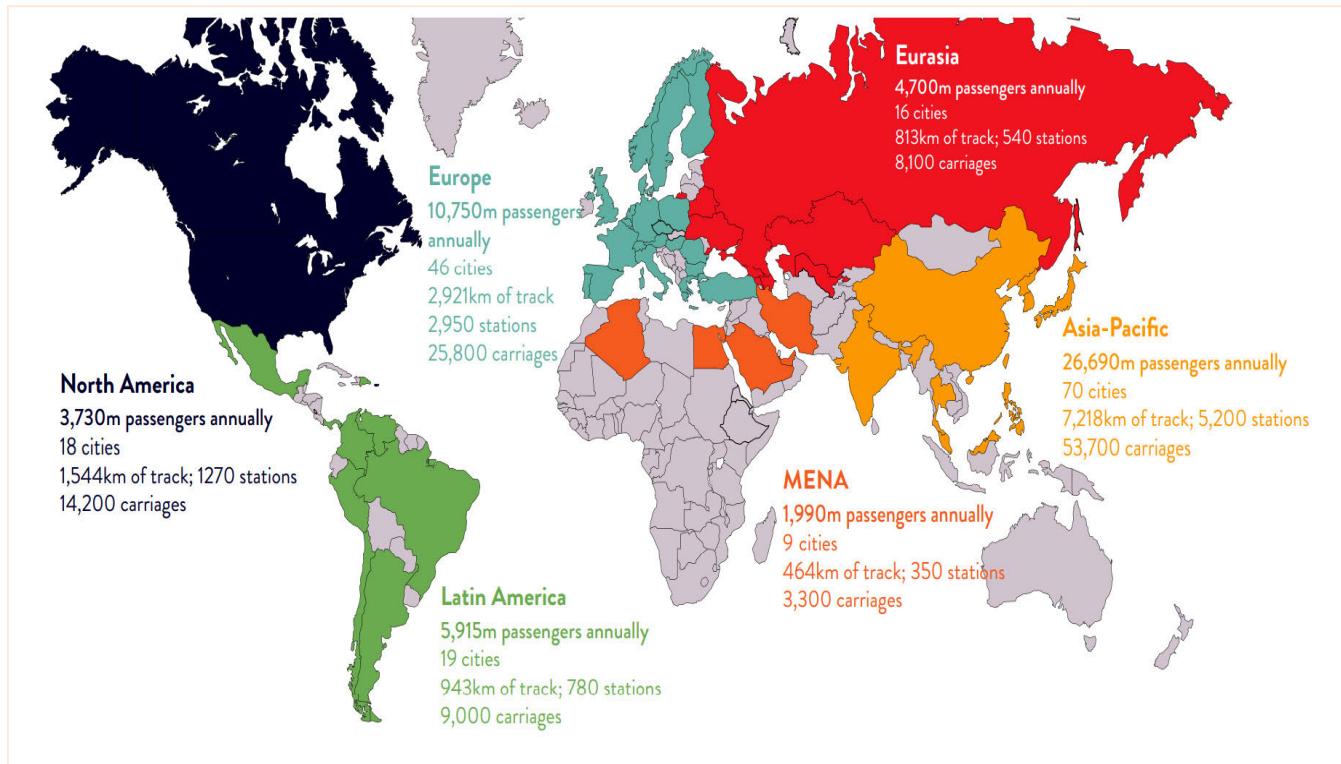
In contrast, none of the top two cities boasted the busiest LRT systems in the world, instead Budapest is positioned ninth in the list and Vienna did not even make it to the list. If the annual passengers were enumerated in per km of track, Hong Kong Tuen Mun recorded the highest number of passengers with 4,813 per km of track as shown in Fig. 3, whereas Budapest has only 2,538 passengers per km. The data is provided by UITP (Union Internationale des Transports Publics) which is an international association for public transport authorities and operators, policy decision-makers, scientific institutes and the public transport

TABLE 1. Comparison between the types of Transit Transportation (Rapid Transit, LRT and BRT) [5].

ITEM	RAPID TRANSIT	LIGHT RAIL	BRT
Running ways	Rail Tracks	Rail Tracks	Roadway
Required roadway space	Low impact on existing roads	Two lanes (narrow 5 to 8 metres)	Two to four lanes of existing roads (7 to 15 metres)
Type of right of way	Underground/elevated/at-grade	Usually at-grade (some elevated / underground)	Usually at-grade (some elevated /underground)
Segregation from the rest of the traffic	Total segregation	Usually longitudinal segregation (at-grade intersections), (some with full segregation)	Usually longitudinal segregation (at-grade intersections), (some with full segregation)
Type of vehicle	Trains (multi-car)	Trains (single to three cars)	Buses
Type of propulsion	Electric	Electric (few applications are diesel)	Usually internal combustion engine or hybrid transmission or electric trolleybuses
Traffic impacts during operation	Reduced congestion (does not interfere with surface travel)	Variable (takes some space from traffic)	Variable (takes space, reduces traffic interference by buses)
Air pollution	No tailpipe emissions, power generation pollutants dependent on energy source and technologies used	No tailpipe emissions, power generation pollutants dependent on energy source and technologies used	Tailpipe emissions for internal combustion engine, depends on the engine, fuel and emission control technology
Greenhouse gas emissions	68 to 38 grams per passenger-kilometre	100 to 38 grams per passenger-kilometre	204 to 28 grams per passenger-kilometre
Passenger experience	Smooth ride, high comfort (depending on occupancy)	Smooth ride, high comfort (depending on occupancy)	Irregular ride (sudden acceleration and braking), medium comfort (depending on occupancy)
Project investment (million US\$/km)	60.7 to 106.3	45.5 to 75.9	6.1 to 8.3

supply and service industry proved that with proper and forward-thinking of transit management, LRT can arise as a very effective solution to some of the mobility issues in urban areas [1]–[3].

The light rail transit of Malaysia was left out of the list of global LRT networks, even though the transit system bore the name Transit Ringan (Light Transit). Not just that, Malaysian officials and media also consistently refer to this network as light rail transit. The LRT network in Malaysia consists of two main lines which were formerly known as Sistem Transit Aliran Ringan (STAR), which translates to Light Rail Transit System and Projek Usahasama Transit Ringan Automatik Sdn Bhd or Automatic Light Transit Joint Venture Project (PUTRA-LRT). These two lines were then renamed as LRT Ampang Line and LRT Kelana Jaya Line after their respective former terminus, following the procurement of these two companies in the early 2000s by its current owner Prasarana Malaysia Berhad (Malaysia Infrastructure Limited). The LRT



**FIGURE 4.** Metro Transit around the world (2017) [20].

Kelana Jaya line runs from the north eastern suburbs of Kuala Lumpur and Petaling Jaya to the west of Kuala Lumpur. Whereas the LRT Ampang line consists of two routes; both routes start at the Sentul Timur LRT Station in the north Kuala Lumpur, with the first route ending in Putra Heights in the south, while the second course ends in Ampang in the eastern suburb of the city.

Despite being referred to as an LRT, these two lines are totally segregated which leans towards the metro trait in defiance of the LRT at grade intersection characteristic. Yet, there is one attribute of the Malaysian LRT that bears a resemblance to the LRT trait which is the total passengers per hour in the peak direction. Initially it was 10,000 passengers per hour in each direction (p/h/d) with the current ridership capacity at 30,000 p/h/d [16], [17]. Since ridership capacity ultimately defines the design and the size of the rail transit system, resultantly the Malaysian LRT falls in the category of a medium-capacity system or better known as light metro [18] as referred to in Table 2. Although usually the ridership is forecast ahead of any future transit establishment for the purpose of characterising the system capacity, many forecasts are revised in the first few years of the operation of the project. Still, ridership forecasts are notoriously difficult to establish with any accuracy. Nevertheless, a medium capacity system may also result when a rapid transit service fails to achieve the requisite ridership due to network inadequacies or a changing demographic.

On the whole, the Light Rapid Transit is likely appropriate when referring to the Malaysian LRT acronym as ‘rapid’ implying the same subject matter as with a metro. In short, light rapid or light metro like most of the world refers to it, translates as a rail transit that features the physical characteristic of a metro but has a capacity slightly more than a light rail transit but lesser than a metro. By that, as shown in Fig. 4 indicating the metro transit whereabouts across the globe, it can be seen that the Malaysian LRT obviously did make it on the list. Furthermore, with a route coverage of 46.4 km the Malaysian LRT Kelana Jaya line is the second longest fully automated metro transit (as of 2019) in the world and the longest self-powered metro in Asia [19] seen here in Fig. 5 with other international automated metro transits (as of 2015).

### III. THE HISTORY OF DC AND AC OVERHEAD WIRES OF RAILWAY ELECTRICAL TRACTION

Rail transit systems and rail electrification are related reciprocally. Electrification is the reason for the credibility services of rail transit with reference to speed and short travel time amongst others. Furthermore, the world is becoming ever more urbanised and rail travel is well matched to urban needs. Rail electrification or the electric traction system as it is commonly called, has a number and variety of traction choices for metro transit anywhere in the world, specifically built according to the location of the transit, the type of transit railway

and the transit technology available at the time of installation. To be precise, those are not all. The choice of preference for electricity supply for electric traction nowadays is influenced by a few technical considerations such as [22]:

- a. Operational requirements (whether for metro transit, high-speed passenger or heavy-haul freight)
- b. Physical route characteristics (gradients, bridge and tunnel clearances)
- c. Available traction technology (converters, traction motors and regenerative capability)
- d. Capacity (service level, number of passengers per train, number of cars)
- e. Types of trains (electric multiple unit (EMU), power car or locomotive driven)
- f. Maximum power demand of each train as this will affect the top speed of the trains
- g. Journey time
- h. Availability of land for installing the DC substations/AC feeder stations
- i. Proximity of generating plant and utility or railway-owned power networks
- j. Availability of high voltage supply connection points for DC substations/AC feeder stations along the route

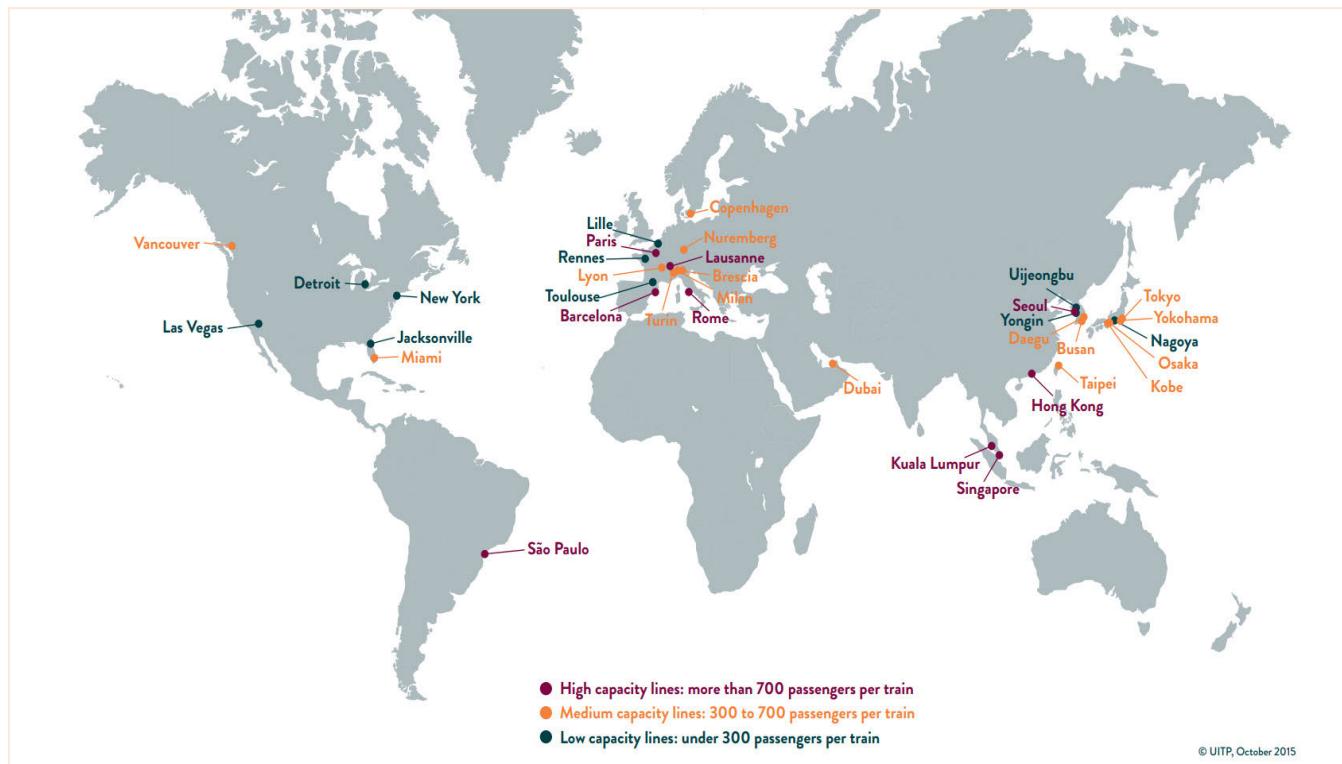
This however was not the case in the early commencement of electric traction in the 1830s. A preference was not given as DC technologies were the only choice available. For instance, the success of Faraday's invention of a rudimentary electric motor in 1831, a miniature electric railway exhibition in 1837 by Thomas Davenport and an experimental locomotive powered by electric batteries on Scottish railway lines the following year by Robert Davidson, all these depended on storage batteries for electricity supply, hence the usage of DC supply [23]. However the supplied power to the trains through this approach was pricey, approximately 20 times higher than being supplied by a steam engine for the equivalent amount of power. In that respect, the dynamo and electric motor were later developed by Werner von Siemens in 1870s and eventually became the basis of electricity generation and distribution.

The journey discoveries in the railway history timeline thereupon led to the first running of an electric tramcar at Licherfelde, Germany in 1881 [23] by conveying the centrally produced electricity to the rail-guided cars through an overhead continuous conductor. Notably, in 1900 electric trams were at their height in Belgium, France and Germany illustrated by the increase in tramway track length by threefold by 1910, marking the dawn of the tramway revolution in Europe [23]. At that time, when the technologies were just emerging the economic way of conveying electric power was by transmitting it with a voltage as high as possible thus enabling a given power to be delivered with the smallest current and therefore losses. However, with a higher DC voltage it would be difficult to break fault the current due to the inherent DC motor inductive effects. Hence, a sound decision was made among tramcar companies to

practice 3000 VDC tramway electrification (based on the U.S. experience), explaining the extensive of 3000 VDC main line systems dating from 1920s and 1930s [22], [24] in Belgium, Spain, Italy, Poland, the northern region of the former Czechoslovakia, and the former Soviet Union [25]. Although research was done in Italy to try and prove the viability of a 12000 VDC system but this did not really take off [26]. Furthermore the usage of DC electric motors provided simplicity of the vehicle-mounted traction equipment and also eased the control of the motor speed by only switching from series to parallel connection as the speed increased. These are indeed the reasons that the 1500 VDC system still going strong in Netherlands, southern and south-western parts of France [25]. Presently, for lines up to about 100 km, the standard voltage for any new light rail transit is between 600 VDC to 1500 VDC [22].

Meanwhile, prior to the second Industrial Revolution which began in Belgium in the mid-19th century before spreading to the rest of the Europe [27] subsequently influencing and transforming traction technologies there was the introduction of the series-wound commutator motor in 1903. This astounding discovery allowed electrification at even higher voltages [25] led to the idea of electrifying the traction directly with AC voltage. After all a single phase AC power was already made available as Budapest had introduced it in 1878 [28]. As a result, there was parallel development of traction technologies encircling AC advantageous in those industrial countries which led to a plethora of different electrification systems. Each of them was racing in introducing and proving theirs was better than the others. For example, in the early 20th century (1912 to be exact), 15 kV  $16\frac{2}{3}$  Hz networks were very extensive and expanded throughout Europe [22], [26], especially in Germany, Austria-Hungary, Switzerland, Sweden and Norway [25]. This new network frequency was reduced from 50 Hz for a safer value of induced voltage as well as combating the issue of eddy currents in the iron which caused overheating and loss of efficiency [29]. These networks ceased to exist except those in use today in Northern Europe (Germany, Sweden, Austria and Switzerland) [22], [26].

On the other hand, there were also some parallel early work done on a three phase, double pantograph 3.6 kV,  $16\frac{2}{3}$  Hz network in northern Italy and Switzerland as well as 6.6 kV, 25 Hz in the U.S. [29] to take the advantage of the AC motor regenerative ability when descending from mountains. However, these networks were abandoned in the 1960s because of the complexity of current collection [22], [26] especially at crossings and intersections whereas in Italy the line from Genova to Torino was converted to 3000 VDC in 1964 [22]. Having said that, these lower frequency operations in earlier AC traction requires the high initial cost of a separate generation and distribution system and also the need for frequency convertors that led to the preference of using the standard frequency of the 50 Hz system of the electric utilities. Thus with this notation the Germans led a series of successful trials in the 1930s and two decades later the French



**FIGURE 5.** Cities with automated metro transits, as of 2015.

employed the same 25 kV 50 Hz system in their north-eastern lines [30], [25]. Consequently, this preference of electric network spread over all Europe (Great Britain, Ireland, Portugal, Denmark, Finland and the majority of South-Eastern and Eastern European countries) [22]. Notably, it has been received today as the standard supply for any new AC traction system [22], [26]. Table 3 (while may not be exhaustive) tabulates the classification for a few electrical tractions across the globe. All in all, DC and AC traction systems have led the world transit network bloom from a mere overhead wire arrangement to a selection of third rail and fourth rail with each bringing distinct pros and cons.

#### IV. METRO TRANSIT TRACTION PREFERENCE – IS IT AC OVEHEAD WIRE OR DC THIRD RAIL?

Electric traction technologies have come a long way since its first introduction in the early 20th century. The impediment to choosing the type of electricity supply for electric traction back in the old days is old news now. Today's new constructions of rail transit systems are more than just people-moving assistance but also act as a community-building strategist. How urban dwellers get by with their everyday commute, whether they are travelling safely, comfortably and in a cost-effective manner, all add up as part of the overall economics of an urban community. Thus choosing the type of electricity supply and also how it should be delivered to the vehicle nowadays is not merely just a choice but a promising alternative for travelling as it leads to the type of transit

system as shown in Table 2. Presently, electric rail transit has taken up a pivotal role in alleviating traffic congestion in urban areas, to reduce urban pollution and improve urban life. The trend that started in Western Europe and re-emerged in Japan in the aftermath of World War II has generally spread progressively throughout the world. As of 2016, the regions with the highest share of electric train activity are Europe, Japan and Russia [50].

Before an urban neighbourhood can settle down with an electricity supply preference of electric traction, many factors come into play (as listed in Section 3) and most importantly how to sustain the high mobility of the urban population (expressed in passengers-km or passenger-trips per capita per year). Otherwise, the endeavour of presenting a competitive alternative to private motor vehicles and allusively tackling the traffic congestion issues goes down the drain. First and foremost for any future rail-transit planners, they should take into consideration the percentage of population living within one kilometre from a future rail transit station and also the percentage of jobs within a kilometre of the station [9], corresponding to an inability to provide a cheap service to lightly trafficked routes. On that account, a forecast should be made predicting the expected daily ridership and frequency of the transit services at the time of peak hours. These predictions lead to the determination of the following factors [51]:

- a. number of seats per car,
- b. number of standees per car,
- c. number of cars per train,

**TABLE 2.** The Characteristics of Various Rail Transit Systems [18].

SYSTEM TYPE	REVENUE SPEED	PEAK CAPACITY (PASSENGERS PER HOUR IN PEAK DIRECTION)	TYPICAL DEGREE OF SEGREGATION	COMMON TECHNICAL TRAITS
Streetcar or Tram	Low	Low (5,000 or less)	No significant degree of segregation	a. Frequent street crossings b. Primarily at grade c. Single-car rolling-stock configurations
Light Rail Train	Low-medium	Low-medium (10,000 to 12,000)	Partially segregated	a. Mostly at grade b. Single and double car rolling-stock configurations
Electric Commuter Rail	Very high	Medium (about 30,000)	Completely segregated	a. Greater distances with stations b. Mostly at grade
Grade-Separated Medium-Capacity Light Metro	High	Medium-high (15,000 to 30,000)	Completely segregated	Either elevated or underground
Grade-Separated Heavy Metro	High	High (60,000 or more)	Completely segregated	Either elevated or underground, involving complex civil works

d. train headway (headway is a measurement of the distance or time between two vehicles in a transit system. The minimum or closest headway delivers the maximum capacity).

Not only that, the design of a future rail transit also revolves around the likely ridership levels, as it ultimately defines the system capacity and the type of transit system, hence the contact system of the rail transit.

In theory, with a ridership between 15,000 and 30,000 p/h/d adopting the light metro transit is the best option. The next step is to single out the type of electricity supply and ways to deliver it to the future light metro transit. Most metros are operated with DC voltage third rail at varieties of voltages such as 600 V on the Tokyo metro, 750 V for the Malaysian LRT, 825 V in Moscow, 1.2 kV in Berlin and 1.5 kV in Guangzhou [31] with 750 V being the most common and 1.5 kV being the most economical [31]. Alternatively, the electricity can be supplied to the metros through overhead wire either at AC voltage or DC voltage. An AC traction system could be one way of achieving greater capacity and high daily ridership because it allows the operators to use longer trains and run at a higher speed, but when applied in an urban environment, it produces a few minuses. For example, if the metros are routed through any tunnel, the construction cost will be sky-high due to the requirement of a larger profile [31]. In addition, as AC voltage is a source for electromagnetic interference, the impact of the magnetic fields on properties and activities close to the line has to be considered.

Nevertheless, it is not a peculiar sight to notice a light metro transit operated with DC overhead wire in Europe. For example, the Tyne and Wear Metro in the United Kingdom (Fig. 6(a)), the second busiest transit in the UK after the London Underground, operates at 1500 V [9], [45] the Metro de Madrid in Madrid Spain, home to the most extensive metro systems in the world, to be exact the seventh longest metro network [52], [53] operates at 600 V and 1500 V on its respective selected lines throughout the network [33] since its opening in 1919 and even the smallest metro system in



(a)



(b)

**FIGURE 6.** Mass Transit (The Tyne and Wear Metro, UK) (a) [59] and Shanghai Metro Line 2, China (b) [60].

Europe with a network length of 60 km, the Metro of Rome operates at 1500 V [55], [46], [47]. On the other hand, it is unlikely for Asian cities to have a light metro operated with overhead wires with exception of few transits. To give an example the Shanghai Metro, as shown in Fig. 6(b), operates at 1500 V [56]. Correspondingly, these light metros operate at 1500 V at most as this magnitude is considered the most economical solution for metro transits [57]. Yet DC power distribution through an overhead wire has a lot to consider even at this magnitude compared to its AC counterpart which can carry up to 25 kV AC. The DC light

metro transit manufacturer has to deal with the challenge of introducing an ideal contact system (pantograph) that can stand the relatively high currents and the voltage drop along the line [58]. The pantograph must have a low mass to be able to follow the overhead wire efficiently as well as it also contributes to the accumulated weight of the train, which eventually affects the passenger per car capacity and the speed of the transit. Quite the opposite an AC overhead wire that is able to deliver a much higher voltage hence enabling it to operate long runs at a much higher speed or pulling heavier loads. A case in point is the renowned Japan Bullet Train. Based on these grounds, it is practical to deliver DC voltage through a third rail and AC voltage through an overhead wire.

Despite the fact that DC voltage is preferred to be delivered through a third rail it does not mean that a third rail cannot accommodate AC voltage, it just that through a third rail a DC voltage can carry 41 % more power than an AC voltage operating at the same peak voltage via the same medium [29]. From another point of view, third rail represents low-maintenance power distribution and is advisable for voltages up to 1500 VDC whereas above this magnitude the rail insulator sizes will become impractical [58]. Moreover, a 1500 VDC transit system presents a 13 % reduction of maintenance cost compared to a much lower DC voltage as there are fewer substations to be supervised and also the power supply equipment is virtually maintenance-free with only regular inspections and cleaning required [31].

It also allows the carriage of more than 60,000 passengers per hour per direction as against the 750 V transit network [31]. Even so, a 750 VDC system does have its own advantages as it offers a power supply transmission efficiency average of 92 to 94 % [31], but at the cost of short stop spacing (short station spacing), a trade-off for speed, and as a consequence requires a large number of trains or trip frequency [31], [58].

In short, after a deliberate presentation taking into account each traction system its gains and losses, generally third rail at a DC voltage is the favourable contact system and supplied voltage for an urban metro. Table 4 lists out other advantages and disadvantages between these two electricity supplies, while Table 5 lists out the preference contact system corresponding to practical transit systems. Also Table 6 points out the pros and cons of selecting either an overhead wire or a third rail contact system for many metro transits.

## V. WHAT ABOUT A DC FOURTH RAIL TRACTION FOR METRO TRANSIT?

At the very beginning of rail track electrification, way before the development of the third or fourth rail, there was the simple two-rail traction method of working. The two rails made for electrical traction happened to be the same rails structure made for running the train on the track bed. The practice was to electrify both the running rails with each rail acting as a conductor for each current polarity and was insulated from the earth by the track sleepers. The insulation should secure



(a)



(b)

**FIGURE 7.** The Volk's Railway in 1883 (a) and in 2019 (b) in Brighton, UK [62].

the current flowing through the running rails, and prevent current going astray and leaking to the earth. This practice worked fine with most scale models, but not for large trains as the sleepers turned out to be a mediocre insulator. As a consequence, for supplementary insulation the trains resorted to insulated wheels or insulated axles. Nonetheless, the Volk's Railway in Brighton, England (seen in Fig. 7) amongst others, picked up this practice in 1883 [23] by electrifying its rail at 50 VDC. A year later it increased the voltage to 160 VDC to conveniently propel two cars compared to one car prior covering a route of more than a kilometre along the seafront of Brighton.

Still, the continual issue of sleepers being an imperfect insulation, later made the railway opt for an offset additional rail in 1886 after becoming aware of its advantage [61]. As seven years prior, the German firm of Siemens and Halske demonstrated an experimental episode of rail electrification through an additional rail placed in between the running rails hence the third rail moniker. The demonstration took place in the Berlin Industrial Exposition [23], and was a success from the get-go. A year later, the third rail system ventured into the public urban transport such as large tram network in New York, Chicago, Washington DC, London and Paris but flubbed badly. Economically it was better to receive the power through the overhead wire.

**TABLE 3.** Rail Electrification around the World.

VOLTAGE MAGNITUDE			COUNTRY	NOTES	CONTACT SYSTEM		
DC Voltage (V)	AC Voltage (kV)	Frequency (Hz)			Overhead	Third Rail	Fourth Rail
600			Japan (Tokyo)[31], Italy (Milan)[29],[32], Spain (Madrid) [33]	Metro de Madrid (seventh longest in the world)	X[29],[33]	X[31]	X[32]
650			UK (shared line in London Underground)[32],[34],[29], USA(Dallas)[35]	Piccadilly and Metropolitan Line Operated June 1996		X[31],[32]	X[29],[32]
750			UK[22],[36],[37](Southern London[29],[32])		X[36],[29]	X[29],[32]	X[29]
			Singapore[38],[39]	18 Jan 2002		X[38],[39]	
			Malaysia[40]				X[40]
			China[41],[42]			X[41]	
			Japan (Tokyo)[31]				
			India (Kolkata)[29]			X[29]	
			USA (Portland)[43]	May 2004	X[43]		
825			Russia (Moscow)[31]				
1200			Germany (Berlin)[31], (Hamburg)[29],[32]		X[29]	X[31],[29],[32]	
1500			France[29],[22],[29],[32], Netherlands[29],[22]	France (Third Rail till 1976) later to overhead	X[29]	X[29], [32]	
			UAE(Dubai)[31]			X[31]	
			India[29] (Ahmadabad)[31]			X[31]	
			China[41],[42][44], (Guangzhou)[31]		X[41]		
			Singapore[39]				
			UK[36]	Tyne and Wear Metro (Overhead at 1500 V)[45]	X[36]	X[36]	
			Portugal[29], Spain (Madrid) [33], Italy (Rome) [46], [47]		X[29],[33],[46], [47]		
3000			Japan[29], Hong Kong[29], Ireland[29], Australia[29], New Zealand(Wellington)[29], US[29], Slovakia[29], Denmark[29], Portugal[29], UK[29],[32]	UK (was used in 1954) before converted to 25 kVAC	X[29],[32]		
			Belgium[29],[22],[32],[37], Spain[29],[22], Italy[29],[22],[32] Poland[29],[22],[32],Northern Czech Rep[29],[32], Slovakia[29], Slovenia[29],[32],Western Croatia[29],[32] Spain [29],[32]		X[29],[32]		
			Italy[26], Former USSR[26],[32] South Africa[29],[26],[32]		X[29],[26],[32]		
12	25	60	New York[22]	Operated Early 20th Century			
3.6	16 <sup>2</sup> <sub>3</sub>		Northern Italy[26]	Abandoned 1960's	X[48]		
15	16 <sup>2</sup> <sub>3</sub>		Europe[22]	Operated Early 20th Century			
			Germany[31],[22],[26],[37] Austria[22],[26],[37] Switzerland[22],[37],Sweden[22],[26],[37] Norway[22],[37]		X[31]		
25	50	60	Belgium [32],Spain[22],[37],[29],[32] France[22],[37],[32](Paris)[31], Germany[31], India [32](Delhi)[31],[29] (Mumbai)[29], UK[32](Manchester)[29], US (New Jersey)[29],[49], (Connecticut)[49], Czech Rep[29], Slovakia[29], Italy [29],[32], South Africa [29], Canada(Montreal) [49], Netherlands[32],[49], Turkey [32]	Operated Early 1950[22], New Jersey conversion from 3000 VDC was in 1984 [49], Connecticut conversion from 11 kVAC,25 HZ to 25k VAC,60 Hz was in 1986 [49] Montreal conversion from 2400 VDC to 25 kVAC, 60 Hz was in 1995 [49] The Netherlands conversion was from 1,500 VDC to 25 kVAC, 50H z [49]	X[31],[29]		
50	50	60	Canada [37], South Africa [37]	Heavy-haul (mine lines)[26]			
25	50		UK[22], France[22], Russia[29],[22], South Africa[22], Finland[22], Denmark[22], [37], Luxembourg[22], Portugal[22], Spain[22], Former USSR [32]		X[32]		

Nevertheless, the London Underground decided on taking the risk and made use of the third rail advantage. London Underground was the first metro transit to employ this scheme, targeted it as a fixer to the ever increasing complaints about the poor quality of air in the carriages and in the stations owing to the smoke emission from its former steam

locomotives. Its City and South London Line was opened in 1890 and was among the first line of the London Underground operated with third rail traction [23]. The difference between these two traction technologies was that the positive polarity of the current was set to flow through the newly placed rail; the third rail, and the negative polarity of the current

**TABLE 4.** The Advantages and Disadvantages of Using DC or AC Voltage.

TRACTION ELECTRIFICATION TYPE	ADVANTAGES	DISADVANTAGES
DC Voltage	<ul style="list-style-type: none"> <li>a. Ease on rapid acceleration and braking of DC motor [30]</li> <li>b. Less energy consumption [30]</li> <li>c. The equipment is less costly, lighter and more efficient [30]. Lighter trains allow to carry more passengers on-board [31]</li> <li>d. It causes no electrical interference with nearby communication lines [30]</li> <li>e. Requires less complex traction control system [57]</li> </ul>	<ul style="list-style-type: none"> <li>a. Frequent interval substations require constant monitoring as each substation includes transformers and rectifiers [31], [29], [32] but they minimise the generation of stray currents as the vehicle moves away from the power source (substation) [63]</li> <li>b. DC systems are limited to relatively low voltages and this can limit the size and speed of trains [29]</li> <li>c. Expensive substations are required at frequent intervals as the railway authority has to provide its own high voltage AC distribution network linking to wayside substations as well its own rectifier plant [30], [57].</li> <li>d. The overhead wire or third rail must be relatively large and heavy [29], [30]</li> <li>e. Voltage goes on decreasing with increase in length [30]</li> <li>f. Requires thick cables and has significant resistive losses [29],[32]</li> </ul>
AC Voltage	<ul style="list-style-type: none"> <li>a. Quick availability and easily stepped up or down [30] (without rectification)[31],[49]</li> <li>b. Fewer substations are required[49],[30],[57], but allows operation with longer trains [31]</li> <li>c. Easy control of AC motors [49],[30],[57],</li> <li>d. Lighter overhead current supply wire can be used [30],[57]</li> <li>e. Reduced weight of support structure [30]</li> <li>f. Reduced capital cost of electrification [31],[30],[57],[64]</li> <li>g. Improved efficiency [31],[57] reduction of voltage drop over distance [49]</li> <li>h. Using energy from brakes more effectively [31],[57], lower energy loss and more precise wheel adhesion because of more precise control technology [49], thus brake maintenance is reduced [57]</li> </ul>	<ul style="list-style-type: none"> <li>a. Significant cost of electrification [30]</li> <li>b. Increased maintenance cost of lines [31], [30]</li> <li>c. Overhead wire further limits clearance in tunnels [31], [30]</li> <li>d. Upgrading needs additional cost especially in case there are bridges and tunnels [31],[30]</li> <li>e. Railway traction requires immune power with no cuts [30]</li> <li>f. Potential interference with electromagnetic and magnetic fields on properties and activities close to line [31],[49]</li> <li>g. On-board transformer imposes significant weight on the ac-powered rolling stock [31],[49]</li> <li>h. AC electrification must deal with inductive reactance which increases proportionally with frequency thus needs a higher voltage on the overhead wire system [49]</li> </ul>

(recognised as the return path or return circuit) still made use of either one of the two running rails. Sadly, the unsettling issue of stray currents arose and clouded the performance of the London Underground third rail services, of what was thought should have resolved the issue. The complication was not from the third rail, but from the return path. Accordingly, stray current from a DC railway is an inevitable consequence of using the running rails as the return path for the traction supply current [66], [67]. Due to the poor insulation provided by the sleepers, a proportion of return current will definitely leak to earth, with the earth now forming an unintended current return path. Stray current is an issue to be entertained proactively as it leads to the corrosion of the supporting and third party infrastructure that are in close proximity to the railway [66].

Theoretically, this can be easily understood by the concept of science in terms of the oxidation and reduction reactions. Bearing in mind that the current that flows in a metallic conductor is known as electronic, while the current that flows through electrolytes (such as earth or concrete) is known as ionic [68]. Thus, the journey of stray current leaving the running rail to the earth is the journey of electron-to-ion; indirectly producing an anode. This by-product reaction is otherwise called by the term oxidation. On the other hand, the journey of stray current re-entering the running rail from the earth is the journey of ion-to-electron; an electron-consuming reaction also known as reduction. Yet the latter is not thermodynamically preferred as an ion does not plate back onto the rail. Accordingly, the corrosion defects occur at the point of place where the current is leaving the rail (oxidation)

or from any other metallic elements in the vicinity [68]. Subsequently, it was not for another two decades for the proper principles and guidelines of mitigation methods to be organised in addressing this issue. Wherefore due to the limited technology available at that time of occurrence that resolved to provide another additional rail acting as the return path, hence the fourth rail traction. London Underground was the first to apply the fourth rail traction around 1903 to 1907 [69] and it is still in use today. The prior additional rail in between the running rails now acts as the fourth rail (the return path) whereas the third rail is mounted outside of the running rails [29], [70]. The third rail is at a potential of +420 V while the fourth rail is at -210 V, with a combined voltage operation of 630 V. In addition, the two running rails have one of its rails to be electrically continuous and at earth potential [69].

A fourth rail traction technology came to light as a post development of the third rail traction technology. Whilst its realisation has not entirely taken off, but its involvement in the revamp of the London Underground services really paid off [71]. The main advantage of the fourth rail traction is that the running rails would not have to carry either polarity of current, thus avoiding corrosion and even arcing if the tunnel segments are not electrically bonded together. As London Underground is running through Victorian mains that predated the railway section, the pipe segments were never constructed to carry currents and were not electrical bonded either [29]. Interestingly, with the advantages that the fourth rail traction brings, there still are only three urban transits in the world that employ this marvellous traction technology,

**TABLE 5.** The List of Traction Types according to the Respective Trains and Transits, and Their Applied Voltage Magnitude.

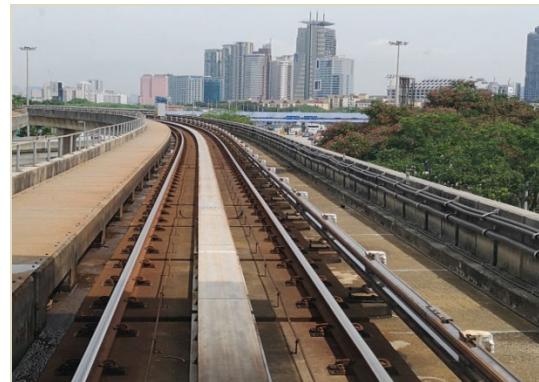
TRACTION TYPE	VOLTAGE MAGNITUDE (V)	DC SUPPLY TRACTION	AC SUPPLY TRACTION	NOTES
Overhead	600 to 750 [22],[58],800 [32]	Urban metros[22],[57],[58], [32], Tramways and Trolleybus [32]		For supply voltages less than 1000 V, power distribution to trains is made through third rail and overhead catenary for light rail system involving street running [22] 750 V is the sensible rate to energise the street running [57],[58] and is required due to safety issue [58], (touch potential and step potential)[63]
Overhead	1500 [26],[30] 3000 [26],[30],[58]	Intermediate System [58], Suburban and mainline [26],[30]		This 1500 V system is the economic solution for heavy metros [26], for urban mass transit or light rail systems [57] 3000 V system is applied almost entirely to the main line system in order to maximise substation spacing. [57]
Overhead	600 to 1000 [26]	Metros, Light Rail Transit, Street-cars and suburban railways [26]		
Third Rail	600 to 1500 [22]	Urban and Regional lines [22]		This rate of voltage is the standard for urban and regional lines up to about 100 km long [22]
Third Rail	600 to 1200 [30]	Urban railways (tramways and light metro train) [30]		1200 V is the reasonable maximum voltage for a third rail [29]
Third Rail	750 or 1500 [31],[58]	Suburban or urban metro [31],[58]		This rate of voltage forces a large number of trains and relatively short journeys [58]. Short journeys (short station spacing) requires frequent and high acceleration [31] This rate of voltage represented a low-maintenance power distribution network [58] and offer high efficiency (a 750 VDC system offers a power supply transmission efficiency average of 92 to 94 %)[31]
Third Rail	1500 [22] 550 to 1500[58]	Interurban and regional systems [22]		This rate of voltage reduces maintenance costs (13 % lower) because fewer substations to be supervised and also power supply equipment is virtually maintenance-free with only regular inspections and cleaning required [31] compared to 750 VDC This rate of voltage capable of carrying more than 60,000 passengers per hour per direction compared to 750 VDC [31]
Overhead	<b>Single Phase</b> 15000 ( $16\frac{2}{3}$ Hz)[26]		The original AC system in the early 20th Century.	This low rate frequency needs a special frequency supply due to field current flux lag resulting from eddy currents in the iron (technology at that time) which does not work well at high frequency. [26]
Overhead	<b>Single Phase</b> 11,000 to 15000 (16.7 Hz and 25 Hz)[30]			This low frequency requires that electricity be converted from utility power by motor-generators or static inverters at the feeding substations, or generated at altogether separate traction power stations. [29] This rate of voltage and frequency uses step down transformers and frequency converters to convert from the high voltages and the fixed industrial frequency. [30]
Overhead	<b>Single Phase</b> 25,000 (50/60 Hz) [31] [22],[26],[30],[58]		Common for brand new overhead systems[31], [26],[30],[58]	The evolution of overhead traction from 1,500 VDC, 3,000 VDC and s15,000 VAC to 25,000 VAC (or 2x25,000 VAC) [30], [31] has improved power supply efficiency by 98 % (depending on rolling stock) [31]
Overhead	<b>Single Phase</b> 50,000 ( $16\frac{2}{3}$ Hz) [22],[26]		For dedicated heavy haul railways such a mine lines. [26]	
Overhead	<b>Three Phase</b> (two pantograph) 3,600 ( $16\frac{2}{3}$ Hz)[26]			This early trial system was to try and take advantage of the regenerative ability when descending from the mountains. This was abandoned in the 1960s because of the complexity of the current collection. [26]
Overhead	<b>Three Phase</b> (two pantograph) 3,300 (16.7 Hz)[30]			This rate of voltage and frequency uses a step down transformer and frequency converters to convert from the high voltages and fixed industrial frequency. [30] This rate of voltage and frequency raises many problems at crossings and junctions. [30]

namely London Underground, Milan Metro Line 1, Italy and the LRT Kelana Jaya line in Malaysia [29]. Fig. 8 and Fig. 9 show the third and fourth rail of the London Underground and the LRT Kelana Jaya line, while Fig. 10 shows a testing track in Old Darby, England for all three traction modes; the overhead wire, third rail and fourth rail traction. Table 7 shows the issue of battling stray current associated with the third rail. In spite of much research and debate over many years, yet

there seems to be no universal solution to the problem. Only that, if there are more than a handful of international standards concerning railway system design uniting the different approaches of electrical safeties, and solving the contrasting views concerning the liabilities and responsibilities either to prevent them at source or to limit the consequences that had been put into practice by individual countries worldwide might produce a plausible best resolution [71].

**TABLE 6.** The Advantages and Disadvantages of Using Overhead Wire or Third Rail.

TYPE OF TRACTION	ADVANTAGES	DISADVANTAGES
Overhead	<p>High catenary voltage implies lower currents (means smaller conductor size) and smaller power losses, so fewer substations are required compared with lower voltage DC traction networks[22], [57]</p> <p>Simple and reliable structure of traction [64] and good anti-idling performance of traction [64]</p> <p>As there are no mechanical parts (commutator as in DC traction motors) makes AC traction motor suitable for operation of high-power, high-speed trains [64]</p> <p>As the contact system is placed overhead, thus the voltage can be increased and the danger to personnel is greatly reduced [57]</p>	<p>Overhead wire more prone to failure, thus regular maintenance is necessary and requires a plan that is supported by a 24-hour maintenance team [30]</p> <p>Has the risk to be affected by electromagnetic interference and the impact of magnetic fields on properties and activities close to line [30],[65]</p> <p>Is not practical for any tunnel travelling as the clearances needed for this operation is impossible [26]</p> <p>And as voltage is constrained, the current and the series impedances become corresponding larger [26]</p> <p>If the power requirements exceed the capability of the overhead catenary it is necessary to include parallel feeds along the overhead masts. Connections are made at regular intervals to the catenary to ensure good current sharing [57]</p>
Third Rail	<p>Third Rail also eradicates the impact of electromagnetic interference on electrical components [31] and is more rugged than an overhead wire and has a longer life expectancy [31]</p> <p>The system similarly benefits from high reliability because it is fed on both sides by rectifiers from adjacent substations [31], [57]</p> <p>Third Rail prefers DC as it can carry 41 % more than an AC system operating same peak voltage [29] and is more compact than overhead wire and be used in smaller-diameter tunnels [29],[32]</p> <p>Third Rail has a lower construction cost (re-establish suitable electrical clearances by using existing railways) [22] and is usually cheaper for surface line insulation problems [57]</p> <p>Has the advantage of no phase-split along the overhead system thus the trains can run smoothly [64]</p>	<p>Unavoidable gaps in the power supply at points and level crossings [31] and signalling costs increase as the return current has to be carried by the running rails that may also be required for automatic signalling (as the discrimination between these two currents) [57]</p> <p>Speeds are also restricted to 160 km/h due to the technical limitations of the system (such as above that speed – reliable contact between the contact shoe and rail cannot be maintained)[29],[32] while on lines electrified at 750 VDC peak-time line capacity is limited to 60,000 passengers per hour per direction [31]</p> <p>Third Rail systems are limited to relatively low voltages and allows only a limited amount of air-conditioning on the train[29], [32]</p> <p>Stray currents are also possible, although improvements in technology are managing and controlling this factor [31],[64]</p> <p>The build-up of ice and snow on the conductor rails is a serious hazard as the collector shoes are unable to make contact with the rails and it is likely to cause the service to be withdrawn [32], [57]</p>

**FIGURE 8.** Ealing Common on the District Line of London Underground [29].**FIGURE 9.** LRT Kelana Jaya line.

## VI. THE NEWEST FOURTH RAIL METRO TRANSIT – LRT KELANA JAYA LINE, KUALA LUMPUR MALAYSIA

Kuala Lumpur was founded in 1857 by Raja Abdullah, a member of the Selangor royal family. He began a quest for a new tin mining area and stumbled upon tin ore near Ampang after travelling up the Klang River and making through deep jungles along with Raja Jumaat and 87 Chinese workers [73]. Since then, Kuala Lumpur has flourished from a humble tin mining muddy city to the Malaysia main gateway and home to more than 6.8 million KLites [74]. Amidst this overwhelming number of urban populace, the traffic congestion became

unbearable particularly during peak hours. Peak hour traffic congestion is an inherent result of the way modern societies operate.

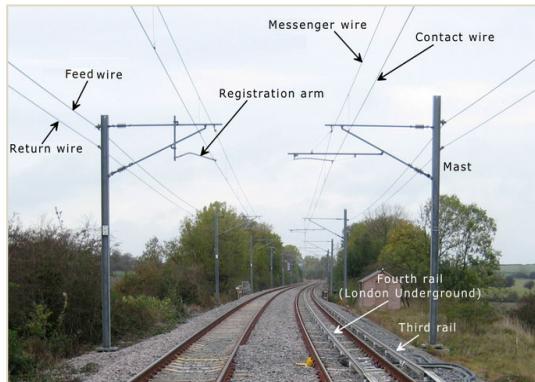
This ramification was forewarned almost 50 years earlier through a survey conducted by a group of researchers from the Committee for International Coordination on National Research in Demography (CICRED). They speculated the future trends in Peninsular Malaysia urban area population growth would rise to 7.1 million within 15 years from a mere 2.54 million in 1975, which was more than 64 % growth. [75]. On that note, in 1984 the then Minister of Federal Territory Shahrir Abdul Samad proposed to put into

**TABLE 7.** The Stray Current Issues of a Third Rail System and the Suggestions for Mitigation.

VOLTAGE SCHEME	STRAY CURRENT	SUGGESTED MITIGATION
Third Rail	Stray current is a function of the track circuit potential or negative rail potential rise. [63]	<p>State a few approaches that can be used to control the generation of stray currents.</p> <p>To maintain the rise of negative rail potential: [63]</p> <ul style="list-style-type: none"> <li>a. increase the conductance of the negative return circuit</li> <li>b. reduce the maximum distance between the load and power source (may result in an increase of the number of substations)</li> </ul> <p>The level of stray current can be controlled via: [63]</p> <ul style="list-style-type: none"> <li>a. the train current [63]</li> <li>b. the voltage developed across the negative circuit resistance [63], [81]</li> <li>c. the effective resistance between the negative circuit and earth (by increasing it to a very high value) [63]</li> <li>d. * the controlling methods applied are as listed in [63]</li> </ul>
Third Rail	<p>The stray current does not return to the substation through the running rails, but travels instead through the soil, where the metallic pipelines are located. As these metallic structures have a lower electrical resistance than the soil, the stray current flows in the pipelines towards the supply station. [82]</p> <p>The DC flowing in the soil can travel through a new high-speed rail transit system especially where there is an extended and very close parallelism between the two systems and may interfere with other surrounding or crossing metallic structures (methane and gas pipelines, and cables). [82]</p>	<p>Some of the protective provisions prescribed by the CENELEC standard to minimise stray currents caused by DC railways and are required to maintain: [82]</p> <ul style="list-style-type: none"> <li>a. a high level of insulation of the running rails and of the whole return circuit from earth</li> <li>b. an adequate clearance between ballast and running rails</li> <li>c. an effective water drainage</li> <li>d. the conductance per unit length values of running rails and return circuits</li> <li>e. appropriate insulation of the equipment connected to the running rails, relative to foundations that are earthed.</li> </ul>
Third Rail	<p>The track is found to have a varying voltage which needs to be kept to a safe level [83]. When the train draws no power, thus no current flows in the rails and the entire track is at earth potential.</p> <p>But when the train draws power, the current flows in the rails and a longitudinal voltage is set up in the rails.</p> <p>To reduce the magnitude of the stray current, a diode-grounded system is an improvement over a solidly grounded system [81]</p>	<p><b>Solution Suggested</b> [83], [84]</p> <p><b>On street track</b> – electrically floating stray current collection mat is the most efficient solution [83], [84]</p> <p><b>Diode connection</b> – the easiest solution for monitoring performance where a mat exists and reduces the efficiency of stray current prevention [83], [84]</p> <p><b>No Diode</b> – scope for improving the monitoring methodology [81], [83], [84]</p>
Third Rail	<p>The fundamental approach towards the stray current issues by the United Kingdom are: [71]</p> <ul style="list-style-type: none"> <li>a. the power system is fully insulated and return paths (rails) are solidly bonded to earth at the substations for safety reasons. Stray current collection methods are applied to intercept earth leakage currents.</li> <li>b. the power system is fully insulated and not deliberately bonded at the substation. Safety is provided by secondary protection schemes performing a vital function. No special stray current collection methods are provided.</li> </ul> <p>The fundamental approach towards the stray current issues on the Continent and the United States is:</p> <ul style="list-style-type: none"> <li>a. The systems are not deliberately insulated from the surrounding environment nor are there any connections made to earth at substations. There is no system of stray current collection.</li> </ul>	<p><b>The pro and cons of each approach:</b> [71]</p> <p><b>Fully insulated earth system</b> - To have a good conducting path the buried mats are equally important in achieving effective protection. The mats should therefore be made continuous. However, they should not be centre tapped but connected at both ends to parallel up with any conductors so that full conductivity is provided.</p> <p><b>Floating negative return system</b> - No deliberate path back to the substation is made for any current which penetrates earth and therefore the propensity to have stray currents using this path in preference to the return rail is reduced significantly.</p> <p><b>The floating of non-insulated system</b> - Any form of insulation through rubber pads for example is often done for reasons of vibration isolation rather than electrical isolation.</p>
Third Rail	<p>The control of corrosion and DC stray currents are critical to the operation and longevity of a transit system. Corrosion can cause structures to weaken and deteriorate, and stray current electrolysis can cause damage to buried structures. [85]</p> <p>Among the benefits gained through controlling the corrosion and stray currents are:</p> <ul style="list-style-type: none"> <li>a. <b>Traction power system:</b> a clean, low resistance path with low voltage drop is maintained for the electrical return circuit.</li> <li>b. <b>Signal system:</b> high resistance path is maintained between rails and earth</li> </ul>	<p><b>The suggested mitigation for:</b></p> <ul style="list-style-type: none"> <li>a. <b>Traction power system:</b> install the negative return running rails with special fasteners as they have a high rail-to-ground resistance. This also includes all additional components that may come in contact with the return rail be insulated or isolated from ground.</li> <li>b. <b>Signal system:</b> installed impedance bonds at insulated joints which can offer a low impedance path thus the DC traction power return circuits travel in almost equal amounts in each rail.</li> </ul>
Third Rail	The stray current can bring hazards to personnel safety and electrolytic corrosion of buried pipes and metal structures if the amount is significant. [86]	<p>Proposed a stray current automatic monitoring system which can provide valuable information for stray current corrosion control and prevention. [86]</p> <p>The system allows the stray current to be calculated indirectly by using running rail resistance, rail to earth resistance and rail to earth voltage parameters. [86]</p>
Third Rail	Raise the issue of the effects of vehicle running mode on rail potential and stray currents. [87]	Proposed field tests and numerical simulations to study whether different vehicle running modes have an impact on rail potential and stray currents. It was found that they did have an impact on the rail potential and the buried-conductor potential, particularly during the acceleration and braking modes. [87]

**TABLE 7. (Continued.) The Stray Current Issues of a Third Rail System and the Suggestions for Mitigation.**

VOLTAGE SCHEME	STRAY CURRENT	SUGGESTED MITIGATION
Third Rail	Raise the issue whether the impedance bond of the tie line has an impact on rail potential and stray currents. [88]	Proposed field tests and numerical simulation using a distributed two-layer ladder circuit model. It was found that the rail potential could be reduced by disconnecting the impedance bond of the tie line so that the negative return current cannot flow to the rails. [88]
Third Rail	Current leakage from a DC railway is an inevitable consequence of the use of the running rails as mechanical support/guide way and as the return circuit for the traction supply current. [66]  The production of stray currents by DC light rail systems leads to the corrosion of the supporting and third party infrastructure in close proximity to the rail system. [66] (nearby buried metallic structures such as pipelines and cable sheaths)	Proposed resistive model networks that significantly reduce simulation runtime and CPU memory usage. [66]. This resistive model network is to demonstrate the influence that different soils have on the corrosion performance of the rail, track bed and metallic pipe.  For uniform soil layers it can be seen that as the soil resistivity increases the proportion of the stray current retained on the track bed is increased while for the metallic pipe the proportion of the stray current is decreased. [68]
Third Rail	Stray current control is essential in direct current mass transit systems where the rail insulation is not of sufficient quality to prevent a corrosion risk to rails, supporting and third party infrastructure. [89]  It should be noted that in a DC system the current loss is direct leakage. Induced effects found in alternating current systems are significant in terms of corrosion damage. [89]	Proposed to use floating return rails to provide a reduction in stray current level in comparison to a grounded system as it was found to significantly reduce the corrosion level of the traction system running rails. [89]
Third Rail	Raise the issue of the nature of the earth underneath the railways could not be represented by a homogeneous medium. The characteristic of the soil varies depending on the location and locally with depth and a homogeneous earth model might be inadequate. [90]	Proposed a comparison between the calculation of the stray current propagation based on a one and a three dimensional earth model. The three dimensional method is more advantageous as it allows the distribution of current around the ground in three dimensions. It is also suitable for a wide range of applications from prediction of the stray current in a railway to the calculation of step voltage around the grounded power system. As three dimensions are also suitable for the calculation of the performance of a resistance to earth made it useful for transient events. [90]
Third Rail	Raise the issue of previous resistor models being incapable of fully predicting nonlinearities that can occur within a stray current collection system under specific conditions such as low ground resistivity. Furthermore the simulation of complex structures is difficult. [91]	Proposed a generic resistor model that can be used to estimate the intensity of stray currents from a DC-electrified railway. The proposed model detailed a DC-electrified railway on a viaduct suspended on concrete piers. The proposed model accurately assessed the current flowing in various elements at different vehicle positions and also voltage impressed at an external underground pipe.[91]

**FIGURE 10. Old Dalby test track for train testing of London Underground [72].****FIGURE 11. LRT Kelana Jaya fourth rail track layout.**

practise Malaysia's first urban transit system but this plan did not take off as expected as Malaysia was not in a state of financial stability.

Nonetheless 14 years later, the transit did come to Kuala Lumpur brought by Sistem Transit Aliran Ringan (STAR), which translates to Light Rail Transit System Star, and Projek Usahasama Transit Ringan Automatik Sdn Bhd or Automatic Light Transit Joint Venture Project (PUTRA-LRT) running from east to west across the city. It runs on two major routes, the LRT Kelana Jaya line and LRT Ampang line with a combined route network of more than 90 km. As these

LRTs commenced during existence of Kuala Lumpur, hence it would be irritatingly bothersome to run at street level. Thereupon these LRTs were built to run on either an elevated or an underground guideway hence guaranteeing a reduced journey time. Relying on this prospect and the ability of the LRT projects to move seamlessly within and between cities, the LRTs in a way gave a reasonable assurance to the public to provide an efficient commuting experience for the urban societies. The trust was reciprocated by the public through the growth of ridership per year for these two LRTs. After almost two decades of service and operation, the LRT Ampang line



**FIGURE 12.** Urban Rail Transit in Kuala Lumpur [77].

has an astonishing increase of 63 % whereas the LRT Kelana Jaya line garnered an 80 % increase. The LRT Kelana Jaya line ridership in 2018 was 87,216,597 passengers with a daily average of 238,950 passengers [76] compared with the daily average in 1999 of only 47,267 passengers, showing signs of future success.

The LRT Kelana Jaya line is unique in its own way. It is the only LRT line in Malaysia that adopted the fourth rail technology and the third in the world. Notably, fourth

rail technology provided a solution to the stray current setback that third rail technology cannot handle. The difference between fourth rail and third rail technology is that fourth rail refrains from using the running rails as its return circuit thus eluding the stray current issue. As those running rails are not insulated from the sleepers (the structures on which they are fixed to), that being so sets up a poor insulation from earth. This poor insulation permits a proportion of the traction return current to leak to earth hence the stray

current. It then flows to any buried metallic conductors and in the LRT Kelana Jaya line case the metallic conductor is the tunnel linings (as this line has to travel through five consecutive underground stations en route to Gombak from KL Sentral), inadvertently forming as its new return circuit instead [32], [57], [66], [68]. This can cause electrolytic damage and even arcing if the tunnel segments are not electrically bonded together [7]. On the contrary, by making use of the fourth rail, its traction technology employs track insulated rail brackets or polymeric insulation [57] as shown in Fig. 11 constraining the return current forces it to return through the appointed conductor.

Boasted as the busiest light rail transit with 46.4 km line length, the Kelana Jaya LRT line runs seamlessly to and fro between the north eastern suburbs of Kuala Lumpur to Petaling Jaya and west of Kuala Lumpur as shown in Fig. 12 with 37 stations to let passengers to board or alight. This electric transit train runs on a 750 VDC fourth rail system and has been operating for two decades. As to why DC voltage was chosen it was primarily for the reason that this line service required frequent stops and acceleration. Another point for DC voltage exertion is for lighter equipment and hence a lighter train allows the carriage of more passengers on board.

In short, light rail came to Kuala Lumpur in 1998 with the creation of the first section of an automatic light transit system (LRT), running from east to west across the city. It ran on two major routes, the LRT Kelana Jaya line and the LRT Ampang line. The LRT Kelana Jaya line is [29 km] running from the north eastern suburbs of Kuala Lumpur and Petaling Jaya to the west of Kuala Lumpur [78]. On the other hand, the LRT Ampang line consists of two routes covering a distance of [27 km]; both routes start at the Sentul Timur LRT Station in the north Kuala Lumpur, with the first route ending in [Sri Petaling] in the south, while the second course ends in Ampang in the eastern suburb of the city. The then existing LRT lines provided transportation for approximately 109,177,817 commuters per year, almost 64 % growth from their first year of service operation [79] within their ten years of service. This inspired the government to initiate a line extension for both routes targeted to allure more commuters. Notably in 2009, the Environmental Impact Assessment of the LRT extension project was approved. The LRT Ampang line and LRT Kelana Jaya line extension commenced in 2010 extending the Ampang route for another 17.7 km from Sri Petaling to Putra Heights and for the Kelana Jaya it was a 17 km route extension from Kelana Jaya and ended with integration with the LRT Ampang line at Putra Heights station [78]. The extensions were completed in the first quarter of 2016 [78]. By 2018, both lines succeeded to increase their ridership by 38,999,225 commuters per year, a 26.32 % distinction. Even so, the LRT Kelana Jaya line had an excellent increase of 33.3 % during the same period [80]. The increase in ridership per year proved just how vital the LRT lines are for the urban commuters especially for the LRT Kelana Jaya line com-

muters proving the success of the fourth rail technology implementation.

## VII. CONCLUSION

Transit is regarded as a sound public transportation system and was born as a reliever to ease the pressure on city streets. The city streets are pressured by the excessive dependency on autos which contributes to rising tensions, more fuel use, higher amounts of air pollution, and slower commuting times. Sustainable public transportation system such as the metro and the light rail transit (LRT) which uses electric propulsion are preferred as it offers lower local air pollution impact and possibly smoother rides for urban travellers. LRT has evolved since its re-emergence in Japan in the aftermath of World War II after the world saw its potential in contributing to Japan's rapid economic growth and social mobility. Nowadays, LRT systems are in operation in 388 cities, the majority of which are in Europe and Eurasia, followed by Asia and North America. As for Malaysian LRT, despite being referred to as an LRT it was left out of the list. The plausible reason why it was left out of the list could be due to the ridership capacity as this ultimately defines the design and the size of the rail transit system. Resultantly, the Malaysian LRT falls in the category of a medium-capacity system where the 'R' in the LRT should be known as rapid instead of rail appropriately fit to its light rapid category.

In the early development of the electric traction system, DC voltage stood as the main power supply as DC technologies were the only choice available. Still, prior to the second Industrial Revolution the series-wound commutator motor was introduced which led to the idea of electrifying the traction directly with AC voltage. As a result, there was parallel development of traction technologies encircling AC advantageous in those Europe industrial countries which led to a plethora of different electrification systems. Nonetheless, this paper was aimed at showing what the main differences in employing the AC voltage and DC voltage traction voltage supplies, the selection of traction types and at mentioning their respective advantages and disadvantages. The main conclusions that can be drawn are the following: AC traction system is preferred to be delivered via overhead wires as it has the capability delivering a much higher voltage hence enabling it to operate long runs at a much higher speed or pulling heavier loads, on the flip side, DC traction system is preferred to be delivered via third rail as it has the advantage of carrying more power than an AC voltage operating at the same peak voltage via the same medium. Third rail traction is a technology that resorts the issue of sleepers being an imperfect insulation when delivering the DC power through the running rails. Accordingly, stray current from a DC third rail is an inevitable consequence of using the running rails as the return path for the traction supply current.

Subsequently, a fourth rail traction technology came to light as a post development of the third rail traction technology, by providing another additional rail acting as the return path. Yet with the advantages that the fourth rail traction

brings, there still are only three urban transits in the world that employ this marvellous traction technology, namely London Underground, Milan Metro Line 1, Italy and the LRT Kelana Jaya line in Malaysia.

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