Analysis of Electric Bus against a Diesel Bus

Project Report Submitted
for the course

Dynamics, control and diagnostics of ground transportations systems

by

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Introduction

Roadways are enormously important to all countries. Countries or regions without adequate roadways cannot function. They are among the widely used means of transporting passengers and goods. In this project we will focus on the role of mass transit by road. Public transportation provides people with mobility and access to employment, community resources and recreational opportunities across the region. It benefits those who choose to ride, as well as those who have no other choice: over 90% of public assistance recipients do not own a car and must rely on public transportation. It provides basic mobility service to these persons and to all others without access to a personal vehicle. Public transportation also aids in reducing road congestion and travel times, air pollution and energy and oil consumption, all of which benefits both riders and non-riders alike.

As the usage of public transportation increases, speed, safety and comfort remain paramount concerns for the passengers. The extensive use of public buses in urban regions provides economic benefits to the communities and offer location advantages to business and individuals choosing to work or live in them. In this project, one such Battery Electric bus – operating in the Line 501, Santiago, Chile has been deliberated and analysed in detail with respect to dynamics, noise & vibrations, infrastructure, emissions produced in comparison with an alternative Diesel Bus currently in use and finally maintenance and diagnostics.

Vehicle Dynamics – Longitudinal and Lateral Dynamics deal with the study of speed and acceleration profiles, which gives noteworthy data on the vehicle operation throughout the line of operation. This data in turn provides information on the driving inputs in detail. It is very important to understand the dynamics of the vehicle as it could support better vehicle handling, comfort, safety of the passengers and improve overall driver vehicle interaction.

Comfort can be obtained by regulating objectionable vibrations and noise sources. These noise, vibrations and harshness levels (NVH) are the essential part of a vehicle as it provides a tactile feedback the vehicle delivers as its driven. It is caused by the vehicle's mechanical and electrical systems, as well as the its interaction with the road surfaces and passage through the air. Removing and isolating passengers from NVH is a field that's seen monumental advances over the past few decades. Appropriate analysis is needed in order to improve the ride and also attract passengers towards this mode of shared public transport.

Infrastructure is alternative significant perspective of looking at any transportation systems. They serve as the foundational structures and systems for transporting people and goods. It concerns with supply of energy for battery electric vehicle and also quality of service provided i.e., road infrastructure. A better quality will attract more demand, which also improves the economic situation.

Emissions testing determines the level of air pollutants emitted from either production of a vehicle or the operation of the vehicle. They have adverse effects on the ecosystem and thereby on human health. Majority of today's vehicles run on gasoline or other fossil fuels and emit harmful pollutants. A detailed comparison of the pollutants released in Combustion and Electric vehicles is discussed.

Finally, like any other transportations system, it is subjected to failure and repair over time. Diagnostics measures are implemented in identifying and consequently repairing these problems across vehicles and infrastructure.

All of this is parallelly compared with an equivalent diesel bus which is currently under operation in Line 501, which also provides a perspective for decision makers or investors.

Vehicle Specification

The vehicle evaluated was a Chinese electric bus Foton U12, in Santiago de Chile are operating 215 units, that represent close to 27% of the electric buses running currently in the city [1]. Foton U12 single windshield coach features streamlined design and optimized lighting, building a more comfortable and pleasant environment for passengers. In the following table the specification of the electric buses is shown, these characteristics will be used in the analysis of this report.

Figure 1; Foton U12 Bus

Length	**12**	**m**
Max passengers	90	
Seats	28	
Consumption[2]	1,1	kWh/km
Slope Max	20	%
Battery capacity	385	kWh
Max Power	350	kW
Max Torque	3.500	Nm
Weight (curb weight+ 50% pax + driver)	16.325	Kg

Table 1: Foton U12 Bus Specifications

[1] https://www.dtpm.cl/index.php/homepage/noticias/647-transporte-publico-metropolitano-alcanza-historica-alza-en-evaluacion-y-usuarios-valoran-incorporacion-de-buses-red

[2] Transantiago Cycle

Figure 2: Volvo 8900 Bus

Volvo 8900, the current bus under operation in Santiago, Chile. We will use this bus to evaluate against the proposed E-Bus.

Length	**12**	**m**
Max passengers	97	
Seats	40+2+1	
Consumption[3]	1,1	kWh/km
Slope Max	20	%
Emission Standard	Euro	6
Max Power	260	kW
Max Torque	1,700	Nm
Weight (curb weight+ 50% pax + driver)	19000	Kg

Table 2: Volvo 8900 Bus Specifications

[3] Transantiago Cycle

Route Characteristics

The route evaluated was the number 501, which operates in the west-east direction, in the steepest sector of the city. The path does not have night operation; hence it could be suitable for depot charge electric technology. In order to analyse the vehicle dynamics, the line has been created by taking certain points using google maps and google earth pro for elevation profile of the created path as shown in Figure. Exporting the map to AUTOCAD software helped us to obtain the radius of curvature for all the turns in track.

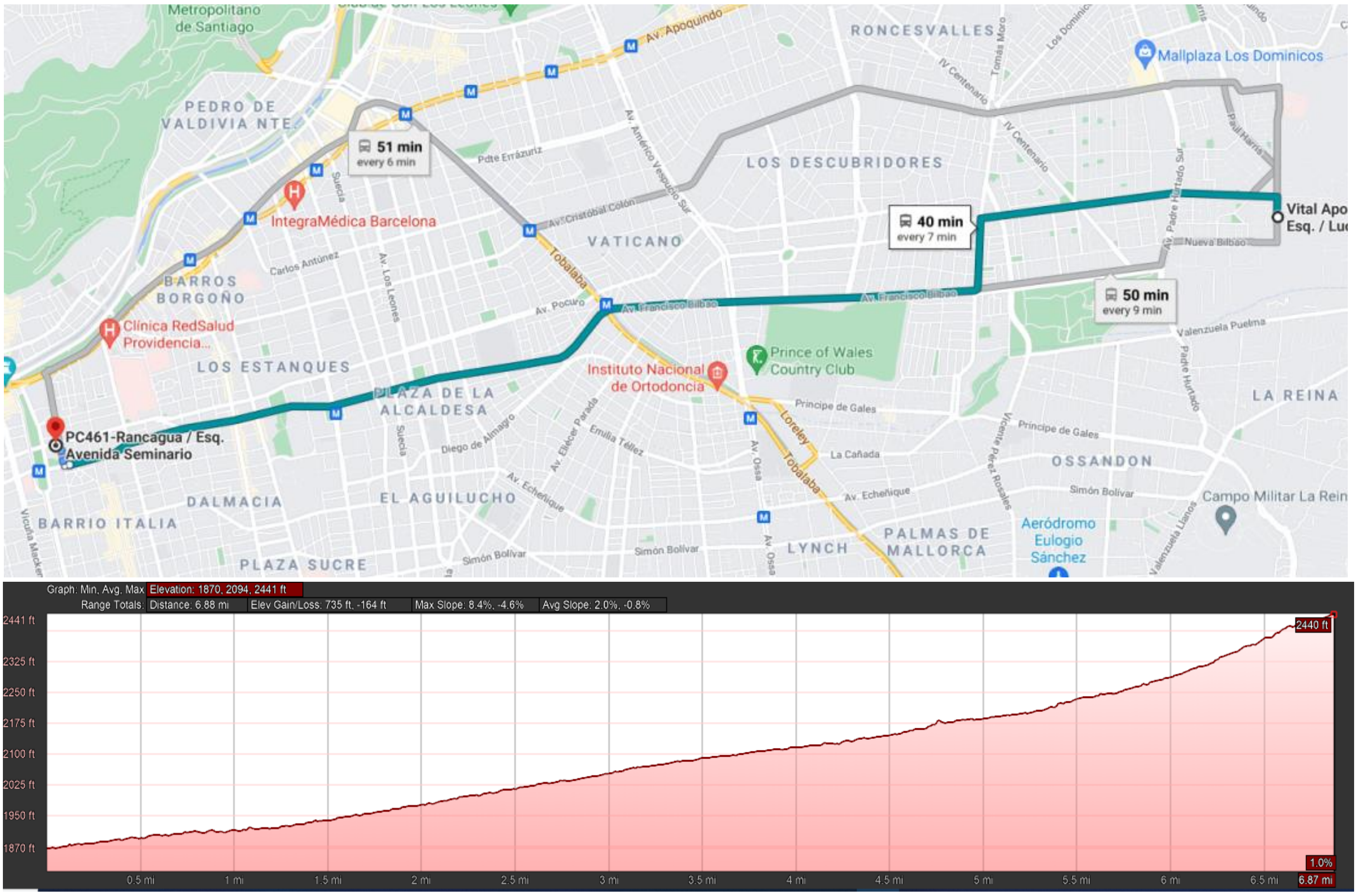


Figure 3: Line 501 and its Elevation Profile

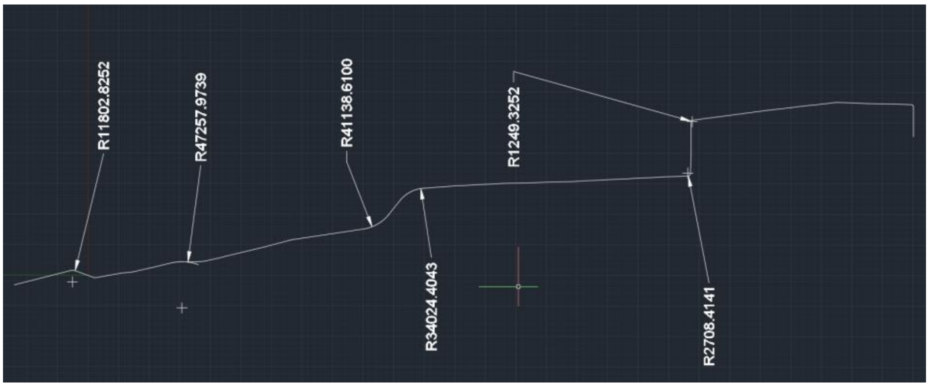


Figure 4: Line 501 curve radius

- Uphill Path length – 10 Km
- Number of Stops – 34 (Stops at 300 m in average)
- Average slope – -2%

The same route was assessed in reverse, using the same method to create path and elevation profile.

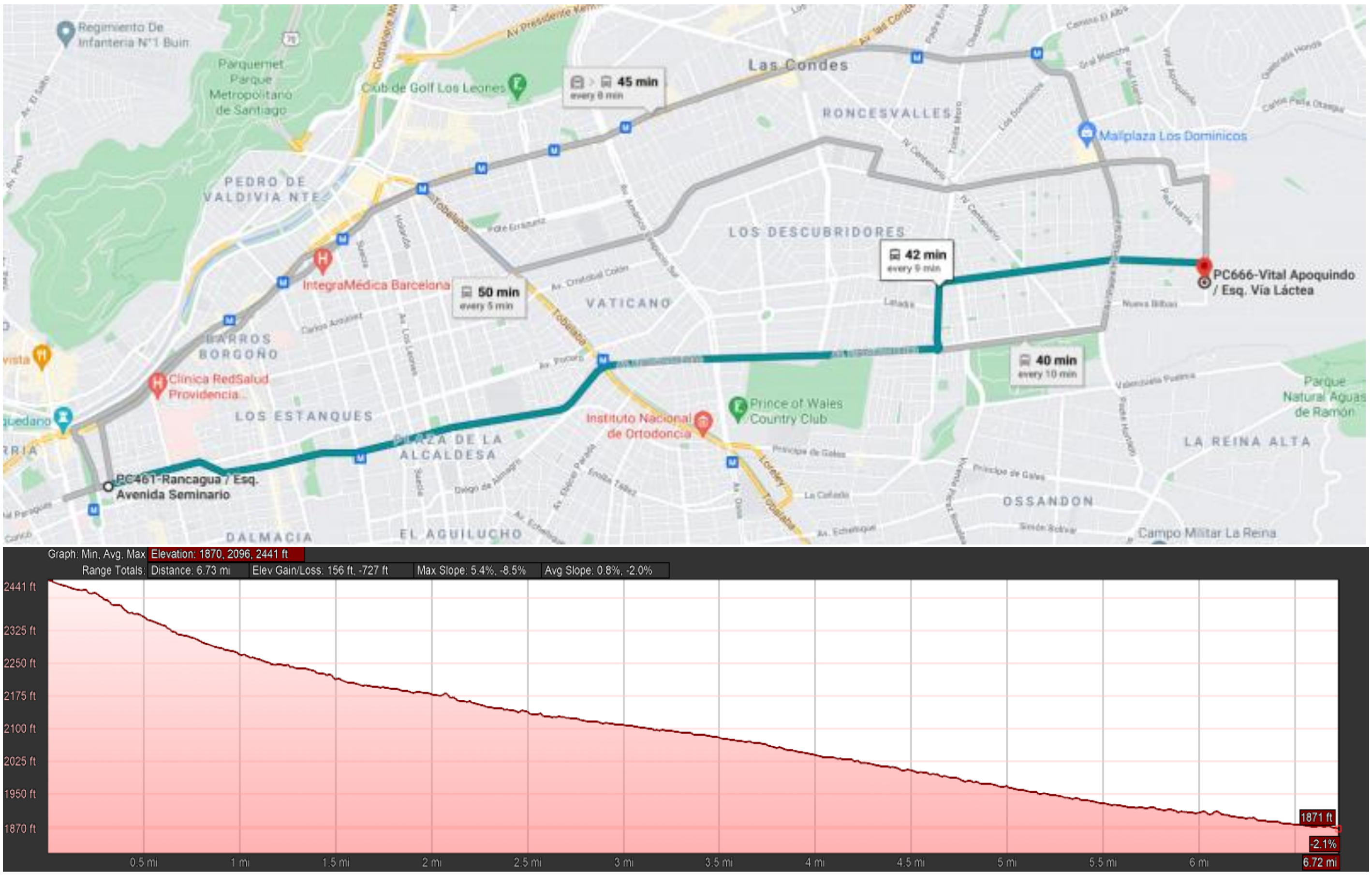


Figure 5: Line 501 Reverse and its elevation profile

- Downhill Path length – 10,8 Km
- Number of Stops – 34 (Stops at 300 m in average)
- Average slope – 2

Vehicle Dynamic Analysis

Vehicle dynamic analysis includes longitudinal and lateral dynamic analysis. In the 1990s, the global automobile industry and market structure underwent tremendous upheaval. Vehicle safety, environmental preservation, and intelligent control are all in high demand. As a result, modern technologies such as computer technology, virtual reality, and clever algorithms have found widespread use in the automobile sector. Automotive dynamics is critical to the advancement of the vehicle industry.

Early vehicle dynamics research focused on varied working circumstances and service performance under external stimulation [1]. Researchers began to work on steering, suspension mechanics, and driving stability in the 1930s. Lanchester Maurice and Segel investigated the impact of the external environment (such as road surface roughness, air flow, tire and driver) on vehicle dynamics, as well as the coupling interaction of these factors [2]. In the Proceedings of the Institution of Mechanical Engineers in 1993, Segel [3] gave a thorough overview of vehicle dynamics achievements prior to 1990. Vehicle ride comfort and handling stability research was intensively explored in the following decades.

The handling dynamics of a vehicle are concerned with its lateral or transverse dynamics, which primarily pertain to vehicle handling stability, vehicle sideslip produced by tire lateral force, yawing, and roll motion. The handling stability of vehicle dynamics study evolved from experimental investigations to theoretical analysis, from open-loop to closed-loop. “Vehicle Handling Dynamics Theory and Application” by Abe [4], and “Vehicle Handling Dynamics Theory” by Guo [5] are examples of exemplary vehicle handling dynamics monographs. The driving dynamics of a vehicle are classified as longitudinal dynamics and vertical dynamics, which comprise driving, braking, and ride comfort. The research of vehicle longitudinal tire force solves the problem of driving slip and braking slip, which may also enhance driving and braking economy. Ride comfort is concerned with vehicle vibration and pitch movement generated by vertical tire force.

The representative monographs are Rajamani's "Vehicle Dynamics and Control" [6] and Zhang's "Vehicle Dynamics Theory and Applications" [7]. Furthermore, the vehicle 123 386 field S. Yang et al dynamics research also includes longitudinal tire force while cars are speeding up or stopping, as well as vehicle vibration generated by a running engine, among other things. The vehicle body (sprung mass), suspension component (spring and damper), and tire (unsprung mass) are all critical components of the vehicle dynamics system. The vehicle-road coupling is another important aspect of vehicle dynamics. In this report the vehicle dynamic analysis is performed on Electric bus and comparison of the results with the diesel bus.

Longitudinal Analysis

Longitudinal Dynamics is concerned with the equation of motion of a vehicle and its reliance on various factors impacting the vehicle's motion. A bus travel along a route is regulated by the equation of motion and limited by speed limitations. Newton's Second Law of Motion is used to create the vehicle dynamic model. The speed limitations are intended to limit the bus's maximum speed along the route for safety reasons. In addition, a specific operating aim may be defined to steer the bus's movement. The movement of a bus along a route is controlled by a variety of factors, including tractive effort, railway resistance, braking forces, and equivalent mass. Tractive effort generates traction for the bus to overcome resistances and accelerate. Bus resistance is caused by the properties of the bus as well as the alignment geometries. Braking force is employed to slow the bus down and bring it to a complete stop. The wheels, shafts, and axles of the bus may store kinetic energy while it is moving. As a result, the net force available for accelerating and decelerating the Bus comprises both its static and rotational masses. Their total is known as the Bus's equivalent mass.

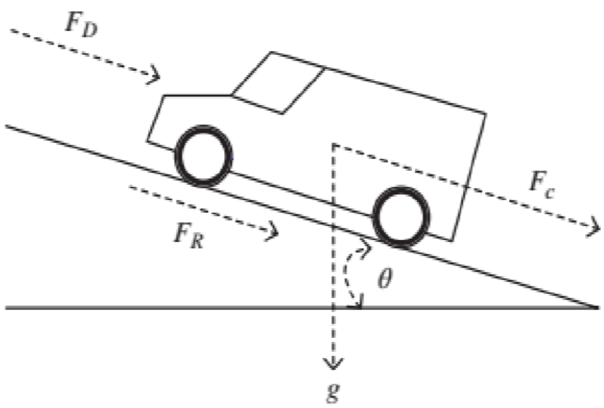


Figure6: Forces acting on the vehicle

The forces acting on the vehicle are
F_D - Aerodynamic force
F_c - Spinning and rotational losses
F_R – Rolling resistance
Θ – Gradient
The load forces acting on the vehicle are represented as

$$F_v = A + Bv + Cv^2$$

Where,

- **A** correlates to the rolling resistance;
  The rolling friction is modelled as
  - $A = F_r = C_r m_v g cos(\alpha)$

  Where:
  m_v is the vehicle mass [kg],
  g is the acceleration due to gravity [m/s^2],
  Cr is the rolling friction coefficient [−] and
  α is the slope angle [deg]

  The rolling friction coefficient Cr depends on many variables. The most important influencing quantities are vehicle speed v, tire pressure p, and road surface conditions. For many applications, particularly when the vehicle speed remains moderate, the rolling friction coefficient Cr may be assumed to be constant.
- **B** relates to the spinning / rotational losses (generally very small);
- **C** relates to the aerodynamic drag;
  C - Aerodynamic friction losses usually, the aerodynamic resistance force Fa is approximated by simplifying the vehicle to be a prismatic body with a frontal area A_f. The force caused by the stagnation pressure is multiplied by an aerodynamic drag coefficient cd that models the actual flow conditions

  $$C = F_a (v) = 1/2\ \rho_a A f C_d v^2$$

  Where,
  v is the vehicle speed [m/s2]and

  ρ_a the density of the ambient air [kg/m3]. The parameter Cd is the coefficient of drag estimated using Computational fluid dynamics (CFD) programs or experiments in wind tunnels.

- v relates to speed of the vehicle

The gradient force is given based on the vehicle whether the vehicle is moving uphill or downhill. The climbing resistance or downgrade force is given by

$$F_c - mg\ sin\vartheta$$

Where,
m – mass of the vehicle
Θ – is the gradient angle of the road
The force required to accelerate or brake the vehicle is given by

$$Fa = ma = m\ *(dv/dt)$$

Where,
m - mass of the vehicle
dv – change in velocity
dt – change in time
The forward motion force required for the vehicle to accelerate is given by power balance equation

$$Fm = F_a + F_v + F_c$$

$$Fm = m\ *(dv/dt) + A + Bv + Cv\ 2 + mg\ \sin\vartheta$$

The operating modes of the bus are considered as

		Tractive effort condition	
Train operation mode		$T_e = 0$	$T_e > 0$
Braking force condition	$B_e = 0$	Coasting mode	Powering mode
	$B_e > 0$	Braking mode	

Table 3: Bus Driving Modes

Bus dynamics are additionally governed by speed restrictions imposed by bus formation, curve, downhill, switch, track strength, blocking signal, weather, and temporary construction, in addition to the equation of motion. A Bus traveling along a bus line must adhere to all speed limitations at all locations along the route. Observing the speed limits.

In this project we considered four operating conditions obeying the equation of motion and speed constraints between station-station. The operating modes are stop, acceleration, constant speed, and deceleration.

Results

Two buses an Electric bus and a diesel bus are used to simulate the behavious of the vehicles to operate in the route. The total cycle time of the bus is divided into two parts uphill and downhill with a total kilometers as 10.082km uphill and 10.805km downhill. The time taken by the bus to cover the 10.082km of uphill is 16.4minutes without considering the terminal time and 10.805km of downhill it takes 17.6minutes without considering the terminal time.

Speed profile of the electric bus while going uphill.

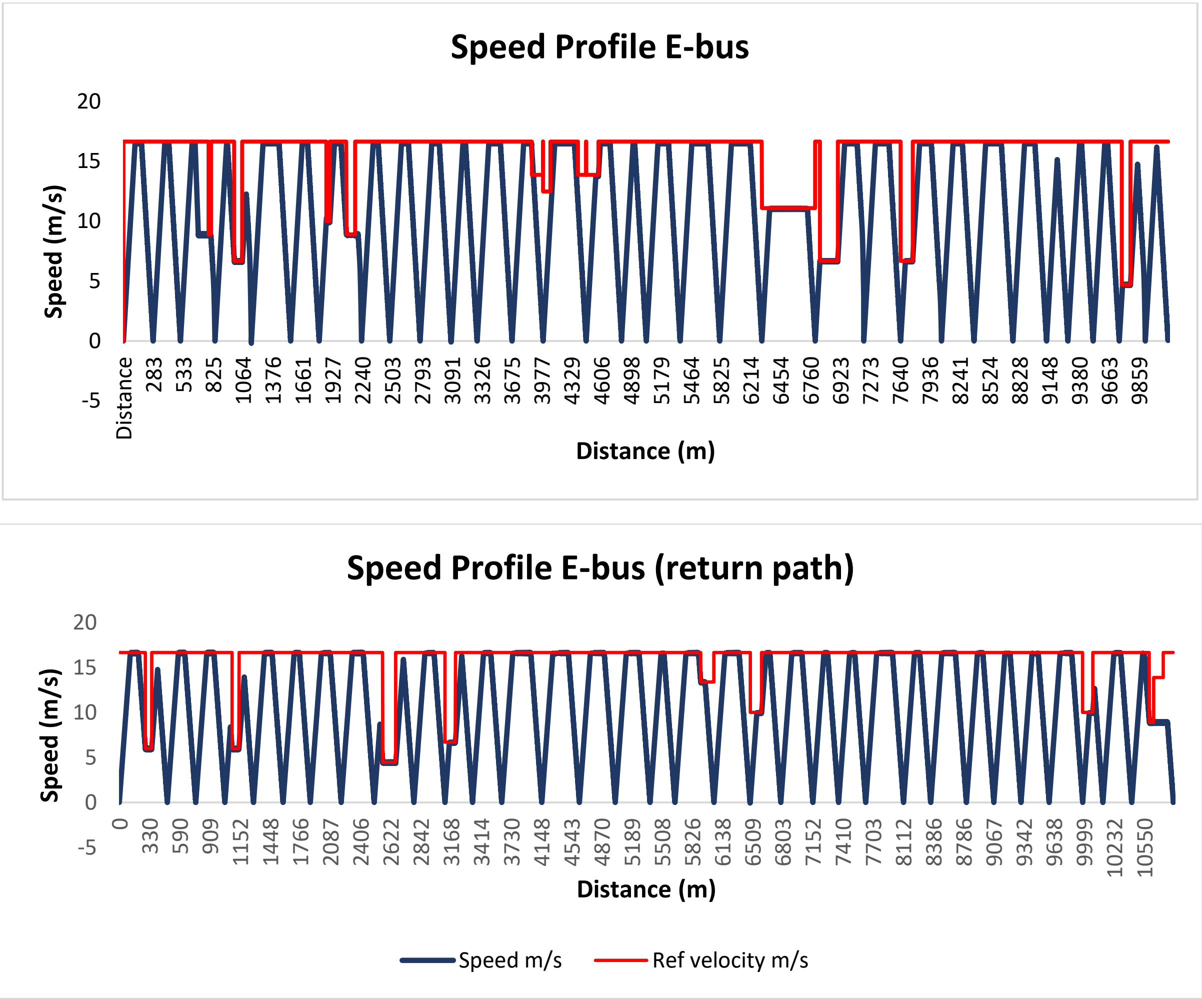
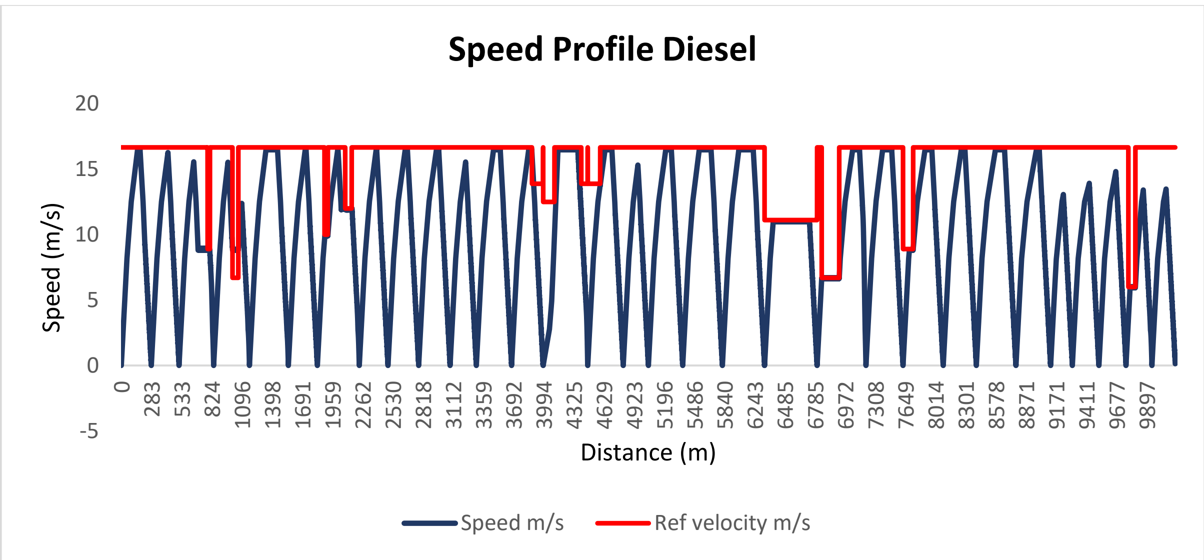


Figure 7: Speed profiles of Electric bus

For the same distance the speed profiles for Diesel bus are computed



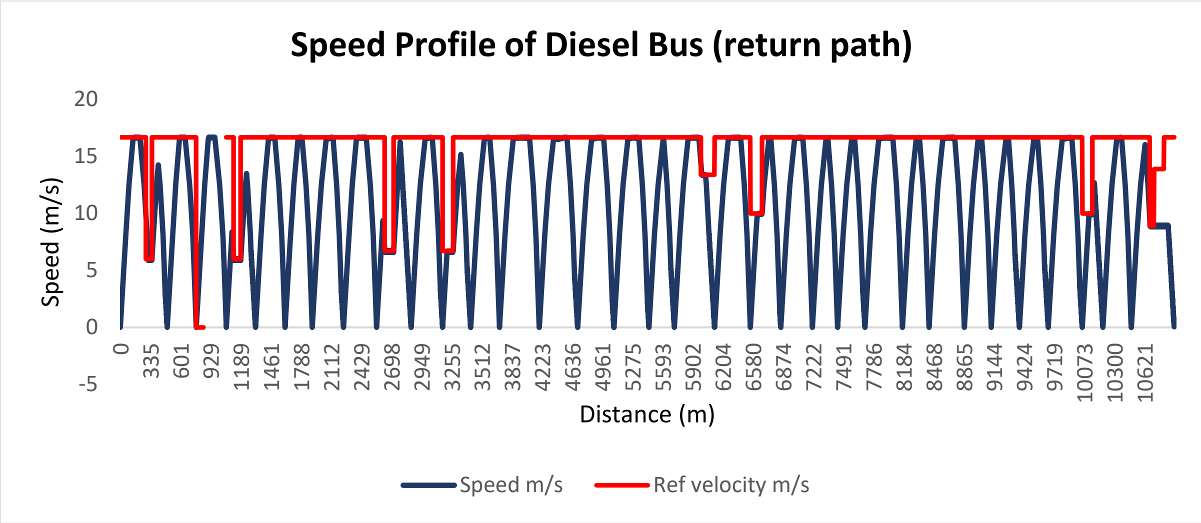


Figure 8: Speed profiles of Diesel bus

We can see that the Electric bus and Diesel bus have taken almost same time to cover the distance even though the diesel bus is powerful with gear ratios, various speeds can be achieved but considering the limitations and speed limit of the roads the vehicle follows the same profile with diesel bus taking 17minutes to cover a distance of 10.082km and 18 minutes to cover the return path.

Lateral Dynamics

A vehicle's lateral motion is required to follow the curves of the road and pick a path in junctions, as well as to avoid obstructions that emerge laterally. The vehicle must be manoeuvrable. With some simplification, lateral dynamics is concerned with how steerable the vehicle is at certain longitudinal speeds. Vehicle steering is mostly investigated using the degrees of freedom of the vehicle: yaw rotation and lateral translation.

Lateral acceleration is an important component in lateral stability and driving safety. Roads must be constructed with a particular super elevation to increase their performance for a certain lateral friction coefficient. The recorded acceleration may be used to assess the logic of a highway's super elevation by comparing it to the permitted levels of acceleration that assure human comfort. The lateral acceleration of a vehicle is closely connected to its lateral stability. The quantity of lateral force pressing on the driver influences the driver's driving behaviour on a curve, such as the choice of trajectory and speed; hence, a thorough research of lateral acceleration can present essential parameters for forecasting the trajectory and speed on a difficult roadway.

Hugemann and Nicke from Germany [9] examined the lateral accelerations of a passenger automobile on an interchange ramp, a ring road of a metropolitan expressway, and a rough mountain route. To illustrate the distribution characteristic, the 10th, 50th, and 90th percentile values of lateral acceleration were collected. A model of the connection between lateral acceleration and curve radius was also produced. However, due to the small sample size, no universal implications could be drawn for design practice [8].

Superelevation is defined as highway tilted to assist counterbalance centripetal pressures generated when the car travels around a curve. They, together with friction, are what keep a car from veering off the road. A transition segment follows a highly elevated portion. **Superelevation / Banking of road** reduces the effect of centrifugal force on the running wheels. If super elevation is not provided with the entire centripetal force is produced by the friction between the vehicle's tires and the roadway, thus results in reducing the speed of a vehicle.

Advantages of providing Super elevation: -

1. Super elevation is provided to achieve the higher speed of vehicles. It increases the stability of fast-moving vehicles when they pass through a horizontal curve, and it also decreases the stresses on the foundation.
2. In the absence of super elevation on the road along curves, potholes are likely to occur at the outer edge of the road

Ride comfort is an important serviceability attribute for bus passengers, of which bus operating under the influence of road layout in urban roads is a prominent contributory factor. In this case study, ride comfort from road-induced lateral acceleration and lateral jerk was assessed by correlating subjective evaluation with bus operation performance parameters as well as road layout in Singapore. Lateral ride discomfort thresholds were thus established for bus negotiating roundabouts, intersections and along links. Proposed three levels of ride discomfort are Uncomfortable, Very Uncomfortable and Extremely, Uncomfortable with average lateral accelerations of ay = 1.5, 1.75 and 2.0m/s^2 , respectively[12].

Considering the level of discomfort factor of lateral acceleration, the superelevation and speeds are considered from the below table.

e (%)	L_B=Basic Runoff in Feet for Design Speed*													
	15 mph	20 mph	25 mph	30 mph	35 mph	40 mph	45 mph	50 mph	55 mph	60 mph	65 mph	70 mph	75 mph	80 mph
2	30	30	35	35	40	40	45	50	50	55	55	60	65	70
3	45	50	50	55	60	60	65	70	75	80	85	90	95	105
4	60	65	70	75	75	85	90	95	100	105	110	120	125	135
5	75	80	85	90	95	105	110	120	130	135	140	150	160	170
6	90	95	105	110	115	125	135	145	155	160	170	180	190	205
7	110	115	120	130	135	145	155	170	180	185	195	210	220	240
8	125	130	135	145	155	165	180	190	205	215	225	240	250	275
9	140	145	155	165	175	185	200	215	230	240	250	270	285	310
10	155	160	170	180	195	205	220	240	255	265	280	300	315	345

Table 4: Super elevation with respect to the width of the road and reference speed [10]

From the table based on the width of the road in feet we used the super elevation and the reference speed.

If a ≠ 0, it is called non-compensated lateral acceleration. Lateral acceleration is calculated as follows:

$$a_{LAT} = v^2 / R$$

Where:

$\boldsymbol{aLAT}$ – Lateral acceleration,

v – Bus speed in the curve (m/s),

R – Curve radius (m) and

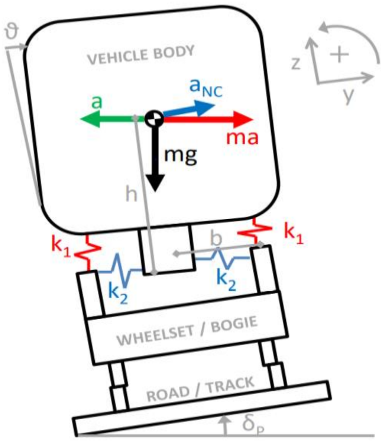


Figure 9: Vehicle inclination due to super elevation

Non-compensated acceleration is as follows:

$$a_{NC} = a\cos\delta_P - g\sin\delta_P$$

It is possible to compute the rotational equilibrium (Figure 8):

$$2k_1 b\Delta l_1 - ma_{NC}h - mgh\ \sin\vartheta = 0$$

$$\vartheta = m * (a_{NC}) * h / (2k_1 b - mgh)$$

And the lateral equilibrium (Figure 8):

$$ma_{NC} - 2k_2\Delta l_2 = 0$$

$$y = m * (a_{NC}) / 2k_2$$

Where

$\boldsymbol{a_{NC}}$ =non compensated acceleration,

$\boldsymbol{\delta_P}$=Cant angle = h/2b0

h = super elevation

$\mathbf{b_0}$ = Gauge

ϑ = Roll angle,

y =lateral displacement

Results:

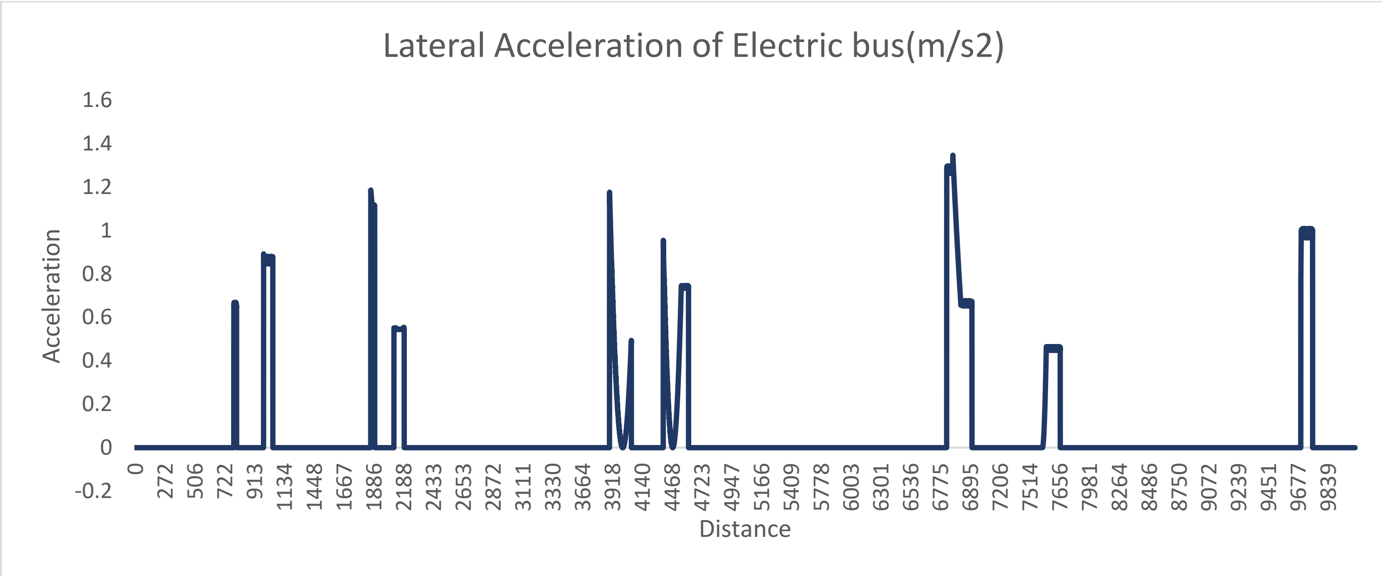


Figure 10: Lateral acceleration of Electric bus

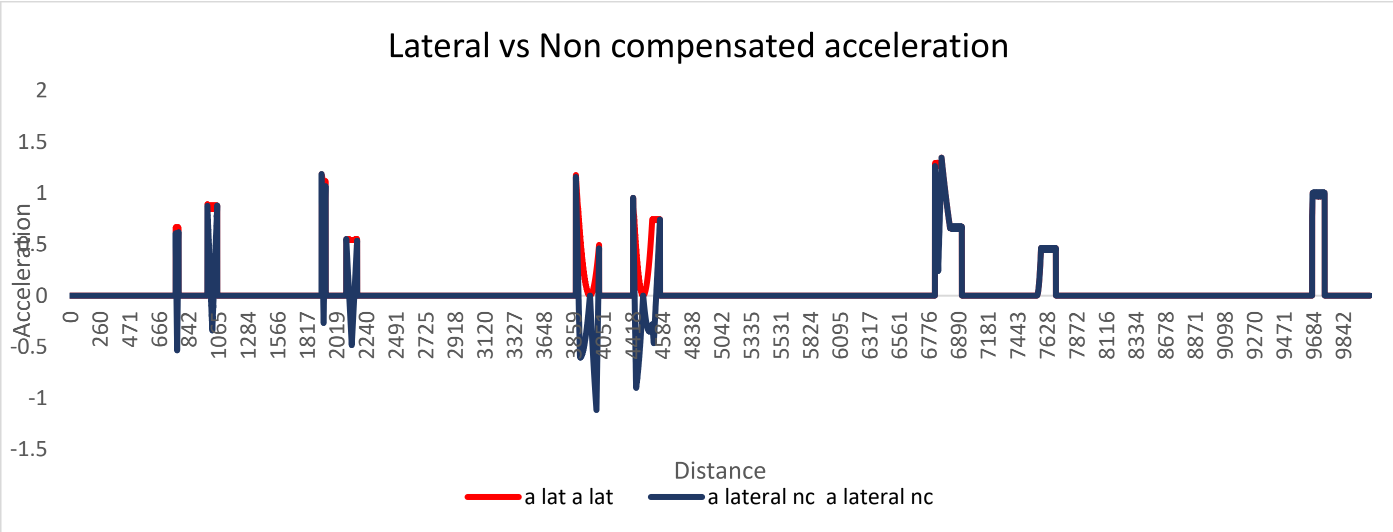


Figure 11: Lateral Acceleration vs Non compensated acceleration of E-bus

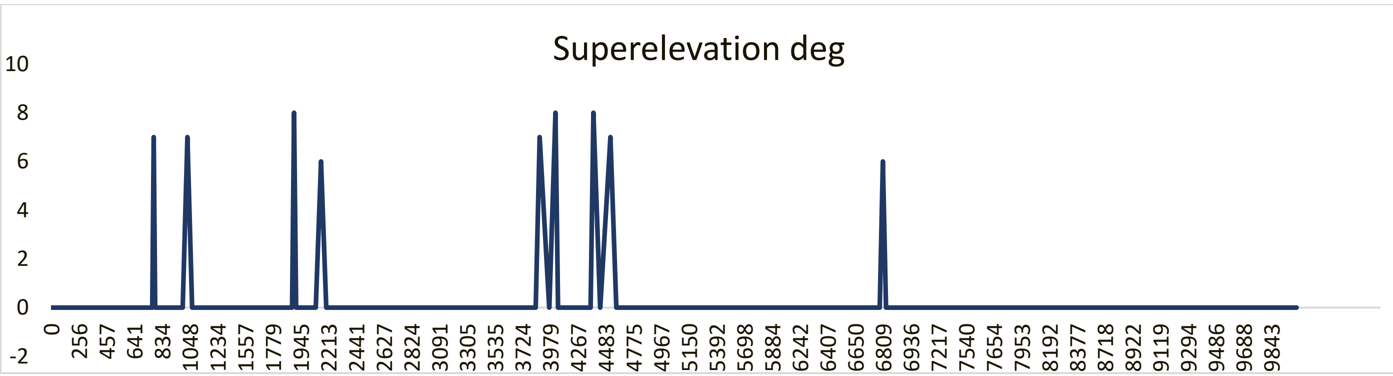


Figure 12: Superelevation of the road along the road profile

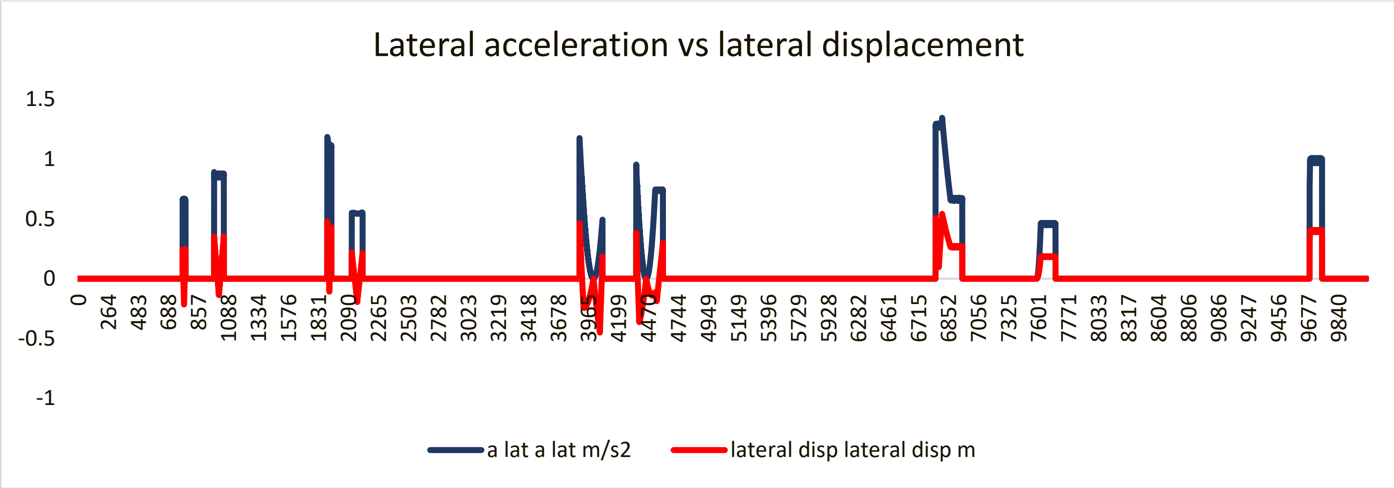


Figure 13: Lateral Acceleration vs Lateral Displacement

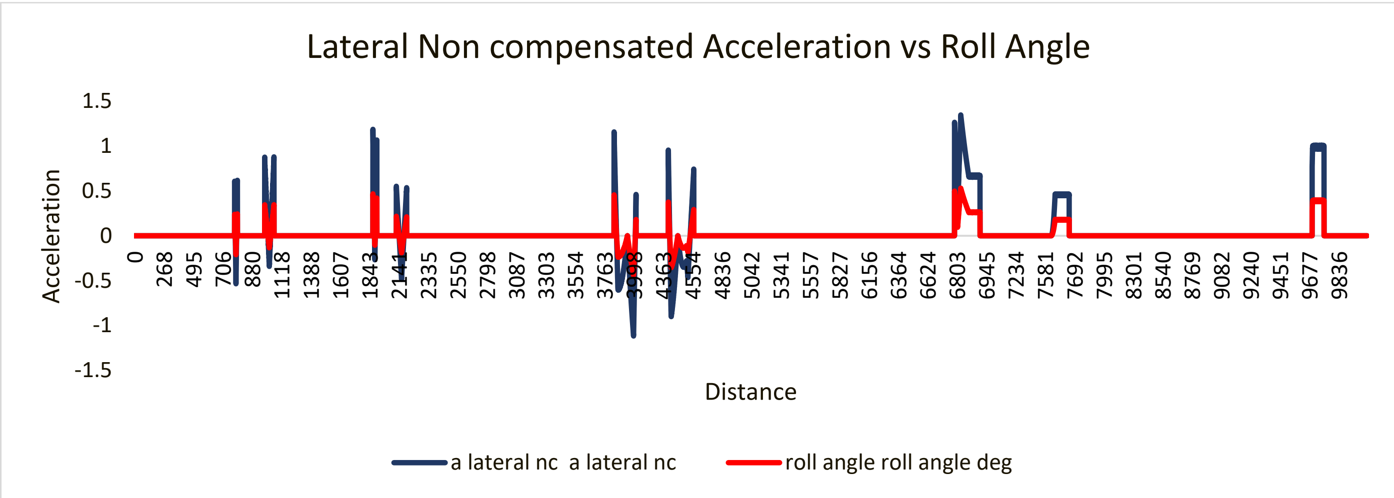


Figure 14: Lateral Acceleration vs Non compensated acceleration of E-bus

Similarly lateral acceleration of the diesel bus along the same route is analysed with results almost being the same.

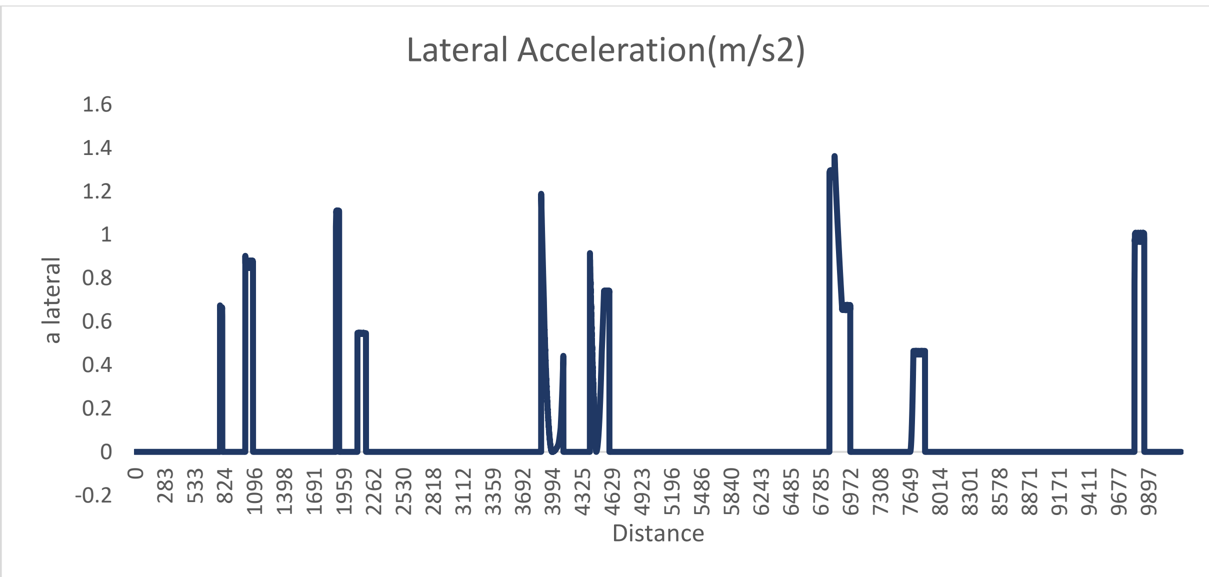


Figure 15: Lateral acceleration of Diesel Bus

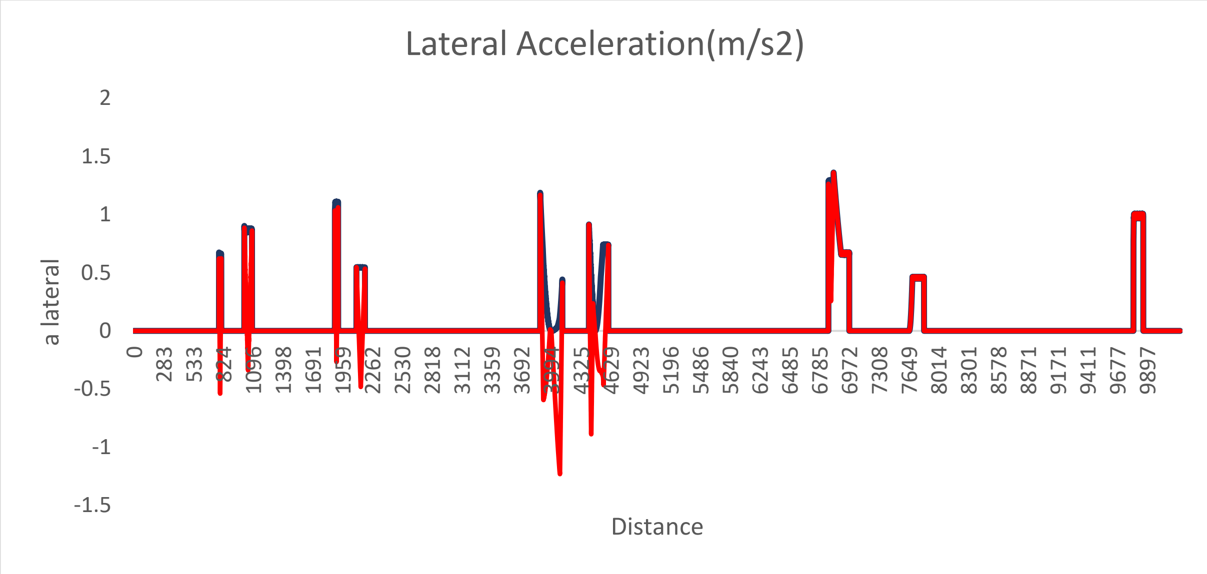


Figure 16: Lateral acceleration vs non compensated acceleration of diesel bus

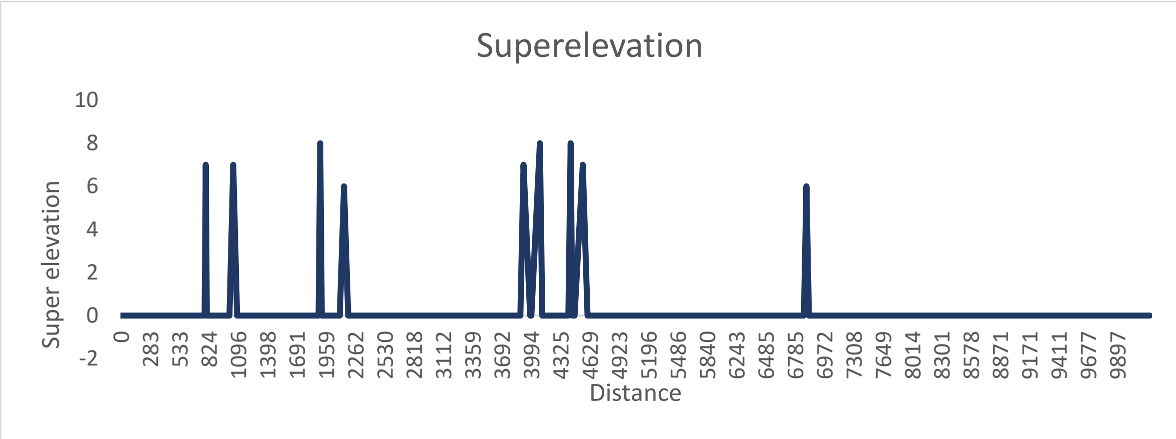


Figure 17: Superelevation of the road

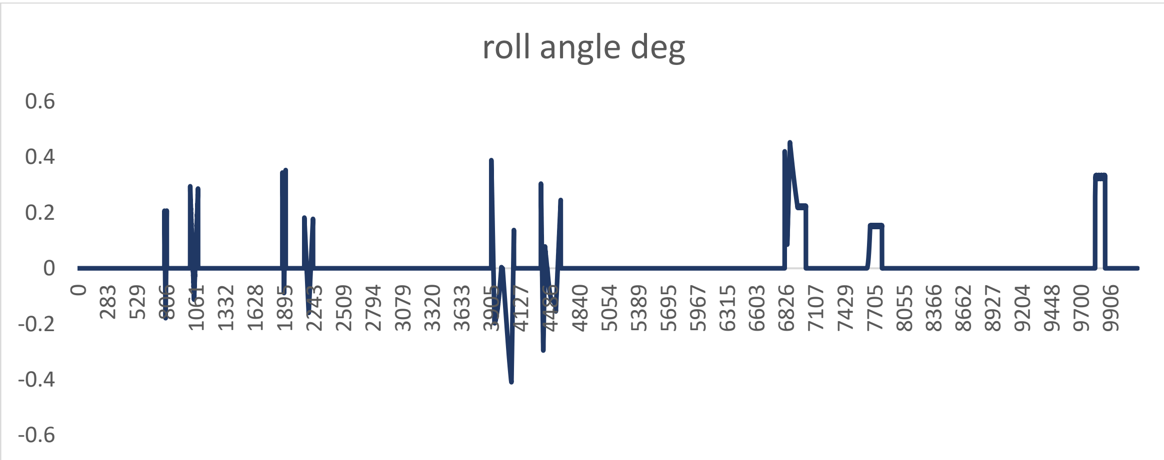


Figure 18: Roll angle of diesel bus

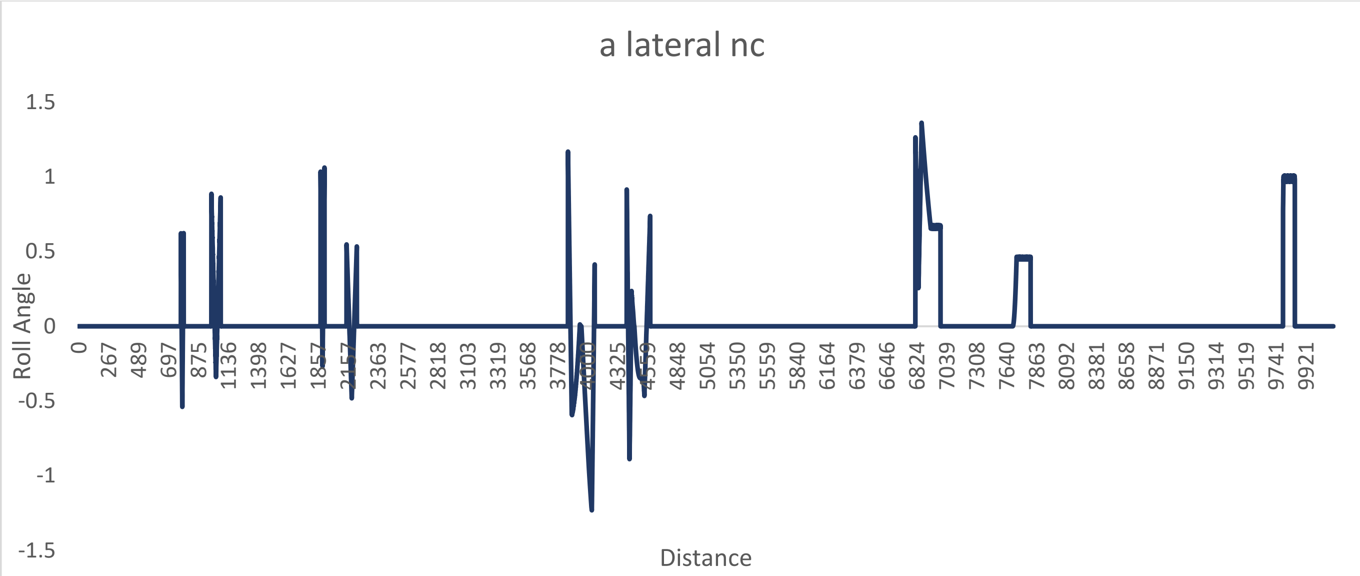


Figure 19: Noncompensated lateral acceleration of diesel bus

Energy Consumption Analysis

After the develop of speed profiles and compute tractive force in each point, energy consumption was evaluated (Equation 1Equation 2):

$$If\ Tractive\ Force\ \geq 0\ \rightarrow Energy = \left(\frac{Tractive\ force * Speed}{\eta_T}\right) + P_{AUX}$$

Equation 1

$$If\ Tractive\ Force\ < 0\ \rightarrow Energy = (Tractive\ force * Speed * \eta_B * Bel_{\%}\ ) + P_{AUX}$$

Equation 2

Where:

η_T, *Traction efficiency, 0,85*

η_B, *Braking efficiency, 0,8*

$Bel_{\%}$, *Regenerative efficiency 70%*

P_{Aux}, *Energy consumption by auxiliar devices (for example air conditioning), 6 kW*

Following figures show energy consumption profiles, where the bus operates downhill and uphill. As it was described before, length of both paths is near to 10 km and when the bus running uphill the energy required is close to

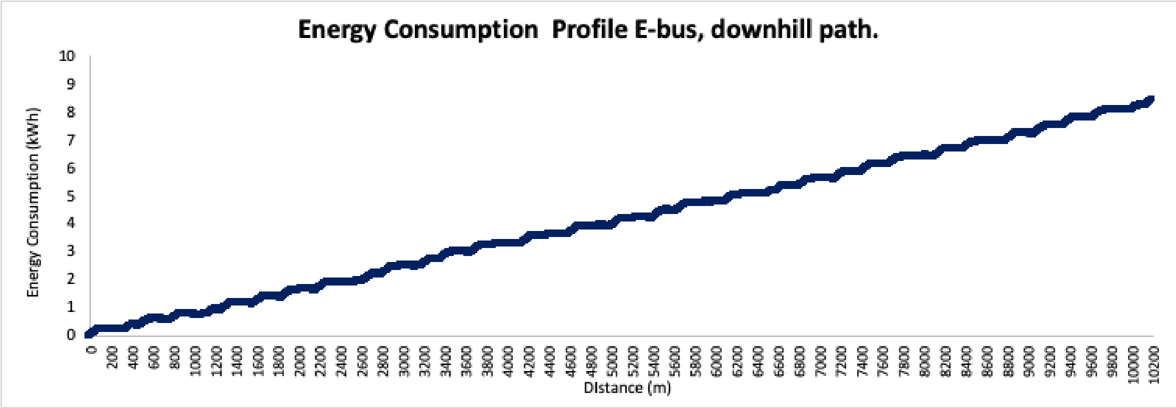


Figure 20: Energy profile electric bus operating route 501 downhill direction

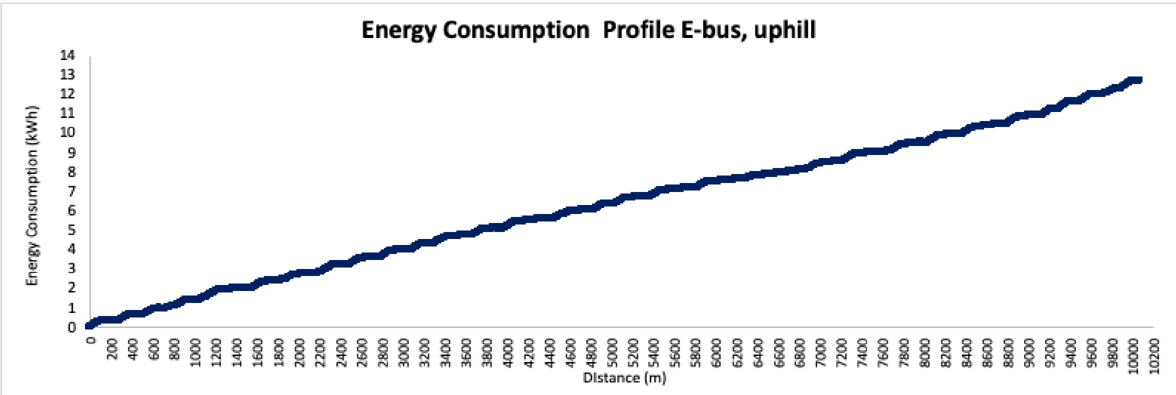


Figure 21: Energy profile electric bus operating route 501 uphill direction

In this table, energy consumption rates are present; as displayed in the last figures, path downhill shows better results than path uphill. The difference between both directions is close to 34% due to the extra energy that requires the bus to overcome the slopes of the route.

	501	
	Downhill	Uphill
Consumption rate (kWh/km)	0,828	1,258
Roundtrip consumption (kWh/km)	1,036	

Table 5: Energy consumption

The following equation is related to the autonomy of the bus operating in this route. If aspects as the maximum discharge of the battery and the driving factor are considering, the bus could run 270 km with only one night charge. It takes into account a discharge of 80% because manufacturers recommend leaving a remaining 20% of energy in the batteries to guarantee their useful life. Moreover, since not all drivers operate the electric buses efficiently and the regeneration of energy could be affected, a "driving factor" is considered, incorporating a margin of 10%.

$$Max.Autonomy\ (km) = \frac{Batt_{Cap} * Discharge_{max}}{Energy\ Consumption * Driving_F} = 270\ km$$

Equation 3

Batt cap: battery capacity = 385 kWh

Discharge $_{max.}$ = 80%

Energy consumption = 1,036 kWh/km round trip

Driving $_{F}$= Driving Factor= 1,1

The State of Charge (SOC) is one parameter used in electric vehicles, and it is related to how is the discharge of the battery in one period or distance. For example, Figure shows the SOC of the bus running route 501, where the vehicle could run approximately 270 km if it starts its operation with 100% of energy, meaning to do 13 round trips.

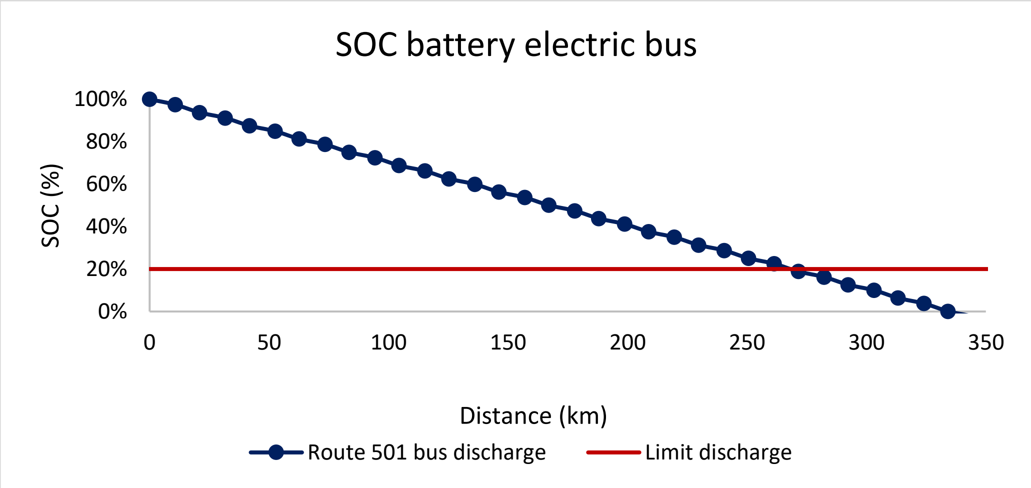


Figure 22: State of charge of 501 route operated by Futon electric bus.

Vibration Analysis

When discussing the topic of dynamic analysis what is usually done is concentrating our attention on the displacement, velocity, acceleration and stresses that a certain body presents while interacting with a force field. Generally speaking, mechanical systems are composed by multiple bodies that will present a certain number of degrees of freedom, each vibrating in a certain way.

A body can perform motions 'in the large' or about a certain position defined as position of static equilibrium, identifiable by considering null all the components of velocity and acceleration of the body. The study is conducted considering the physical properties of the bodies (the mass) and the properties of what connects said bodies (spring stiffness and damping). One possibility for studying the interaction between bodies and d.o.f. is by means of a mathematical model based on the various form of energy the system deals with during its motion. The model is known as Lagrange Equations and it considers the terms of Kinetic energy, Potential energy (stored in both forms of spring energy and gravitational energy) and the amount of energy dissipated by means of the viscous effect.

The level of detail with which the system is analyzed depends on the scope of the analysis. For a single, complex body said analysis can be performed considering the body rigid (and then seeing the vibrations as a pure movement of the body with respect to its defined degrees of freedom) or considering the body deformable, in which case the whole body vibrates with infinite degrees of freedom. In some cases, the depth of a rigid-body-level of study is sufficient in order to estimate all the parameters needed, in other cases much more complex approaches have to be undertaken. For simple, easily schematically, rigid bodies the preferred approach (and the one that has been undertaken for the study proposed) is based on the dynamic equilibrium equations.

Mathematical approach study

Given a system composed of a certain number of bodies (N), each identified by its own coordinates, and a certain number of coupled spring-dampeners, it is possible to consider the forces exchanged between the elements of the system in order to write the differential equations from which the equations of motion will be extracted. The aforementioned equations can be rearranged in matrix form as follows:

$$[M]\ddot{\boldsymbol{x}} + [R]\dot{\boldsymbol{x}} + [K]\boldsymbol{x} = \boldsymbol{F}(\boldsymbol{x}, \dot{\boldsymbol{x}}, \ddot{\boldsymbol{x}}, t)$$

where:

[M] is the matrix that contains the information related to the masses and the inertia of the system;

[R] is the matrix that contains the information related to the viscous elements and in general the dissipative components of the system;

[K] is the matrix that contains the information related to the springs and in general to the elastic elements of the system;

$\boldsymbol{x}$ is the vector containing all the displacements and in general is the vector that contains all the independent variables;

$\dot{\boldsymbol{x}}$ is the vector that contains all the velocities related to the various coordinates;

$\ddot{\boldsymbol{x}}$ is the vector that contains all the accelerations related to the various coordinates;

$\boldsymbol{F}(\boldsymbol{x}, \dot{\boldsymbol{x}}, \ddot{\boldsymbol{x}}, t)$ represents the vectorial forcing term, function of the position, the velocity and the acceleration of each body that composes the system and the time variable.

Study of the forcing term

The forcing term can happen to be either static or dynamic: a static term only influences the resting position of the bodies, while a dynamic term affects also the amplitude of the vibrations as well as the delay between the application of the force and the actual displacement felt by the system. Generally speaking, a static forcing term will be characterized only by its value, while a dynamic one is characterized by both its value and the frequency with which it affects the system.

Each equation Ei composing the aforementioned system of equations will present it's own forcing term Fi, where:

$$F_i = F_{i0s} + F_{i0}\ \cos(\Omega t)$$

In the above equation Ω is linked with the frequency with which the force interacts with the system while Fi0s is the static term, which will not be considered in the following report. The forcing term can be seen not only as a real valued function of time, but also as the real part of an imaginary function where Fi represents a rotating vector in the imaginary field, as follows:

$$F_i = F_{i0}\ \cos(\Omega t) = Re(F_{i0}\, e^{i\Omega t})$$

From the above consideration it is easy to reconsider how said vector rotates with angular speed Ω.

Considering a linear system, it is possible, by means of the Fourier transform, to decompose a generic forcing term F as a combination of harmonic functions whose frequencies are integer multiples of a fundamental frequency Ω_0.

$$f(t) = \sum_{0}^{\infty} |F_n| \cos(n\Omega_0 t + \theta_n)$$

$$F_n = F_n(n\Omega_0) = \frac{2}{T_0} \int_{-\frac{T_0}{2}}^{\frac{T_0}{2}} f(t) e^{-in\Omega_0 t} dt = |F_n| e^{i\theta_n}$$

In the above equation the first forcing term, which presents a n=0 thus making it a static component, corresponds to the average value of f(t). The dynamic response x(t) of the system will be obtained by analyzing for each integer n the solution of a single d.o.f. forced by a certain excitation force Fn. Under above statement it becomes evident the importance the solution of an harmonically excited single d.o.f. has.

By means of this approach a complex, time dependant, force term has been made accessible to a superposition-based study that will yield, once recomponed, the vibration characterising the whole system.

Harmonic transfer function and solution of the harmonically excited system

When approaching the study of a vibrating system it is often useful to study the harmonic transfer function of the system in order to be able to extract values of a certain output given the registered/studied input. In this the vibrating system is seen as a box on which, as an example, we can impose a generic applied force f(t) from which we can extract the displacement x(t) of the system. As long as it it possible to identify an input and an output this approach is viable, even for n d.o.f. systems or more complex ones.

Generally speaking the harmonic transfer function can be used when one wishes to pass from a time domain to a frequency domain using once again the Fourier transform.

Considering now a single d.o.f. system excited by an harmonic force of modulus F_0, phase θ null and frequency Ω:

$$m\ddot{x} + r\dot{x} + kx = f(t) = F_0 Cos(\Omega t)$$

the solution x(t) will be given as the sum of a term describing the transient vibrational behavior and a term describing instead the steady-state vibration of the system. Both cases follow the same approach of expressing the solution as an exponential and then deriving in order to obtain the characteristic equation of the system, from which the vibration x(t) can be extracted:

$$x(t) = x_G(t) + x_P(t)$$

$$x_P(t) = X_P e^{i\Omega t} = |X_P| e^{i(\Omega t + \varphi)}$$

$$X_P = \frac{F_0}{(k - m\Omega^2) + i\Omega r}$$

$$H(\Omega) = \frac{X_P}{F_0} = \frac{1/k}{(1-a^2)+2iah}$$

In the above equations x_G is the term representing the general solution (linked to the transient) x_P the term related to the particular solution (steady-state) and H(Ω) is the harmonic transfer function, or in other words the function that represents the response of a vibrating system following the excitation by a harmonic applied force of unitary modulus. The terms that have been introduced (a,h) are terms fundamental for a generic, non-dimensional approach, and represent the link that runs between the properties of the various physical terms and the forcing term.

In particular:

h is the non dimensional damping, or in other words the ratio between the real damping of the system and the damping that would yield a null Δ in the characteristic equation of the system.

a is the ratio between the frequency of the forcing term and the natural frequency of the system, defined as $\omega_0 = \sqrt{\frac{k}{m}}$.

Since the formulation of H(Ω) is in a complex form of course it will need to be re-arranged in order to better present its real/imaginary components as well as the phase delay of the response, although these passages will be omitted since out of scope of the project.

A further step can be taken by explicitating the **dynamic amplification coefficient** described as

$$A(a) = \left|\frac{X_P}{X_{ST}}\right| = \frac{1}{(1-a^2)^2 + (2ah)^2}$$

Depending on the relation between the forcing term and the natural properties of the system the amplitude of the A(a) will vary as shown in the following graphs (taken by Advanced Mechanics of Dynamical System, F. Cheli, G. Diana, 2015):

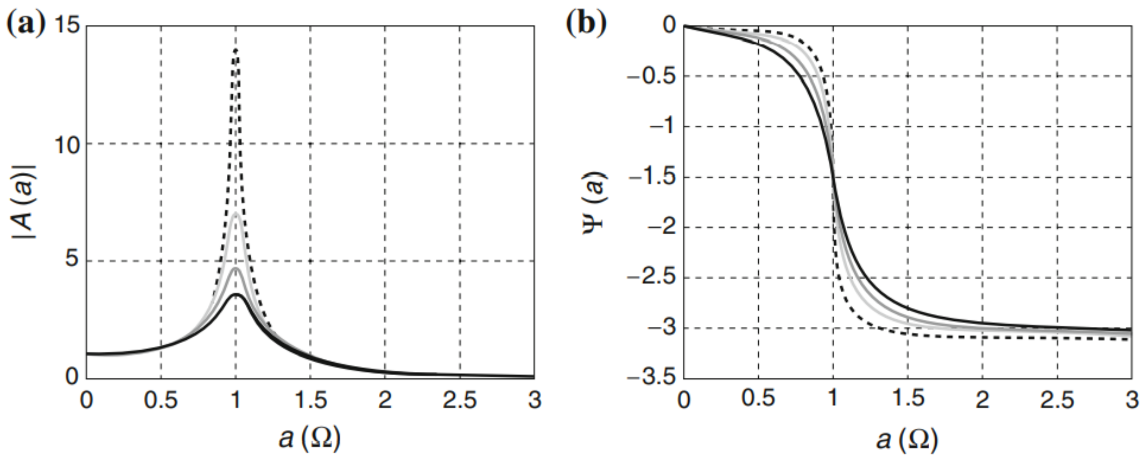


Figure 23: Steady state response of the system to an external forcing term

From this it is possible to see how a forcing term's effect strongly depends on the natural frequency the system possesses and that an increase in the adimensional damping makes the vibration much more tollerable in the neighborhoods of the natural frequency.

Road irregularity and transmission of vibrations

When travelling on a real road a major role on the vibrations is played by the road irregularity. As a matter of fact, due to its natural composition roads will generate a certain number of vibrations to the wheel, which will be then transferred through the suspension to the passengers. Due to comfort limits, regulations and, as will be seen later on, effects on health, particular attention has been posed on the accelerations passengers undergo during a generic trip.

The first step in our study was to mathematically define the cause of the vibrations: a generic asphalt profile can be seen as a combination of sinusoidal functions by means of the Fourier transform. Through the mathematical analysis it has been possible to separately study the effect of the single components that excite the suspension.

The vehicle has been considered to move at a constant speed equal to 60km/h and the parameters of the vehicles have been set to:

h= 0,2;

m = 19350/4 kg (since the model's approach is the quarter of vehicle model);

$\omega_0 = 1\ Hz$.

The values that have been assumed come from considerations based on both the dynamical interaction of the system with street bumps and excitations and passengers' comfort.

In the details the value of h is settled as a compromise between the dynamical response of the system to bumps (step-function) and the dynamical response of the system to general vibrations. Although a lower value of h would benefit the response vibrations it would negatively affect the response to bumps or joints.

The value of ω_0 is settled with respect to the natural frequency of the organs, which may become over-excited by the amplification of the vibrations.

Due to above considerations:

- the longitudinal abscissa is obtainable as $z(t) = V * t$;
- the displacements caused by the irregularity will be named y and will happen at $\dot{y}$ speed;
- the track irregularity is assumed as a known element and is given by the PSD function.

The PSD of track irregularity is:

$$Syy = G_0(\frac{n}{n_0})^{-w}$$

where:

- G_0 is the gain which has been considered in a whole range between 1e-7 and 5e-7;
- n_0 = 1/2π;
- w = 2 is the waviness parameter;
- n is the cyclic wavenumber.

The Syy undergoes the Harmonic Transfer function yielding the PSD of the response of the system

$$Sxx(\lambda k) = Syy(\lambda k) * TR^2$$

from which the amplitude of vibrations (x) can be extracted. The values of x obtained are now used to compute the accelerations and by means of a ponderation filter the final acceleration felt by passengers is obtained:

$$a_w = \sqrt{\sum(W_k a_k)}$$

The particular filter used in above equation is the one related to the way that vibrations at a certain frequency are felt by users while sitting. There is to say that the way the filter behaves is a low-band-passing filter, since the weights assigned to the frequencies present highest values in the range 3-10 Hz, while rapidly decreasing and reaching very low values after 250 Hz.

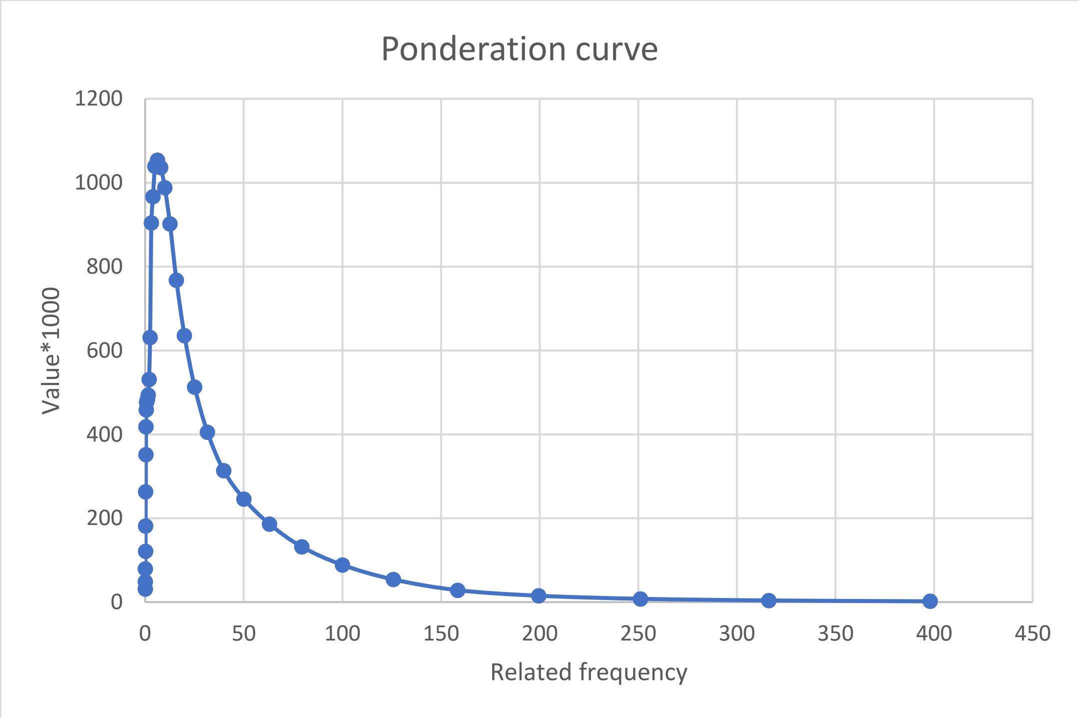


Figure 24: Ponderation curve

The computations done have returned values inside of the range [0,124; 0,279] [m/s^2] depending, as mentioned above, on the value of the gain.

Generally speaking, values below 0,315 [m/s^2] are considered to be totally not uncomfortable while values above 0,315 [m/s^2] are considered to be, on an increasing degree, uncomfortable. Considering an average value of gain equal to 3e-7 the result obtained was 0,2164 for which we consider ourselves satisfied.

Further studies on the effect of parameters

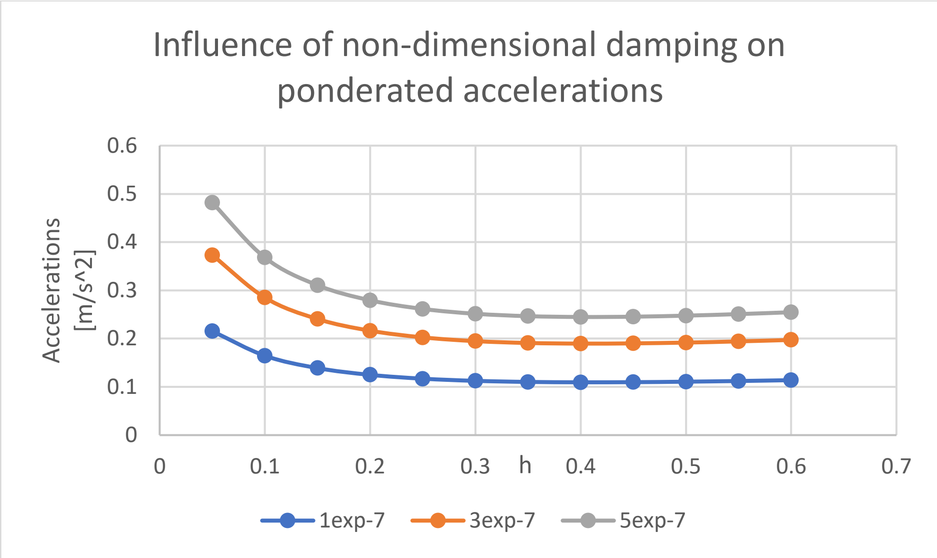


Figure 25: Influence of non-dimensional damping on ponderated accelerations

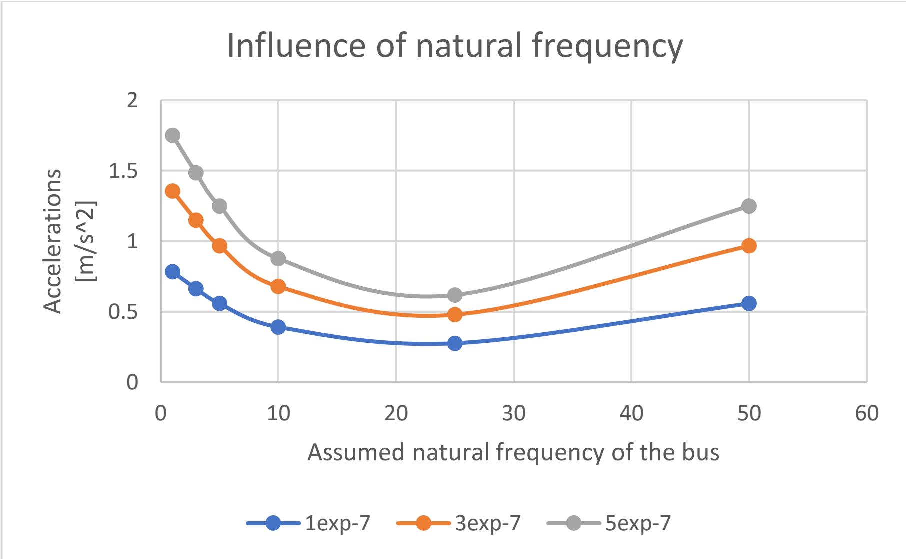


Figure 26: Influence of natural frequency

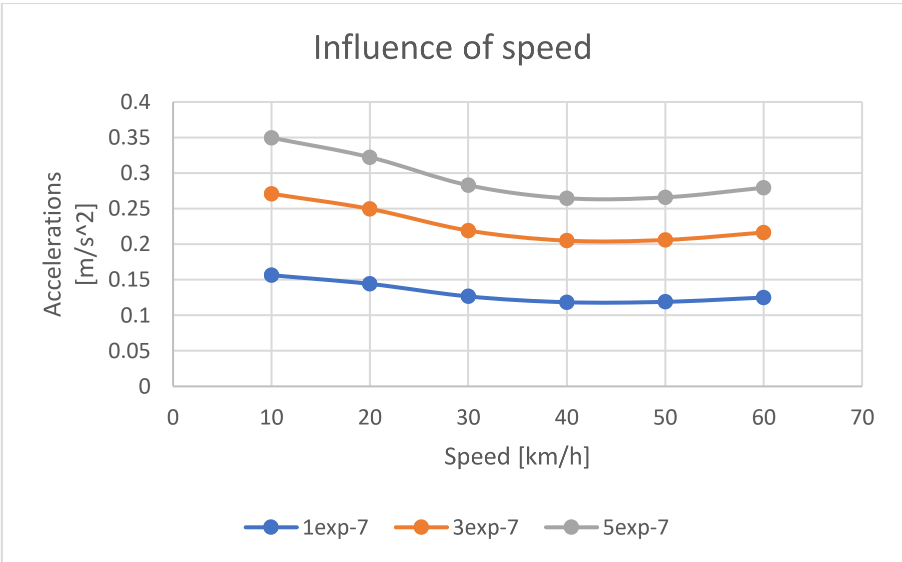


Figure 27: Influence of Speed

Vibrations transmitted to infrastructures

Vibrations however do not only represent a critical factor for people on board of the vehicle: also, people that live in the surrounding area are impacted by them. The vibrations generated by the interaction with road irregularity are also causing forces acting on the wheel that may propagate to the buildings and eventually to residents. Of course, the values 'bearable' by residents are much lower than the ones that affect passengers, so an acceptable range of values is in the order of 10^-3 mm/s^2.

The dynamical interaction of irregularities with the wheel generates inertial forces that impact the ground, making it vibrate. Said vibrations will propagate through the ground reaching the foundation and lastly the building itself.

The propagation of the effect of irregularities is approached by means of a series of PSDs and Transfer Functions which resemble the evolution of the propagating pressure waves.

In particular are computed sequentially:

- displacement of the axle;
- force transmitted from tire to ground;
- terrain displacement;
- acceleration of ground;
- PSD of ground displacement;
- PSD of building displacement;
- Building displacement;
- accelerations;
- final weighted acceleration.

In the process the variables, which more often than not are set and not chosen, are:

- characteristic of the wheel/suspension;
- velocity of the vehicle;
- characteristics of the ground.

What typically happens however is that these are kept the way they are and it is necessary to act on extra-elements added in order to compensate these values, such as vibration-limiting elements etc.

The obtained values have been, again for varying values of gain, between 0,003512 [m/s^2] and 0,005251 [m/s^2], which, as mentioned earlier in this report, are tolerable values.

Further works and discussions

Generally speaking, with the expression human vibration, we are referring to a whole type of problem regarding the response of the body to input vibration caused by different sources.

In the specific we refer to:

- Foot transmitted vibration (FTV) which are related to standing people
- Whole body vibration (WBV) when seated or recumbent
- Hand arm vibration (HAV) vibrations transmitted from operating machines through the arm

When people undergo an over exposition to vibrations, they may develop different typologies of problems:

- a sense of tiredness both physical and psychological
- Musculo-skeletal disturbances (due to low frequency vibrations)
- vascular disturbances (due to higher frequency vibrations)

One aspect that has however to be considered well is the non-univocal definition of the effects of vibrations due to differences in both the perception that different individuals may refer while undergoing a specific kind of vibrations and the strongly nonlinear response of the human body.

While measuring the response of the body to imposed vibrations two parameters are particularly considered:

- the apparent mass, which is given by the ratio between the specter of the force measured at the interface between the vibrating plate and the person and the specter of the imposed acceleration;
- vibration transmissibility, which is given by the ratio between two different zones of the body.

The apparent mass (AM) is measured in kg and is then called a mass, although the real meaning of it is the transfer function between acceleration and forces imposed.

The aforementioned AM resembles in many ways the transfer function of a single degree of freedom system and is strongly affected by the position the person studied holds during the tests: flexing the knees usually leads to a lower value of AM together with a lower naturally frequency (peak in the transfer function).

The measuring is a fairly complex topic and is to be taken with all due necessities, but the results can be elaborated in an intuitive way by considering the components of acceleration along the three axes together with specific weights (wk. is an example of one).

In the end the total daily exposure to vibrations is computed as a vectorial sum along the different dimensions that is then weighted with respect to the square root of the ratio of the time in a single day of exposure over a pre-specified T0.

The above considerations show how passengers' comfort is not the only topic to be considered while proposing a certain bus to a company, since also drivers' safety and health is involved.

Academic research exists on the topic:

Citing 'Whole body vibration exposures in bus drivers: A comparison between a high-floor coach and a low-floor city bus's by authors Ornwipa Thamsuwan, Ryan P. Blood, Randal P. Ching, Linda Boyle, Peter W. Johnson, 2011:

'Low back Pain (LBP) is one of the leading causes for workplace disability; therefore, it would be beneficial for employers and workers to minimize WBV exposures resulting in LBP. To reduce WBV exposures, buses should be assigned to appropriate routes and drivers should rotate across routes to vary continuous and impulsive exposures.'

and 'Whole-body vibration exposure in metropolitan bus drivers' by authors C.A. Lewis , P.W.Johnson, 2012,:

'The seat design used in this study does not seem to effectively attenuate the vibration after being in service for a while'.

It becomes evident how a careful, well rounded decision about the implementation of a specific bus on a specific route goes well beyond the simple accommodation and comfort of passengers and specialistic advice should be seeked by the managing company.

Noise

Noise pollution remains a major environmental health problem in Europe, with the transport sector being a major cause. Road traffic noise is the dominant source affecting human exposure above the EU's threshold of 55 decibels (dB) for daily exposure and 50 dB for night exposure. It causes pain and tension at work, after work, and during leisure time. Exposure to traffic noise in cities is so prevalent that it is impossible to locate a place and time when we are not subjected to its emissions. The following causes of noise may be identified in the vast majority of cars: engine, powertrain, and tires cooperating with the road surface, aerodynamic phenomena during driving, the movement of liquids and gases in the vehicle's systems and installations, and vibration of other vehicle components. The most powerful source of noise and vibration, according to estimates, is not a motor but the interaction of the wheels with the road surface and the wind surrounding the vehicle.

With the rise in traffic volume, there is an issue with noise emission as automobiles ride on ancient stone paving road surfaces. These sorts of surfaces, which are frequently in excellent condition, may be found in both urban and rural settings. These are often old parts of the road surface that, due to their historical significance, are not replaced with less loud ones. Reduced traffic speed is one method of reducing traffic noise. This approach is most commonly employed in metropolitan locations where other ways of limiting noise transmission are impractical.

It is apparent that vehicle noise levels are heavily influenced by vehicle size and construction (cars, trucks, and special vehicles), traffic volume, vehicle speed, and the kind and features of the road surface. Altering the road surface is another option. In high-traffic regions, such a modification will accelerate vehicle flow without adding to the noise.

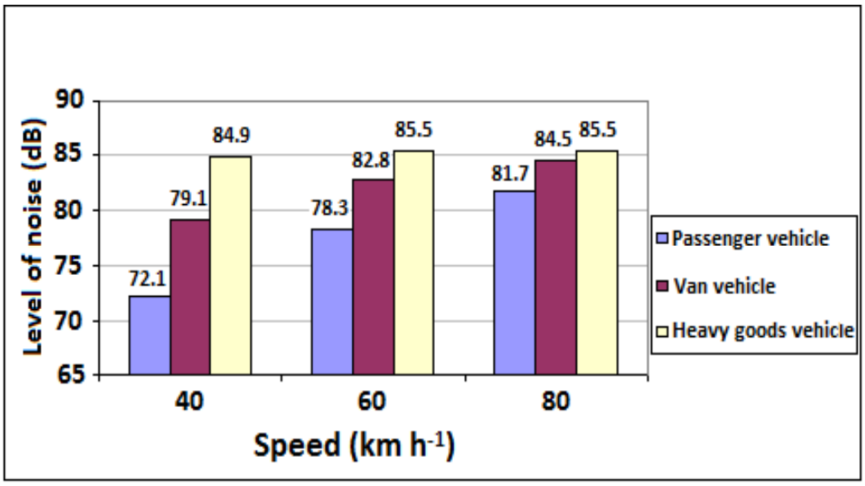


Figure 28: Noise level by type of vehicle and speed [11]

Noise from road vehicles is transmitted into two forms

- Air borne transmission: Airborne transmission occurs when a noise source creates air pressure waves that are directly received or cause vibration in structural parts, causing them to move and transfer sound.
- Structure borne transmission: A noise source is created when one item collides with another, causing vibration and sound to be transmitted.

Potential sources of Noise in road vehicles are:

- Engine
- Powertrain
- Tyre
- Air

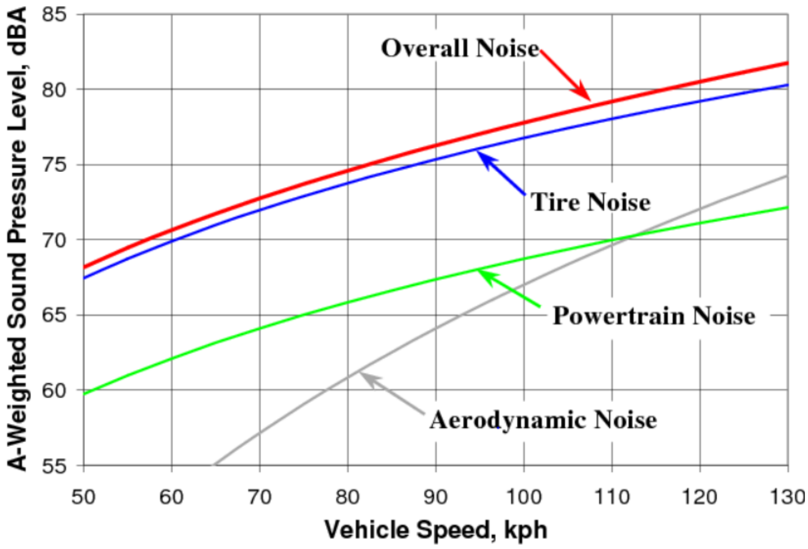


Figure 29: Weighted noise of road vehicle with respect to speed [13]

From the above graph it can be seen that tire noise has highest impact with respect to increase in speed. The tire noise also depends on the road surface.

	Noise level L_{max} (dB(A))			
Type of the surface	50 km h^{-1}		80 km h^{-1}	
	Gear	Neutral gear	Gear	Neutral gear
Asphalt	75.3	74.3	82.5	81.4
Concrete	75.4	74.9	81.6	82.7
Paving stone	81.8	82.6	90.2	91.0

Figure 30: Noise emitted by passenger transport on different roads [11]

The Noise of road vehicles is measured by various techniques such as

- Pass-by test: The **pass-by noise** test is aimed to reflect the exterior **noise** emission levels from the vehicle in an urban traffic environment. By comparing the values obtained with reference to the ISO standards and using technologies to reduce the noise based on the standards.
- Numerical simulation and
- Testing in anechoic chamber: Anechoic chamber is a chamber which absorbs all the noise with almost none reflected back. Using these chambers and sensor the noise source in the road vehicles can be identified.

Health effect associated with Noise

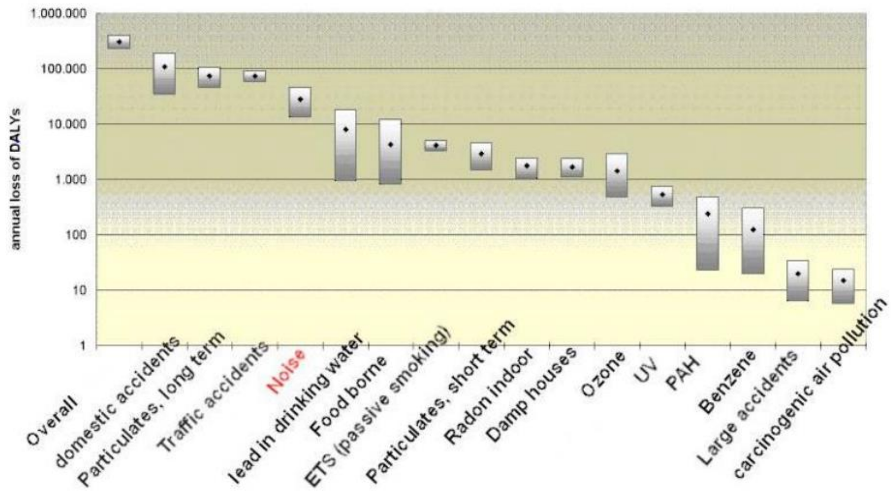


Figure 31: Disability adjusted life years from different environmental aspects

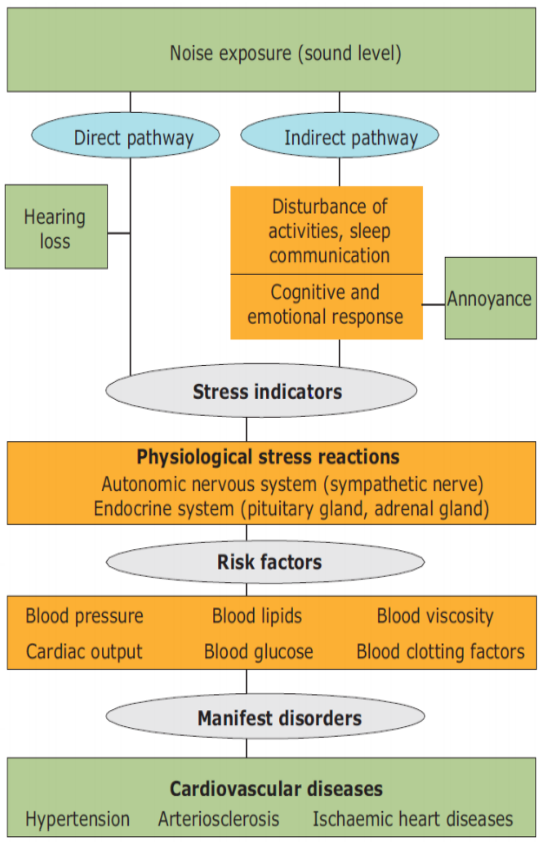


Figure 32: Effect of Noise on human health

Socioeconomic cost associated with Noise

Noise is such a prevalent issue that it has a measurable impact on the value of properties. Econometric or "hedonic" pricing assessments quantify this impact by predicting a house's sales price as a function of a variety of significant factors, such as ambient noise level or distance from a large noise source.

It includes:

- Effect on real-estate cost
- Flexibility of usage
- Includes some health effect costs for long term noise exposure. Mainly cardiovascular diseases and high blood pressure. These lead to increase costs for health.

There are various tests currently in practise to measure the sources of noise in the vehicle and

Structural vibration: Experimental Modal Analysis, System Identification, Finite Element Method Acoustic radiation: noise sources mapping (BF and PNAH), Sound Power Levels (Lw), Directivity Index (DI), Sound Intensity (I), Free-Field microphones, BEM and FEM Methods

By considering the Interior noise, Exterior noise, and Indoor noise.

Solutions for Noise reduction

Through research on and analysis of the mechanical components to identify the noise source and modifying the components to reduce the noise according to standards. But the noise from mechanical components is majorly for the IC engine buses which have lot of moving components which are the sources of noise. Now shifting to the Electric vehicle reduces the overall noise from the moving components and are produce no noise at lower speeds.

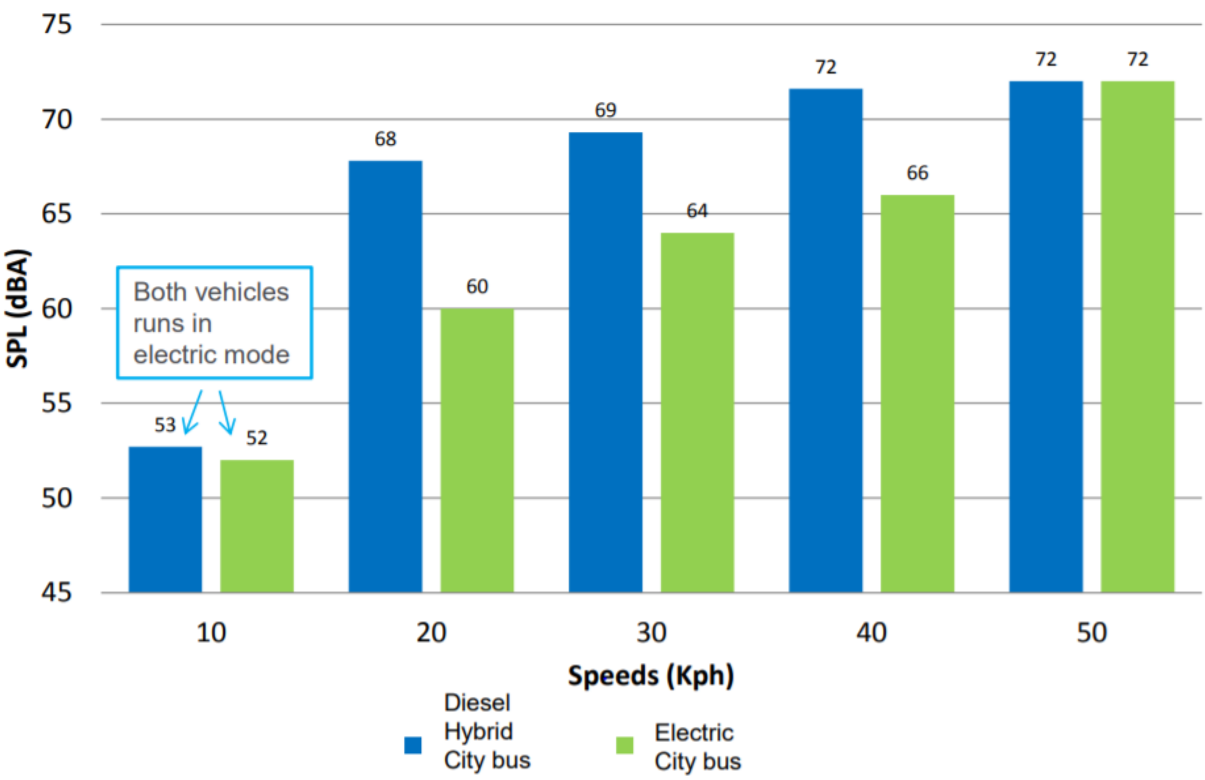


Figure 33: Comparison of Exrior Cruise-By Noise

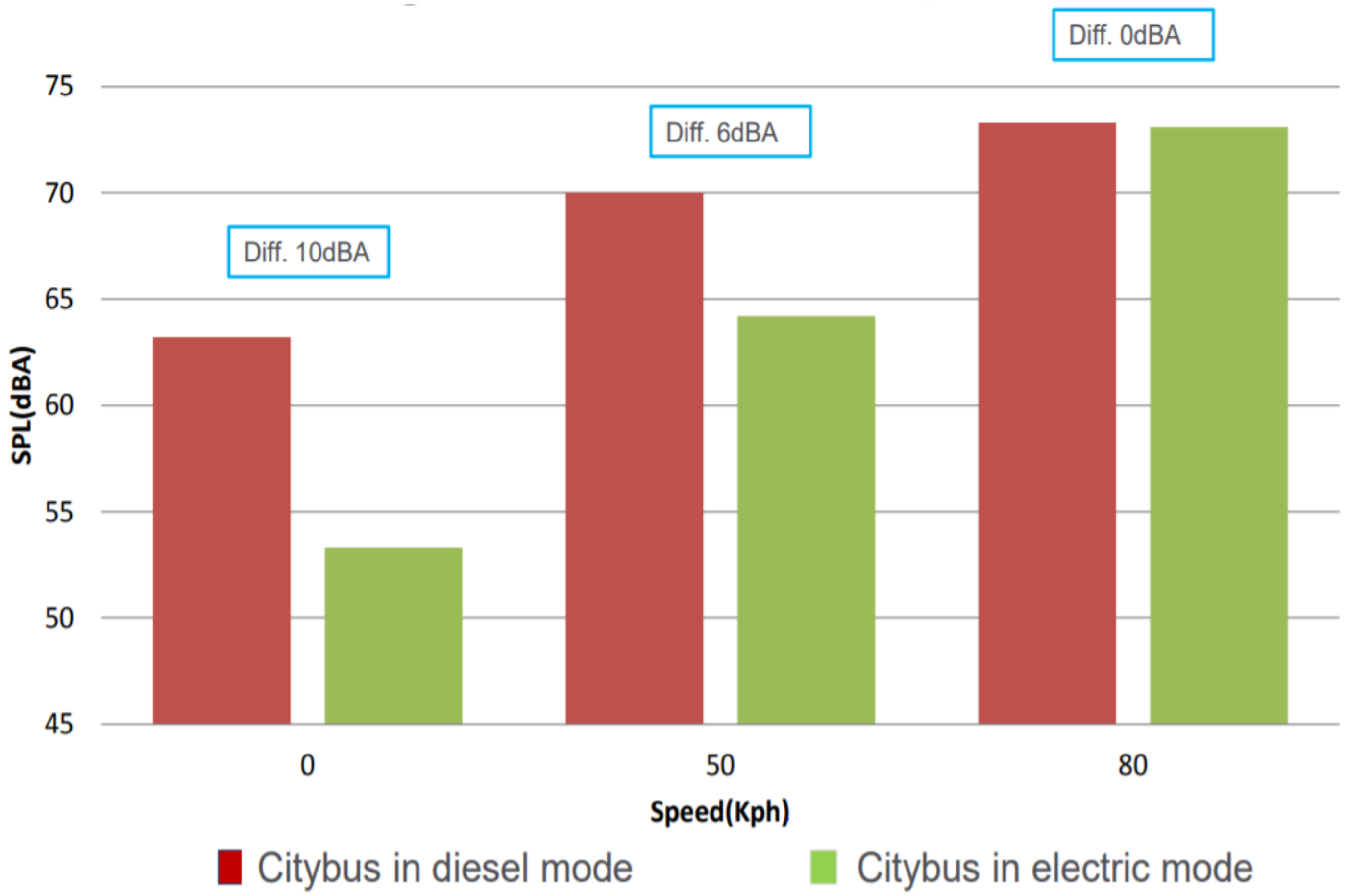


Figure 34: Comparison of Interior idling Noise and constant speeds

From the above graph it can be seen that at lower speed the diesel bus has very low noise levels but at higher speed the aerodynamic noise will be higher and it depends on the aerodynamic shape of the vehicle.

As electric vehicles have lower noise level the EU and other countries have made mandatory the use of Acoustic Vehicle Alerting System (AVAS).

Acoustic Vehicle Alerting System (AVAS)

AVAS (Acoustic Vehicle Alerting System), sometimes known as PWS (Pedestrian Warning System), are electric vehicle warning noises that are required by law. The primary objective is to alert surrounding pedestrians in order to reduce the risk of being driven over, as one of the key characteristics of electric cars until now has been their utter silence. The regulation states that AVAS must be a sound generated by electric automobiles in Europe at speeds up to 20 km/h and in the United States at speeds up to 30 km/h and, as a general rule, also while returning. When certain speeds are surpassed, the system immediately shuts down.

And this electric car warning sound impacts not just private vehicles, but also those meant for both passenger and freight transit.

That sound must be louder than 56 decibels, which is comparable to the volume of a regular conversation, but not louder than 75 dB, which is equivalent to the noise level of combustion vehicles. In terms of frequency, we're talking about 1,600 Hz, which is specifically created for the elderly, who have the most sensitive hearing.

Furthermore, this sound does not remain constant during its voyage, but changes based on the acceleration and speed attained, as well as whether we begin or return.

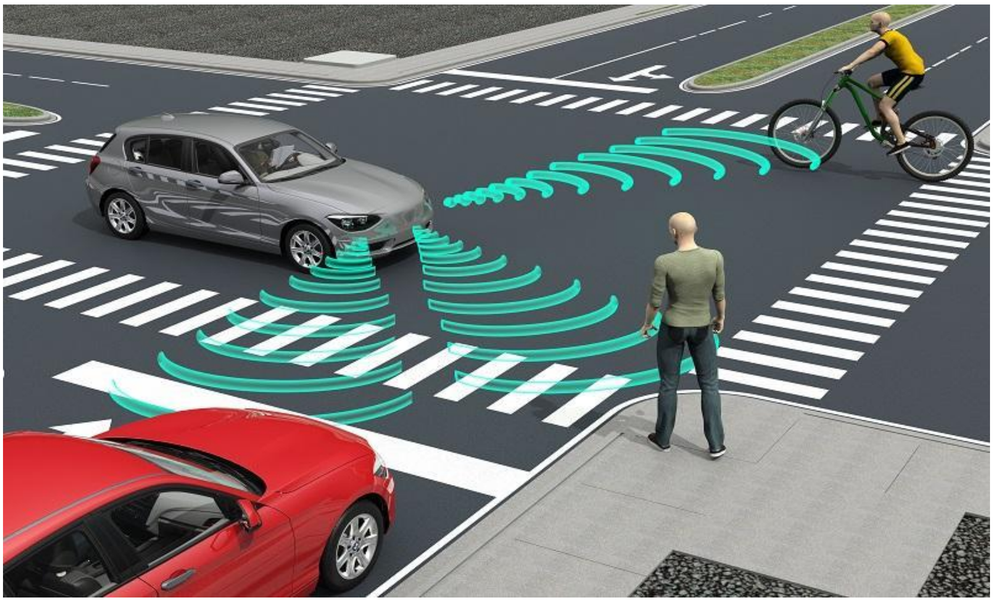


Figure 35: AVAS depiction in real time

Infrastructure Analysis

Santiago Line 501 is 10.8 Kilometres long. It is part of the city's north-eastern road network connecting the northern city centre and the eastern corridor of Santiago. Construction of roads involves the paving, rehabilitation, and/or reclamation of degraded pavements in order to achieve a state of good repair and increase road traffic safety. Road construction involves the use of asphalt, liquid asphalt, concrete, soil stabilization, rebar, paving and pavement recycling machines, and other road repair materials. Public safety on road is responded by introducing safety measures to the infrastructure provided by

1. Traffic Signals
2. Speed Limits and Speed Cameras
3. Road Signs
4. Road and Pavement Markings
5. Road Visibility (Lighting)

On the other hand, to ensure safety form the bus's point of view, it comes equipped with safety standards of its own, including Anti-Lock Braking Systems (ABS), Traction Control Systems (TCS) and Speed Governors to regulate the operation speed. This prevents potential accidents due to the unpredictability in driving behaviour on road and also regulates the driving habits. In case of an unavoidable accident the chassis of the vehicle also acting as the body, should be strong enough to withstand the stress and protect the passengers inside it.

Electric Infrastructure

A major part of readying the ecosystem for Electric buses involves setting up of adequate and efficient bus charging infrastructure. Unlike the Railway systems, an electric bus runs by on-board battery systems. The dynamics of charging infrastructure for electric buses differ from other vehicle segments like electric 2W and cars. There are two major parts of charging infrastructure:

- Charging Solution
- Electrical Infrastructure

1) Charging Solution

Providing appropriate charging solution results in seamless operation of the electric vehicle. They can be charged by three methods:

a) Conductive Charging

It is the most common type of charging available in households and charging stations in urban regions. The energy is supplied to the vehicle directly by either AC / DC. AC charging stations connect the vehicle's onboard charging circuitry directly to the AC Supply.

- AC Level 1: Connects directly to a standard 120 V North American residential outlet; capable of supplying 6–16 A (0.7–1.92 kW) depending on the capacity of a dedicated circuit.
- AC Level 2: Utilizes 240 V residential or 208 V commercial power to supply between 6 and 80 A (1.4–19.2 kW). It provides a significant charging speed increase over Level 1 AC charging.

DC charging is categorized separately. In DC fast-charging, grid power is passed through an AC-to-DC rectifier before reaching the vehicle's battery, bypassing any onboard inverter.

- DC Level 1: Supplies a maximum of 80 kW at 50–1000 V.
- DC Level 2: Supplies a maximum of 400 kW at 50–1000 V.

Electric Buses on the other hand require High Power Dc Charging Infrastructures with power ratings of 150,300 and 450 kW for fast charging the transit vehicle in order to resume operation as quick as possible. Since the bus uses on board battery to generate power for the motor, there are two possible approaches to charge the vehicle.

i. *Opportunity Charging*

This refers to fast charging, where the batteries are charged several times during operation, usually during dwell times at terminal stations. They can be activated by automated charging systems using pantographs. Since the dwell times are short, fast charging with high power is absolutely necessary to resume service operation. With this strategy, the daily range on operation can be extended. With ABB Flash-Charging technology, this method can be beneficial to improve transit frequency and range of the EV as with 600KW charge supply it can give significant boost in just 20 seconds timespan. [ref]

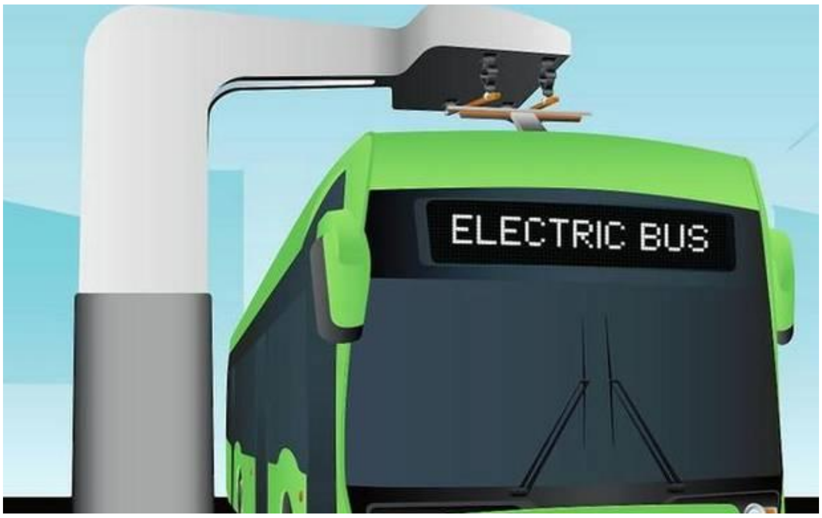


Figure 36: Opportunity Flash Charging
https://www.thehindubusinessline.com/companies/ashok-leyland-abb-arm-ink-pact-to-develop-electric-buses-with-flash-charge-tech/article30524715.ece

ii. *Depot Charging*

In this method, the batteries are charged during the gap between operations in the depot, with a manual plug. Since the bus ranges about 300 Km on a single charge, this usually done overnight with slow charging levels. Depot-charging vehicles in EU are usually equipped with IEC 62196 based manual plug interface (CCS, Combined charging system)

Figure 37: Manual plug in Depot Charging
https://new.siemens.com/global/en/products/energy/medium-voltage/solutions/emobility/ebus-depot.html

b) Inductive Charging

Conductive wireless charging or simply conductive charging uses conductive power transfer to eliminate wires between charger and the charging device. It uses a conductor by the means of electro-magnetic conduction to connect the vehicle and the power source in order to transfer energy. They can be split into:

i. *Static Inductive Charging*

This is the most basic type of inductive charging method, where the charging pads are placed statically in a position, either at charging stations or households, where the vehicle with an electromagnetic coil at the bottom connected to the batter aligns itself with the charging pad. This is usually a slow type charging method, but with bigger coils, fast charging can be achieved. This strategy could also be implemented with *Opportunity Charging* for electric transit buses during dwell times.

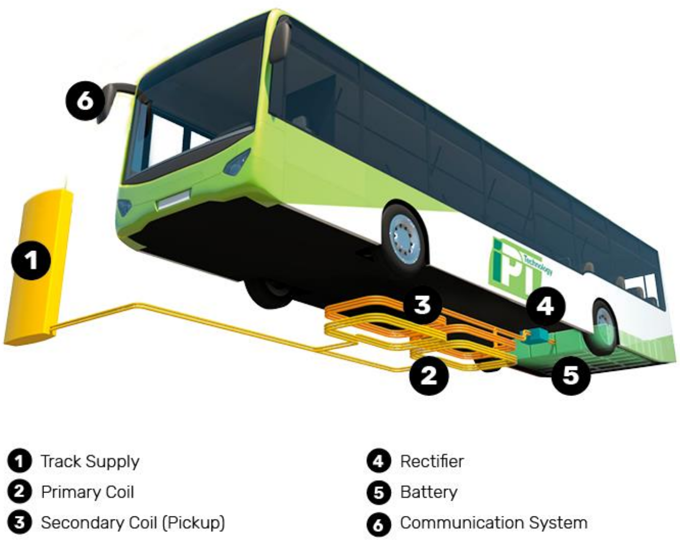


Figure 38: Wireless charging for heavy and light-duty vehicles
https://ipt-technology.com/e-mobility/

ii. *Dynamic Inductive Charging*

A more advanced type of inductive charging, where the vehicle can be charged on the move without needing to stop or slow down. A more expensive method, where the conducting coils are buried along with the road connected directly to the grid. This method can be used in busy transit lines, to improve the range efficiency of the electric bus and increase frequency which would otherwise be deficient due to charging times

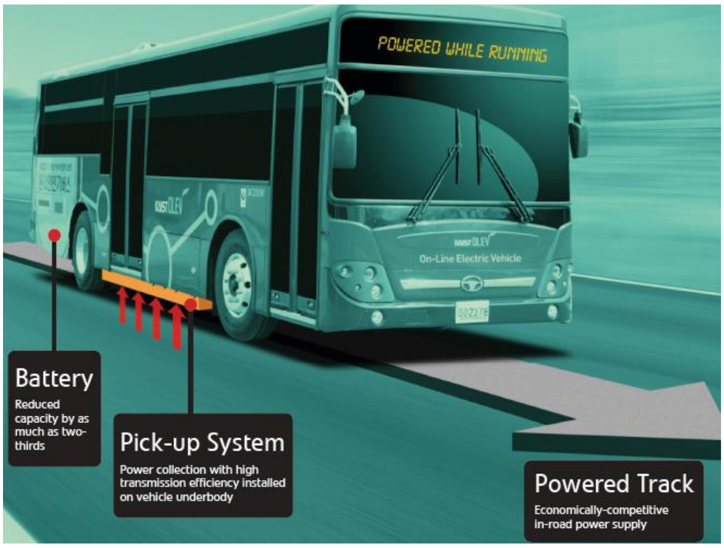


Figure 39: Dynamic Wireless Charging System
https://chargedevs.com/features/olev-technologies-dynamic-wireless-inductive-system-charges-vehicles-while-in-motion/

c) Battery Swapping

This is the easiest form and quickest form of providing energy to an Electric Vehicle. The principle is simple, as the name suggests when the battery drops below efficient operation range, its simply replaced with a fresher / fully recharged battery from the battery charging station. This method is as quick as refuelling a car with fossil fuels. Though with this method, the ownership of the battery comes into question. It also comes with its drawbacks, where the battery needed to be swapped out must be of the same design / specifications in order for efficient operation of the EV.

Figure 40: Battery Swapping Technology
https://www.team-bhp.com/forum/commercial-vehicles/195366-ashok-leyland-circuit-s-bus-auto-expo-2018-a.html

2) Electrical Infrastructure

Just like tram lines, Electric Buses also known as Trolley Bus can be fed with constant overhead traction power supply instead of being run with an onboard battery system with the use of electrical lines and pantographs to establish connection with the vehicle and the power grid. The power from the grid is geographically distributed over to power supply substations. These substations consist of voltage transformers where it steps down medium voltage to lower voltage levels followed by AC/DC rectifier to provide DC power. This traction network comes equipped with protection devices like circuit breaker and insulators to mitigate any injuries and equipment damage.

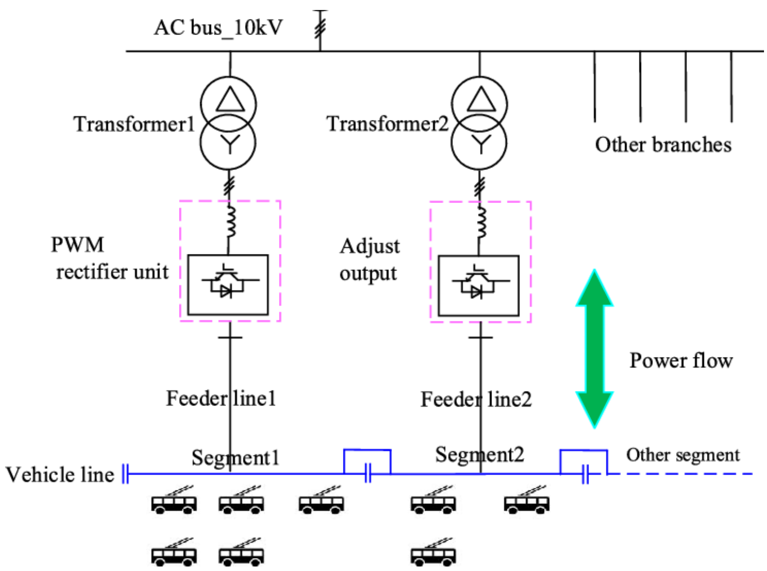


Figure 41: Schematic diagram of Substation

Electric Buses with constant contact can also resupply energy back to the grid by means of Regenerative Braking from the electric motor. Electric Buses with traction unlike trams, do not have specific rails to be set in motion, but they have full freedom of motion on the road. In case of a blockade in front of the vehicle, the E-Bus can simply disconnect from the pantograph and run-on battery power temporarily to manoeuvre around the block and reconnect again. Though these traction lines proved constant power, their efficiency could be subjected to weather situations like the wind or snow, which may hinder with the contact of the pantograph and the traction line.

Figure 42: Trolley Bus
https://www.sustainable-bus.com/trolleybus-tramway/trolleybus-market-zero-emissions/

Operation Analysis

If it is considered that the bus operates 270 km/day, its energy consumed is close to 311 kWh; that is with a charger of 75 kW could full its battery during the night. In the market there are available charger with 150 kW of power, therefore is more cost-effective to install one charger of this power for two buses.

According to the operational program of this route they are necessary 20 buses on-peak hours of the day. If it considers these number of buses, it would be required ten chargers. Hence the installed power in the depot should be of minimum 1,5 MW.

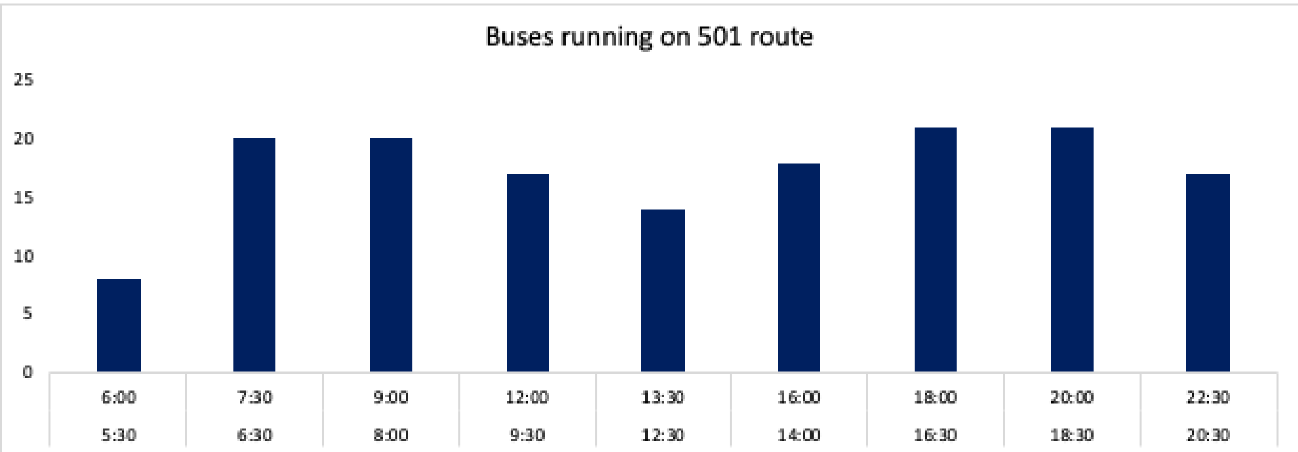


FIGURE 43: NUMBER OF BUSES 501 ROUTE

Maintenance and Diagnostics

Maintenance is an important factor in quality assurance and in some cases determines the long-term lifecycle of equipment or infrastructure. Poorly maintenance can cause instability and partially / completely interrupt operation. Malfunctions or complete breakdowns can become a costly process to fix. Four general types of maintenance that can be identified are namely, corrective, preventive, risk-based and condition-based maintenance. During this study, the maintenance procedures can be fragmented to:

a) Road Maintenance
b) Vehicle Maintenance

Road Maintenance

Maintaining a road regularly is of paramount importance in order prevent fatal accidents or injuries to personnel during driving. Some of the common causes of failures of road pavements include; poor quality of materials, improper design of road structure, defects in road construction methods, improper quality control, inefficient drainage system, increase in magnitude of load, foundation settlement, failure of subgrade and adverse climatic conditions.

Common types of failures on pavements are:

i. Pot Holes
ii. Cracks
iii. Rutting
iv. Corrugation
v. Surface upheaval

Pot Holes

These are isolated depression in a road surface developed due to loss of base course materials in road pavement. They are bowl shaped holes of varying size in surface layer or extending into the base course caused by localised disintegration of material. The most common cause of Pot-Hole formations is the ingress of water into the pavement through surface course. Lack of proper bond between the bituminous surfacing and the underlying water bound macadam base can also cause potholes.

Treatment:

- Pot holes should be cut in a rectangular or square shape up to the defective depth and excavated material is removed.
- The coarse aggregate of the same size is filled up in the pot hole and the level is kept 1 cm above the general surface of the pavement.
- Uneven soiling should be completely removed, repacked and compacted conforming to the normal line of grade and section.

Figure 44: Pot Hole Treatment

Cracks

Common defects in bituminous surface are the formation of cracks. The crack patterns can in many cases, indicate the cause of the defect. As soon as cracks are observed, it is necessary to study the pattern in detail to arrive at the cause. They are hardly observable from moving vehicle, inspection on foot is always optimal. Some of the common type of cracks include; hairline cracks, longitudinal cracks, alligator cracks, edge cracks and reflection cracks.

Treatment:

- Treatment of type of cracks would depend on whether the pavement remains structurally sound or has become distorted.
- In case the pavement remains structurally sound, then the cracks should be filled with a bituminous binder having low viscosity, so that it can be poured and worked in to the cracks. Light sanding is then done to prevent traffic picking up the binder
- If the cracks are wide enough a slurry seal or sand bituminous premix patching an be used to fill the cracks.
- If the cracks are fine and extend over a large area, a light cut-back or an emulsified bitumen can be broomed into the cracks and lightly sanded to prevent the picking up of binder by the traffic

Figure 45: Road Cracks

Rutting

It is a longitudinal depression or grove in the wheel tracks, as they are usually of the width of a wheel path. Swerving from a rutted wheel path at high speeds can be fatal, also accumulation of water in the depression can cause skidding. This is commonly caused due to heavy channelized traffic, inadequate compaction of the mix, weak pavement and high stresses caused by heavy truck traffics.

Treatment:

- The rectification consists of filling with premix open graded or dense graded packing materials. The limits of depression are determined with a string line and marks on the surface.
- Situation indicative of shear failure or sub-grade movement generally require excavation.
- Rut formation can be prevented by performing proper compaction of sub grade layer.

Figure 46: Rutting on flexible pavement

Corrugation and Shoving

Corrugation is the formation of fairly regular undulations across the bituminous surface. They are usually shallow (about 25mm) and are different from the larger depressions caused by weakness in the lower layers of the pavement or the subgrade. The corrugations can be a source of discomfort to the motorists. Some of the common causes are; lack of stability in the mix, faulty laying of surface course, settlement of subgrade soil, selection of weak and poor subgrade material, improper compaction and increase in traffic load.

Treatment:

- If the surface is thin, the same is scarified, including some portion of the underlying water bound macadam base, and the scarified material is recompacted. A new surfacing layer is then laid.
- Spreading of sand bituminous premix with a drag spreader with its blade adjusted to clear the high spots can also be an effective way to make up the corrugations.
- Proper selection of subgrade material to avoid unequal settlement
- Standard and proper construction method should be adopted.

Figure 47:: Corrugated outback road

Surface Upheaval

The excessive deformation in the flexible pavement followed by the heaving of the road surface caused by the heavy wheel loads is called surface upheaval. Some of the common causes include; instability of the pavement due to the failure of either subgrade, base course or wearing course, poor quality control, imperfect gradation of aggregates, excessive stress application and inadequate stability.

Treatment:

- High and Proper Quality control
- Perfect grading of aggregates
- Proper and thorough maintenance of highway
- Proper drainage system
- Use of superior quality road material
- Proper compaction
- Proper assessment or estimation of future traffic load, intensity and volume

Figure 48: Pavement Upheaval

Vehicle Maintenance

EV's typically require less maintenance in comparison with Internal Combustion Engines (ICE), Hybrid electric vehicles (HEV) and Plug-in hybrid electric vehicles (PHEV). It is because the battery, motor and associated electronics require little to no regular maintenance. There are fewer fluids such as engine oil, that require regular maintenance. Brake wear is significantly reduced due to regenerative braking. There are far fewer moving parts relative to a conventional gasoline engine. Few of the Electric Vehicle Maintenance checklists include:

Tire Maintenance

This is a crucial check because unlike ICE Vehicles, the engine and the transmission parts are replaced with heavy battery systems, which adds in a lot of stress on the tires of the vehicles. Since Electric Motors produce instantaneous maximum torque, the tires can easily get ripped apart if not properly maintained. For optimum performance, tires must have the correct air pressure, tread depth, balance and the wheels of the vehicle must be properly aligned. Some of the methods for tire maintenance include:

a) Signs of Tire Wear

Poor tire maintenance can lead to premature tire wear, a flat tire or even a blowout. Factors other than tires themselves also can affect tire wear. Worn suspension parts and wheel alignment both play a direct role in tire wear and performance.

Problems to look for during visual inspections include:

- Over inflation
- Under inflation
- Tread wear on one edge of the tire
- Erratic Tread wear
- Raised portion of tread or sidewall
- Unusual vibration while driving and pull to one side

b) Tire Tread Inspection

Tires depend on good tread condition depth to maintain traction and to shed water on wet roads. The tread should be checked at least once a month for excessive and uneven wear. The most accurate tread depth measurements are made with a simple tread depth gauge available at any parts store

c) Tire inflation inspection

Keeping tires properly inflated is one of the easiest ways to help maintain good gas mileage and extend the life of your tires. Check tire pressure at least once a month with a quality gauge, that measures pressure in pounds-per square inch (psi).

d) Tire Rotation and Balancing

Tires on the front and the rear of vehicles operate at different loads and perform different steering and braking functions, resulting in unequal wear patterns. To gain maximum life and performance from tires, it is essential to rotate vehicle's tires. Usually tire rotation is performed between 5,000 and 7,000 miles.

Properly balanced tires help minimize uneven wear and extend their life. When tires are balanced, small weights are attached to the wheels to limit vibration of the tire and wheels as they turn. Newly installed tires should be balanced, and thereafter whenever a vibration is noticed. Balancing is also called for whenever a tire is removed from the wheel, for example to repair a puncture.

e) *Wheel Alignment*

Wheel alignment is the measurement of the position of the wheels compared to specifications that the vehicle manufacturers recommend. Each vehicle has specific wheel alignment settings. If any alignment measurement falls outside the specified range, uneven tire wear can result, vehicle handling may be affected and fuel economy can be diminished.

Figure 49: Wheel Balancing and Alignment

Coolant Maintenance

Cooling systems are absolutely necessary in both EVs and ICEs, where it prevents overheating of the systems running in the vehicle and avoid unnecessary breakdowns. In case of EVs, coolant systems make sure that the battery supplying energy to the motors function at optimal temperature range, to mitigate any chemical leaks and catch fire to the whole vehicle.

The vehicle's coolant system and radiator should be inspected at least every 12 months. It's a good idea to inspect the system every 12,000 miles, especially if the vehicle travels a great deal. Antifreeze (coolant) helps to protect traction systems from overheating or freezing. However, over time the liquid can degrade. The fluid is also caustic. If it is left in the radiator for too long a time, it will eventually corrode the metal and cause radiator leads. This can lead to Vehicle Breakdown, overheating and poor circulation.

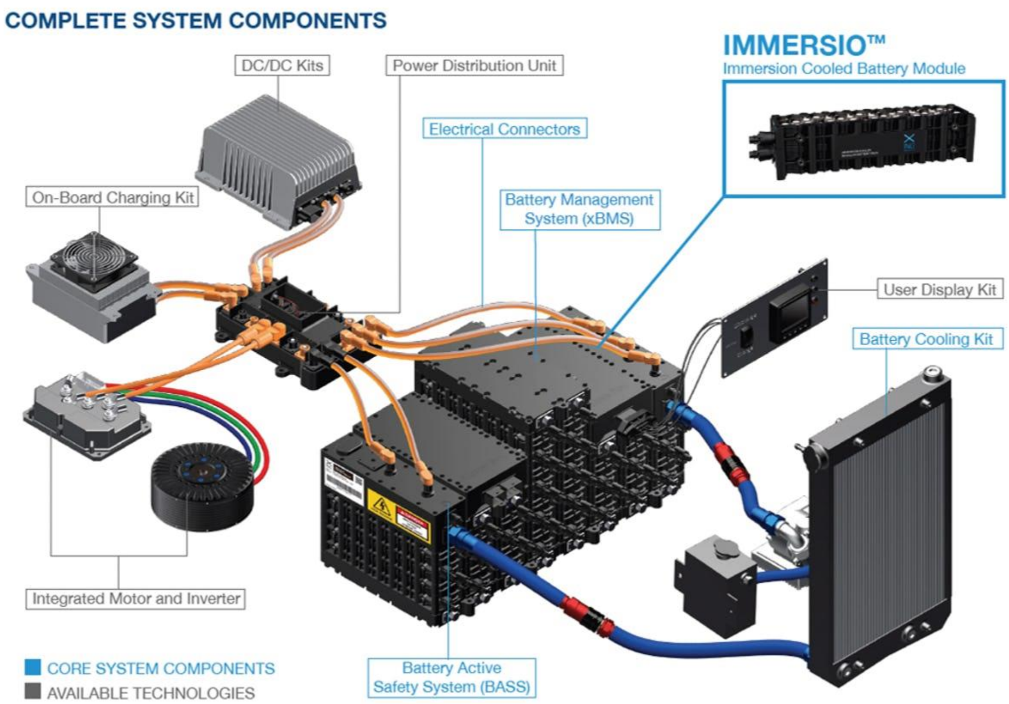


Figure 50: Schematic representation of cooling system in an EV
https://www.idtechex.com/en/research-article/immersion-of-electric-vehicle-batteries-the-best-way-to-keep-cool/20169

Brake Preservation

Though EV's use regenerative braking systems to perform braking, it not always this case. Because EV's are also reliant upon frictional braking systems for high-speed emergency stops. Brake repair is a vital safety issue. Without properly working brakes, normal driving situations would take a turn for the worst. However, there are other benefits in getting routine brake service and brake repair. This includes:

a) *Brake Fluid Inspection*
Stopping a vehicle depends on hydraulics, and brake fluid is literally the system's lifeblood. Pushing the pedal forces fluid through the lines, causing components to expand against the wheels, stopping the vehicle. These should be replaced in case of pressure drop or leakages from the hydraulic pipelines.

b) *Brake Pads Replacement*
Made from a variety of metals, brake pads squeeze the rotor whenever the brake pedal is pushed. Brake pads typically last between 20,000 and 40,000 miles, perhaps much longer with high quality brake pads. The wear of brake pads is often indicated by loud squealing noises, which ignored could do serious damage to the brakes.

c) *Calipers calibration*

Part of a disc brake system, calipers push the brake pads against the rotors when the brake pedal is pushed. This resulting friction between the pads and rotors slows and ultimately stops the vehicle. Waiting too long to replace worn brake rotors puts extra stress on the calipers. The calipers will rub against uneven rotors if the components aren't parallel to one another, creating a vibration that can be felt in the steering wheel during stops.

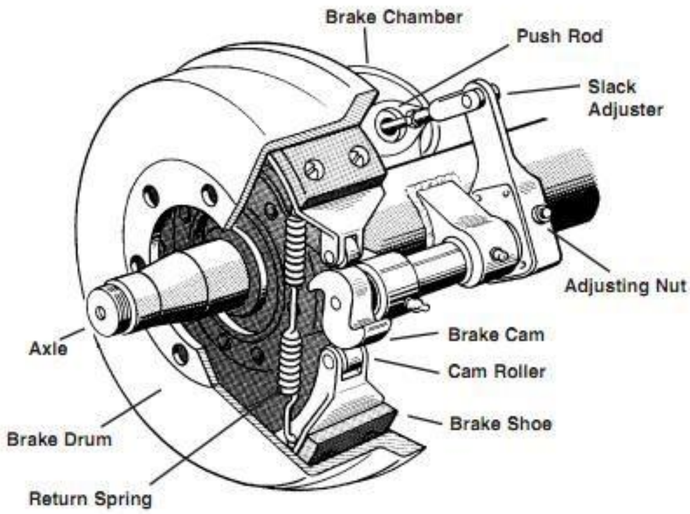


Figure 51: Representation of Air Brake System

Battery Care

The battery is the heart of every EVs, as it dictates the range and the value of the vehicle while leasing or buying it. Though it is known the commonly used Lithium-ion batteries degrade over time and after specific charge cycles, few methods can be used to optimized or improve the battery lifespan. They are

a) ***Minimise 100% Battery Soc***

Electric Vehicles already have installed with a battery management system that avoids them being charged and discharged at the extreme state of charge. Keeping the state of battery charge, from 0 percent to 100 percent, also improves the performance of the battery life of the vehicle. Even though a full charge will give you the maximum operating time, it is never a good idea for the overall lifespan of your battery.

b) ***Control the optimal battery state of charge during long storage***

EVs that are parked or stored with an empty or full battery also degrades the battery. If you do not often or having a long trip plan, get a timed charger, and plug it in. Leaving vehicle at 100 percent while parked at a certain place for a long period, the battery will struggle with preserving its state of charge while away. One strategy is to set the charger to keep the charge just above the low mark, not filling it up to the maximum capacity, at an average charge level between 25 percent and 75 percent.

c) *Minimise exposure to extreme temperatures*

Exposure to the extreme heat while parking unplugged is when the frequent danger occurs. An automated temperature control system installed in EV will needlessly drain your batteries to keep the temperatures down for optimal efficiency. While this performance should only work when vehicle is on the road using its battery, park in the shade or plug-in so that its thermal management system functions only using grid power, and make sure a stable range of temperatures during operation either.

d) *Avoid fast charging*

If batteries are soon-to-be die out, using a fast-charging is a great convenience. However, it presses so much current into the batteries in a short period which strains your EV battery and wanes them faster. While it is hard to notice its degradation, eight years of standard charging will give 10% more battery life compared to 8 years of using fast charging.

Emissions and Environmental Impacts

Local pollutants

One of the advantages of electric vehicles is their zero tailpipe local pollutants emissions, as carbon monoxide, hydrocarbons, nitrous oxides, particulate matter. These components have a direct effect on people's health and historically they have been controlled by emission standards, in the UE case though EURO standards (Table 1), now is adopted EURO IV but it being discussing on EURO VII standard, where pollutants emission will be even lower.

Stage	Date	Test	CO	NMHC	CH_4[a]	NOx	PM[b]	PN
			g/kWh					1/kWh
Euro III	*1999.10 EEV only*	ETC	*3.0*	*0.40*	*0.65*	*2.0*	*0.02*	
	2000.10		5.45	0.78	1.6	5.0	0.16[c]	
Euro IV	2005.10		4.0	0.55	1.1	3.5	0.03	
Euro V	2008.10		4.0	0.55	1.1	2.0	0.03	
Euro VI	2013.01	WHTC	4.0	0.16[d]	0.5	0.46	0.01	6.0×10^{11}[e]

TABLE 5: EU EMISSION STANDARDS FOR HEAVY-DUTY CI (DIESEL) AND PI ENGINES: TRANSIENT TESTING[4]

If you only focus on local pollutants when comparing electric vehicles with CI vehicles, EVs will always have greater advantages in terms of tons emitted and economic cost (health cost). It is for these reasons that other types of analysis are necessary for compared different technologies: estimate global emission pollutants and compare them in terms of well to tank emissions (WTT) and tank to wheel (TTW) emissions.

Global pollutants

Automobiles and trucks are major contributors to global climate change—17.8% of the world's energy-related greenhouse gas emissions come from road vehicles, including 10.2% from automobiles. There are over half a billion automobiles in the world today, almost all running on gasoline. Burning 1 gallon (3.8 litres) of gasoline releases 19.4 lb (8.8 kg) of carbon dioxide (CO_2) into the atmosphere, along with a number of other pollutants. The average car emits its own weight in CO_2 every year. Whereas EV's and PHEVs running only on electricity have zero tailpipe emissions.

The CO_2 emission in its operation phase since it only depends on the country's energy matrix. In Chile, close to 50% of the installed generation capacity corresponds to renewable energies; Hence, the quantity of carbon per MWh is low: 0,383 Ton CO_2/MWh[5]. On the other hand, the efficiency of one diesel Bus Euro VI running in Santiago of Chile is 1,47 km/l[6], meaning an emission

[4] Available at *https://dieselnet.com/standards/eu/hd.php*
[5] Available at http://datos.energiaabierta.cl/dataviews/255509/factor-de-emision-promedio-anual/
[6] Available at https://www.mtt.gob.cl/archivos/5597

of 1,776 Kg CO_2/km. Suppose it considers a mileage of 80.000 km/year, the emission of one electric bus is 32 Ton CO_2, and in the case of Diesel Euro VI bus is 144 Ton CO_2, a 78% of difference between both technologies.

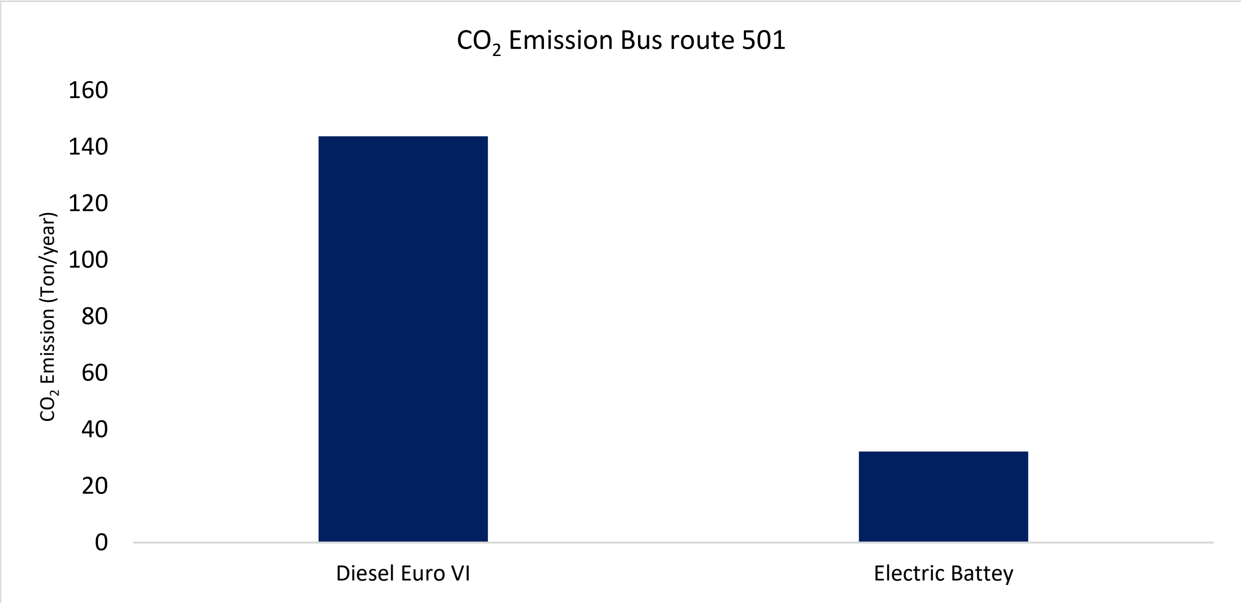


FIGURE 52: BUS OPERATES ROUTE 501 CO_2 EMISSION (TON/YEAR)

Lifecycle Analysis of CO2 emissions[7]

Although the begging question being, are electric vehicles only have CO_2 emissions from the energy grid matrix? Not really, because the battery production of an EV is much more detrimental to the environment than the production of Internal combustion vehicles. The initial environmental footprint from electric vehicle production is greater than production of internal combustion engines. The large batteries EV's use are made with lithium, unlike any raw material needs to mine and the mining process produces lots of greenhouse gases.

The fundamental difference between conventional, thermal cars and electric cars has to do with the process of transforming the potential (stored) energy into kinetic (movement) energy. In thermal cars, this energy is stored in a chemical form and is released through a chemical reaction inside the engine.

On the other hand, despite also having chemically stored energy, electric cars release it electrochemically without any kind of combustion, thanks to lithium-ion batteries. This means that there is no fuel being burned and therefore no air pollution through CO_2happening while driving. They are also more efficient than fossil cars.

Emissions for this comparison study can be split into:

1. Well to Tank Emissions
2. Tank to Wheel Emissions

[7] In the current report, this type of analysis did not carry out.

Well To Tank Emissions

A Well-to-Tank (WTT) emissions factor, also known as upstream or indirect emissions, is an average of all the GHG emissions released into the atmosphere from the production, processing and delivery of a fuel or energy vector. The cycle of making a car starts with raw materials being extracted, refined, transported and manufactured into several components that will be assembled to produce the car itself. This process is very much the same in both conventional and electric cars. Nevertheless, at the end of the manufacturing process, electric cars are the ones generating more carbon emissions

Because electric cars store energy in large batteries (the larger they are, the bigger their range is) that have high environmental costs. This happens because these batteries are made of earth elements like lithium, nickel, cobalt or graphite that only exist beneath the surface of the Earth and therefore depend on mining activities with very polluting processes. That's why asking whether electric cars are greener or not does come with an easy answer.

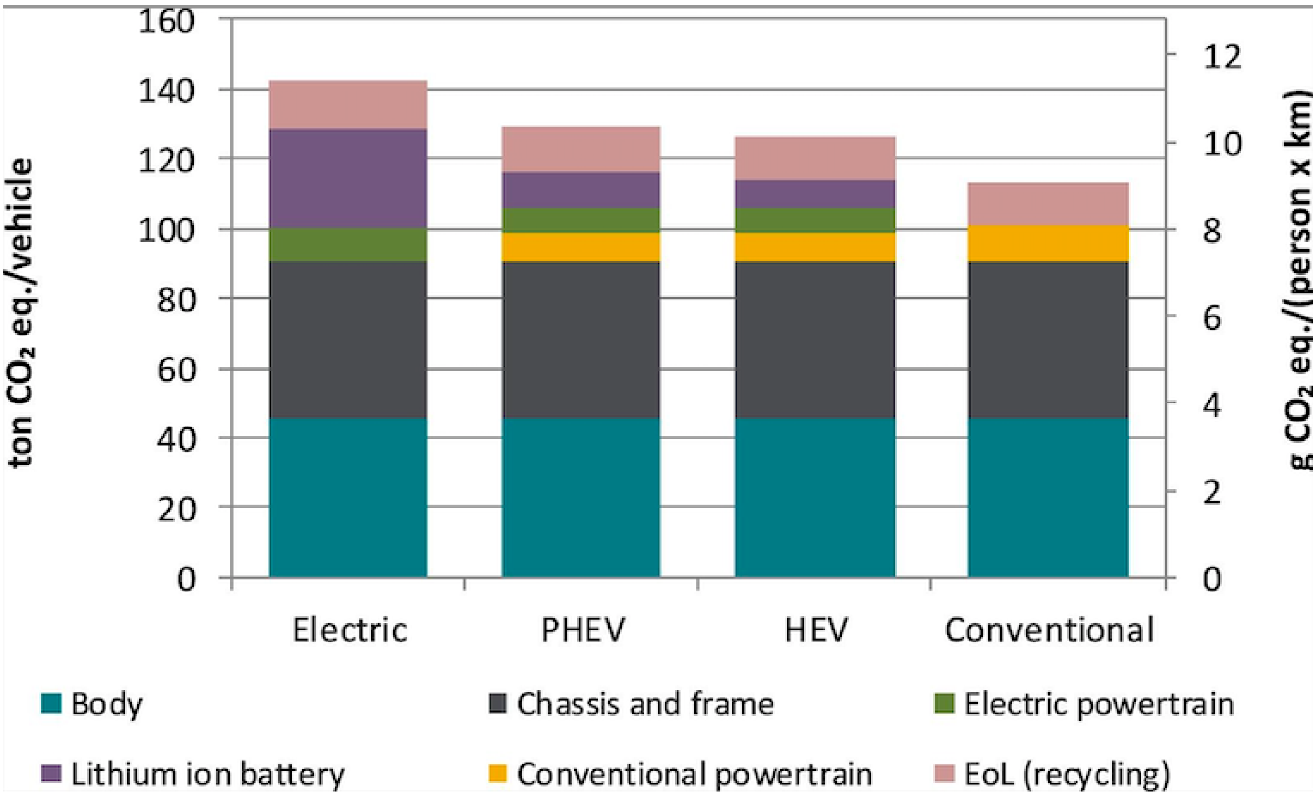


FIGURE 53: VEHICLE LIFE CYCLE RESULTS AND CONTRIBUTION TO CLIMATE CHANGE IMPACTS FROM DIFFERENT PARTS OF THE BUS (EQUIPMENT ONLY, I.E. BUS OPERATION AND WTW LIFE CYCLE OF FUELS AND ELECTRICITY FOR CHARGING ARE EXCLUDED)(A. NORDELÖF, ET AL.2019)[8].

Tank to Wheel Emissions

[8] Life cycle assessment of city buses powered by electricity, hydrogenated vegetable oil or diesel, Transportation Research Part D (2019) 211-222

The term Tank-to-Wheel (TTW) refers to a subrange in the energy chain of a vehicle that extends from the point at which energy is absorbed (charging point; fuel pump) to discharge (being on the move). TTW thus describes the use of fuel in the vehicle and emissions during driving. Since, the study model of this project is an E-Bus, there are no direct emissions emitted from the tailpipe of the vehicle unlike a Diesel Bus. Hence, they are also referred to as Zero-Emissions Vehicle. Which is why it is the main reason why future of mobility is pushing towards electrification in order to reduce the green house gases emitted to the atmosphere.

Economic Analysis

The Total Cost of Ownership (TCO) allows knowing the level of costs that a bus will have throughout its useful life beyond acquisition cost. This methodology seeks to identify the most suitable routes for the operation of battery-powered electric buses, whether with depot charging, the objective of which is that operators can count on a reference of the costs to face.

The analysis captures the 10-year CAPEX and OPEX costs; the primary assumption is a comparison of diesel versus electric buses under current operating conditions; Thus, the CAPEX includes the acquisition cost, and in the case of the electric ones, the external infrastructure and an additional battery is also considered. The OPEX contains the costs of energy and/or fuel, accessory components (oils, tires), the salary of the equipment operator, and maintenance.

In all cases, the technology is evaluated in a unitary way; it was sought to know the orders of magnitude in general terms by route, the purpose of which is to provide a perspective of the cost levels of both CAPEX and OPEX in 10 years for both types of technology. It is pointed out that a residual cost of the electric bus was considered, and the cost of equipment and backup buses is not considered.

CAPEX

Technology	Item	Bus
BEB	Bus Cost	USD 460.000
	Charger	USD 15.000
	Additional battery	USD 28.000
	Connection cost (USD/kW)	USD 222,22
Diesel Euro VI	Bus Cost	USD 250.000

Table 6: Input CAPEX (Regulations and Standards for Clean Trucks and Buses, 2020)

Assumptions:

- Cost of equipment and backup buses is not considered
- The scenario of 1 charger for every two buses is analyzed (cost of a charger USD 30,000)
- Not all routes will need a substation - and in any case, it is not clear who bears the costs, generally it is the energy supplier.

OPEX

Technology	Item	Bus
BEB	$/Km Maintenance	USD 0,059
	Energy Cost (USD/kWh)	USD 0,030
	$/km Tires	USD 0,021
Diesel	$/km Combustible	USD 0,220
	$/km Tires	USD 0,021
	$/km Oil	USD 0,005
	$/Km Maintenance	USD 0,117

Table7:: Input OPEX (Regulations and Standards for Clean Trucks and Buses, 2020)

Assumptions:

- Discount rate: 0,12

Error! Reference source not found. presents TCO between the Futon electric bus and a diesel Euro VI bus, following the methodology shown before. The results are favorable are presented for electrical technology, finding differences of 15% between both technologies.

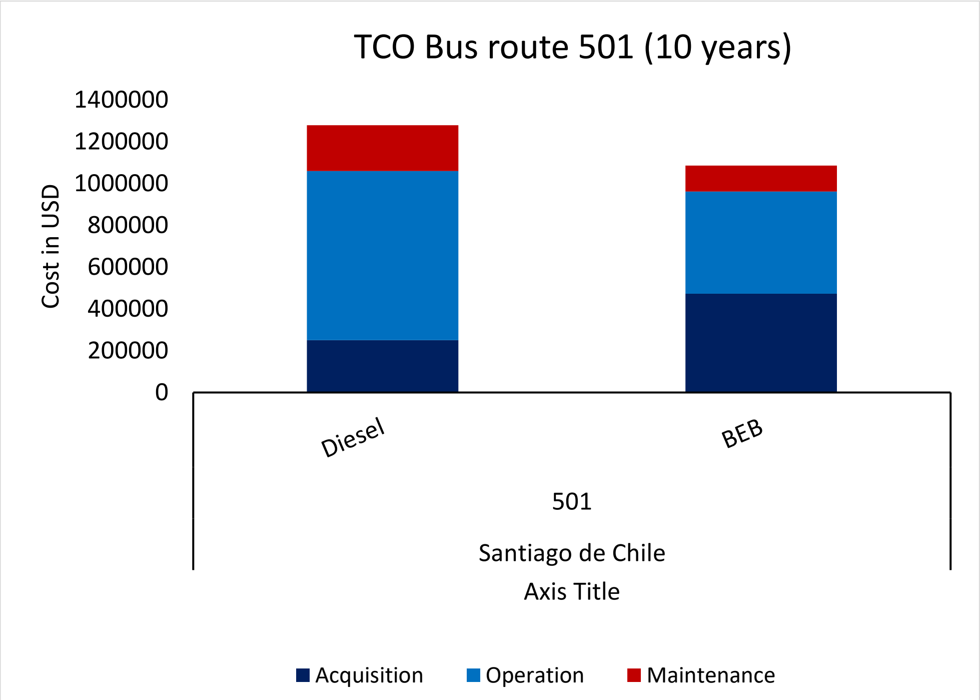


FIGURE 54: TCO ANALYSIS

Conclusion

For optimal operations, control and maintenance of any transportation system, it is vital to monitor vehicle performance. Hence its crucial to study vehicle dynamic behavior, passenger comfort, infrastructure capabilities with regular maintenance to maintain uninterrupted operation of the transport structure.

From the case study presented here, it is evident that there can methods of investigation of the vehicle performance to test its efficiency. The lateral acceleration also can cause discomfort to the passengers during the turns which to make it more comfortable the speeds during the curve are reduced. Vehicle vibrations should also be kept under control to dictate passenger comfort which unattended can have adverse effects on human health. Vibrations from the vehicle to infrastructure were also analyzed and studied. Noise effects on human health were observed and various damping techniques were discussed.

The case study also talks about the infrastructure competences required for smooth operation of the transportation system, where it is crucial for Electric Vehicles of any sort to have adequate charging stations available for a quick resupply of energy. In case of a trolley bus, suitable power supply substations are necessary for seamless traction supply.

Infrastructural issues were also observed and addressed regarding various road damages, and its possible solutions to reduce the affect of comfort level of the onboard passengers and also to decrease the stress levels induced on the vehicle due to uneven surfaces. Similarly, vehicle maintenance and diagnostics were also studied in order to produce optimal efficient operation of the study vehicle and also to prevent breakdowns.

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