Study and Experimental Road Tests of a Double-Articulated Hybrid LTRT

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Abstract

The Light Train on Rubber Tires (LTRT) vehicle has been studied and evaluated in several cities in Europe, the U.S. and other places throughout the world over the past few years. The main idea of the LTRT and the BRT (Bus Rapid Transit) is to provide a fast, flexible, integrated, high-performance system with lower infrastructure costs compared to rail-based systems. In order to examine the possibility of operating new vehicles combining advanced technologies along main public transportation routes in Israeli cities, a double-articulated, low-floor vehicle having hybrid propulsion, automatic guidance and a special futuristic design was tested. During the study period, the vehicle was operated and tested from various technical and transportation aspects. Static weight distribution and dynamic parameters of the hybrid power train, including temperature distribution, velocity, longitudinal and lateral accelerations, vibrations, noise levels and electrical parameters were measured as a function of time and location. Reliability, fuel consumption and emission tests were also carried out and compared to conventional buses. Special guidance roads and stations were constructed for automatic driving tests. The passenger compartment and suitability to individuals having special needs were examined.
The results indicated low noise levels, acceptable acceleration amplitudes, very good maneuverability, proper dynamic behavior, and automatic driving, which enables safe and close entry into the stations. On the other hand, poor reliability was observed mostly because of faults in the hybrid propulsion system, as well as poor ability in driving uphill. The project was performed for the Ministry of Transportation and involved the participation of major urban and public transportation companies. The study, the results of the measurements and the required improvements are discussed and presented in this paper.

Keywords: LTRT, hybrid, guidance, performance, reliability

1. Introduction

Light Train on Rubber Tires (LTRT) is a relatively new kind of public transportation system having the features of Light Rail Transit (LRT) and Bus Rapid Transit (BRT) systems. LRTR vehicles are driven by rubber tires and use different power sources and guidance systems, such as rails, mechanics, optical and magnetic guidance. Examples of LTRT systems are Translohr, Bombardier, Phileas and Civis.
Increasing levels of urban congestion are creating the need for new transportation solutions. A creative, emerging public transit solution is the BRT. BRT offers high-quality public transportation using a variety of transportation systems that can meet or exceed the performance of most rail systems in terms of flexibility and cost advantages of roadway transit. In order to achieve this, BRT uses improvements in infrastructures, vehicles and scheduling. The main goals of BRT are to provide options to personal vehicles, to reduce greenhouse gas emissions, and to promote transit-oriented development.
The main BRT components are: vehicles, running ways, stations and stops, intelligent transportation systems (ITS) and fare payment [1], [2].
BRT vehicles are creating a service image similar to the light train having high average speeds, high capacity, distinctive styling and advanced propulsion.

High average speed is achieved by reducing entrance/exit times, using a low-floor vehicle with multiple doors, level boarding, and precise docking with automatic guidance.
High capacity is achieved by operating long-length, double-articulated lightweight vehicles.
Distinctive styling is an important parameter to distinguish the BRT from regular transport services. Therefore, a modern and futuristic design of the vehicle, both externally and internally, is implemented. Long-length vehicles can also contribute to the style of the BRT vehicle.
Advanced propulsion systems can benefit the vehicle's performance and reliability. It can also improve passenger comfort by reducing noise and vibrations, improve fuel consumption and dramatically reduce emissions. Many alternative fuels are available, such as natural gas, ethanol, methanol, bio-diesel, hydrogen and various propulsion drives such as hybrid, electric and fuel cells.
In order to prove the advantages of BRT, experimental tests were carried out on different vehicle types. Generally, the results show an improvement in fuel consumption and emissions for hybrid BRT vehicles but ambiguous results regarding other performance and reliability parameters.
In order to examine the possibility of operating new BRT vehicles combining advanced technologies along main public transportation routes in Israeli cities, a double-articulated, low-floor vehicle having hybrid propulsion automatic guidance and a special futuristic design was operated and tested from various technical and transportation aspects.
The study, the results of the measurement and required improvements are discussed and presented below.

2. The Hybrid Propulsion System

The hybrid propulsion system incorporates two or more methods of providing power for movement. Hybrid electric vehicles (HEVs) typically combine an internal combustion engine with an energy storage device and an electric motor/generator system. The energy storage devices may be batteries, supercapacitors or flywheels. The internal combustion unit is powered by gasoline, methanol, compressed natural gas, hydrogen or other alternative fuels. During braking, some of the braking energy is returned to the vehicle by charging the batteries in a process called regenerative braking. Hybrid electric vehicles have the potential of being more fuel efficient as well as producing lower emissions compared to conventional vehicles [3-6]. HEVs can have a parallel design, a series design, or a combination of the two.

2.1 Series configuration

In a series hybrid electric vehicle, the wheels are driven by an electric motor that derives its electricity from an internal combustion engine (ICE) generator set, an energy storage device, or simultaneously from both. Series HEVs have no mechanical connection between the internal combustion engine and the wheels (see Fig. 1) [4]. Some benefits of a series configuration include:
The engine never idles, which reduces vehicle emissions.
The engine can operate continuously in its most efficient region.
The design allows for a variety of options when mounting the engine and the vehicle components.
Some series hybrids do not require a transmission system.
The downside is that series HEVs require larger, and therefore, heavier battery packs than parallel vehicles. In addition, the engine works hard to maintain a charged battery since the system is not operating in parallel. The inefficiency of converting energy from one type to the other is also another factor.

2.2 Parallel configuration

A hybrid electric vehicle having a parallel configuration has a direct mechanical connection between the internal combustion engine and the wheels, as in a conventional vehicle (see Fig. 1) [4]. Some benefits of a parallel configuration include:

A smaller engine provides more efficient operation and therefore better fuel economy without sacrificing acceleration power. The vehicle has more power because both the engine and the motor supply power simultaneously.

Power does not need to be redirected through the batteries and can therefore be more efficient.

On the other hand, since the main energy source in a parallel configuration is the internal combustion engine, it often won't work in its most efficient region as in a series configuration. The design of parallel hybrid propulsion is more complicated compared to the series one.

Other hybrid drive configurations are available but the main power trains in buses are the above mentioned series and parallel systems.

The use of hybrid technology offers many advantages compared to conventional drive technology: reduced emissions, improved fuel consumption, a quiet and comfortable drive, and lower maintenance. However, the cost of hybrid buses is higher than conventional buses, even though the number of hybrid buses is continuously growing, especially in the U.S. and Canada. Leading manufacturers of hybrid power trains include the BAE Company with a series hybrid power train, and the Ellison Company manufacturing both series and parallel hybrid propulsions. Other companies such as ISE and Enova have or are developing hybrid power trains. Leading hybrid bus manufacturers are Orion, with their 12-meter Orion IIV using a BAE hybrid power train, and New Flyer with a wide range of hybrid buses using Ellison and ISE hybrid drives. Many leading European manufacturers, including OEM, Volvo, MAN, Mercedes, Scania and VDL are developing or have already built prototypes of hybrid buses. It seems that the hybrid technology in buses has passed the critical initial stage and the future of hybrid buses is promising.

3. Vehicle candidates for BRT application

The following vehicles can be considered today for BRT application:

New Flyer articulated hybrid bus. The vehicle is low-floor with an Allison parallel hybrid drive (Fig. 2 [7]).

Van Hool double-articulated, low-floor conventional bus (Fig. 2 [8]).

APTS articulated or double-articulated, low-floor bus called "Phileas." The vehicle has a hybrid drive, automatic guidance and an innovative design (Fig. 2 [9]).

Irisbus articulated vehicle called "Civis." The vehicle is low-floor with internal combustion engine generator propulsion or is powered by an overhead catenary. The vehicle has an attractive design and optical guidance system (Fig. 2 [20]).

NABI articulated, low-floor hybrid bus using an Allison parallel hybrid drive (Fig. 2 [11]).

Solaris hybrid articulated, low-floor bus using an Allison parallel hybrid drive (Fig. 2 [12]).

Wright bus articulated hybrid bus called "StreetCar" using an ISE series hybrid drive. The vehicle is low-floor with an attractive design (Fig. 2 [11]).

Hess double-articulated, low-floor hybrid bus (Fig. 3 [13]).

Volvo double-articulated, low-floor conventional bus (Fig 3. [14]).

Mercedes articulated 19.6 m low-floor conventional bus called "Capacity" (Fig. 3 [15]).

The Chinese manufacturer Zhejiang Youngman (Jinhua Neoplan) has developed a 25-meter, double-articulated low-floor bus with assistance from Neoplan (Fig. 3 [16]).

The APTS double-articulated vehicle prototype"Phileas" was chosen for experimental operation in Israel because it has most of the characteristics of a BRT vehicle: high capacity, low-floor, attractive design, hybrid propulsion, automatic guidance, and all-wheels steering.

4. Basic Technical Specifications of the Tested Vehicle

As stated above, the vehicle chosen for testing in Israel was a double-articulated hybrid prototype vehicle called "Phileas," manufactured by APTS. The vehicle has the following declared manufacturer's characteristics and technical specifications.

4.1 Characteristics

Low floor over its entire length
All-wheels steering
Series hybrid drive with a LPG (Liquid Petroleum Gas) engine
Automatic guidance based on magnetic markers on the road surface
Modular design
Innovative interior and exterior
Lightweight body design using composite materials

4.2 Technical specifications

4.2.1 Geometry

Length – 24 meter
Width – 2.55 meter
Height – 3.2 meter
Floor height – 340 mm
Entrance height – 320 mm
Wheel base front section – 7,700 mm
Wheel base middle section – 6,010 mm
Wheel base rear section – 7,575 mm

4.2.2 Capacity

Seating – 38
Number of wheelchair places – 1
Standing including wheelchair place (4/8 person/m^2) – 83/167
Total (4/8 person/m^2) – 121/205

4.2.3 Weight

Empty weight – 22,640 kg
Maximum permissible weight – 36,700 kg

4.2.4 Propulsion

Maximum vehicle power – 299 kW
Hybrid drive integrator – Alstom
Engine power – 164 kW, 3,600 rpm
Generator: power – 0-150 kW, nominal rpm – 2,000
Electric engine nominal mechanical output – 39 kW, peak – 53 kW
Batteries: type – NiMeHydride, power – 195 kW, peak – 265 kW

4.2.5 Performance

Maximum speed – 80 km/h
Gradability – 10-13%, with maximum capacity – 8%
Acceleration to 25 km/h – 1.3 m/s^2

5. Test Program

The test program included the following topics:

5.1 Demonstration

Demonstration to government, urban authorities, police, public transportation operators, physically challenged people and other public transportation users.

5.2 Technical lectures and drivers' training

Technical lectures were given to technical employees from public transportation systems. Theoretical and practical training was provided to local bus drivers in order to enable them to drive the vehicle during the test period.

5.3 Transportation tests

The following transportation tests carried out:
Driving on a variety of city and intercity roads, including routes planned for use by BRT
Entrance and exit to and from stations in different driving modes
Capacity and passenger load and unload times
Suitability of the vehicle to physically challenged passengers
Junction passing parameters

5.4 Technical tests

Inspection of vehicle body and components
Static tests: weight distribution and temperature distribution measurements
Dynamic tests: velocity, acceleration, vibration and steering angles, measurements as a function of time and location
Temperature distribution measurements
Internal noise level measurements
Fuel consumption, emissions, currents and voltages of the hybrid drive measurements

5.5 Documentation

Review of documentation, diagnostics, maintenance aspects, and faults treatment.

6. Test Results

The vehicle was tested over a period of about six months according the above test program. The test results are presented below.

6.1 Demonstration of the vehicle

During the operation, the vehicle was demonstrated (Fig. 4) to various bodies, authorities and public transportation users. The demonstration results were:
Positive impressions regarding the special attractive design, rail-like length, very good maneuverability (due to the automatic driving feature, especially on turns; the driver doesn't need to touch the steering wheel)
Negative impressions regarding the multiple faults.

6.2 Technical lectures and drivers' training

6.2.1 Technical lecture

A six-hour lecture was provided to about 80 technical employees. During the lecture, the vehicle's general features and performance were described, and the vehicle was presented in the final part of the lecture. The participants were satisfied with the lecture's contents however several groups had requested more detailed data.

6.2.2 Drivers' training

The purpose of the drivers' training was to provide drivers with enough theoretical knowledge and practice to enable them to drive the vehicle during the test period in order to get their opinions about driving the vehicle. Therefore, the training session was divided into three stages:
Theoretical training, in which the features and components of the vehicle were described by an APTS engineer. Twenty drivers participated in the four-hour lecture, and their feedback was positive.
The second stage was the practical driving for one hour in a drivers' training school. The training was provided to drivers from various public transportation systems and was very effective.
The third stage was driving the vehicle (three hours per driver) on city roads.
Drivers who passed these three stages were authorized to drive the vehicle during the test period. The drivers were asked to fill out a survey; some of the results are presented in Figure 5. The drivers liked the experience of driving the double-articulated vehicle and their main comments were:
Positive impressions about the good maneuverability
The turn of vehicle differs from a regular bus
The braking differs from a regular bus because of the electric braking at the first seven degrees of pushing the pedal
The air-conditioning system is poor and insufficient for the hot Israel climate
The steering wheel is too stiff
No problems with junction passing
Good entrance and exit to and from stations
Lower internal noise levels compared to a regular bus

6.3 Transportation test results

6.3.1 Driving on public transportation routes

During the test period, driving along public transportation routes took place in the major Israeli cities. The types of driving routes were:
Roads planned to be used as BRT routes
Public transportation routes
Public transportation routes especially prepared for automatic guidance testing
The results indicate that the vehicle had no problems in driving and maneuvering along all of the routes tested. The measured acceleration and average velocity were at acceptable levels.
Often when the vehicle was braking, it was accompanied by an uncomfortable feeling, especially when stopping before junctions. In these cases, the decelerations were higher than expected for public transportation vehicles. No problems were experienced in starting on flat surfaces; however in starting uphill, the vehicle sometimes failed to start and slipped backwards. Passenger load and unload times in the stations using manual driving were similar to regular buses. The major advantage of the vehicle when entering a station is the automatic guidance system, which enables small gaps of 40-90 mm between the station and the vehicle. Under manual driving, the driver was afraid of damaging the vehicle, and as a result, the gaps were often considerably greater. This emphasizes the importance of guidance systems for making the vehicle more accessible and in reducing boarding times. No problems of junction passing were noticed.

6.3.2 Suitability for physically challenged people

The passenger compartment was developed and built according to European directives. The main dimensions were above the minimum required by these directives. The passenger compartment enables comfortable passage of physically challenged individuals including wheelchair users.
The automatic driving with the all-wheels steering feature enables the vehicle to come very close to the station in the automatic driving mode. The gaps measured between the station and the vehicle were 60-90 mm at the front end and 40-60 mm at the rear end. Most wheelchair users were able to enter the bus without difficulty, but some wheelchairs having small front wheels experienced problems.
The stations were specially built at the same height as the vehicle's floor. This improved vehicle accessibility especially for physically challenged people, the elderly and small children.

6.3.3 Junction passing parameters

The main junction passing parameters are the appearance of traffic lights and vehicle passing time. In general, no problems of junction passing were noticed. Figure 6 illustrates passing through a 40-meter long junction starting from rest. It takes about 10-11 seconds to pass through the junction, the maximum velocity was 31 km/h, the maximum acceleration was 0.15g, and the average acceleration was 0.07g.

6.4 Technical Tests

6.4.1 Inspection of vehicle body and components

Vehicle body and components were examined before and during operation. The objective was to improve knowledge and ability to understand the results during the tests, including maintenance and reliability. In general, the vehicle was built as a prototype with the following specially developed main systems: hybrid electric drive, suspension and steering, guidance, and rigid composite material body. Therefore, the probability of failures in the above systems was relatively high. However, most of the other vehicle components are widely used in automotive industries. It should be mentioned that most hybrid drive components that are located on the vehicle's roof had good accessibility. Battery maintenance requires the use of special equipment.

6.4.2 Static tests

Weight distribution of an empty vehicle including the measurement devices was measured for establishing the basic empty bus weight. The total vehicle weight was 23,725 kg compared to the declared empty weight of 22,600 kg.
Temperature distribution was measured with and without operation of air-conditioning by 19 thermocouples (see location of thermocouples in Fig. 7), which were distributed inside the driver's cabin and the passenger compartment; and two more thermocouples were located outside the vehicle to measure environmental temperature. Figure 8 show selected results. The conclusions from the results were:
The temperature variation in the passenger compartment was up to 5^{o}C.
With the air-conditioning on, the temperature reduction was about 2^{o}C.
The maximum temperature in the driver's cabin and at the front door was the highest, about 8^{o}C more than in other places in the passenger compartment (probably because of radiation).

6.4.3 Dynamic tests

During the experimental tests, various dynamic tests were performed under different capacity and driving conditions, including driving on flat roads, on graded areas, in a city, along intercity routes, and on dry and wet roads. The measurements were carried out using a high-frequency data acquisition system. Figure 9 indicates the location of the acceleration transducers inside the vehicle. The data collected describe the dynamic behavior of the vehicle. Typical results and a summary are presented below.
The velocity of the vehicle was measured continuously using two independent devices as a function of time and location. An analysis and presentation of the velocity signal included instantaneous velocity (v(t)), average velocity (v_{ave}), route height relative to sea level (h(t)) and part of the map indicating the exact vehicle location. Figure 10 illustrates examples of the results while driving uphill in Jerusalem. An analysis of all of the results shows that the maximum height measured of the tested routes was 900 m; the maximum velocities of the unloaded vehicle were 50 km/h on city roads, 30 km/h while driving uphill and 85 km/h while driving on intercity roads; average velocities were 10-26 km/h on city roads and 58-70 km/h on intercity roads.
The vehicle's longitudinal accelerations were measured continuously. After analyzing the data files, maximum acceleration was 0.28g while typical maximum accelerations were 0.18g, as illustrated in Figure 11. Figure 12 shows, for example, instantaneous accelerations and average acceleration when driving from rest to 68 km/h.
The maximum measured braking deceleration was 0.52g – a high value for public transportation vehicles while typical decelerations are 0.2-0.3g. Figure 13 shows the velocity and deceleration profiles during braking from 67 km/h to rest.
The steering angles of all wheels enabled moderate turning with relatively low lateral acceleration values. In general, the maximum lateral accelerations were under 0.2g. Figure 14 shows the turning of the vehicle at a junction at a velocity of 17 km/h. In this case, the maximum measured lateral acceleration was 0.17g for the rear cabin.
Average vibration amplitudes were 0.1-0.2g, while the maximum value was 0.8g. The frequency analysis shows resonances at frequencies of 1-2, 8 and 10 Hz.
Subjectively speaking, the vibration level was not low, especially in the rear cabin, while driving on unpaved roads. When driving on normal roads, the vibration level was low and the feeling was comfortable. Selected velocity and vibration profiles are shown in Figures 15-16 at time and frequency domains.

6.4.4 Internal noise levels measurements

Internal noise levels were measured in different areas of the passenger compartment, as shown in Figure 17. The results are presented in Table 1. In most of the areas, the noise levels were below 70 dB. These values are relatively low compared to regular buses.

6.4.5 Fuel consumption, emissions, currents and voltages of the hybrid drive measurements

Battery current, voltage and state of charge were measured at defined points. Figure 18 shows the vehicle's velocity and the following battery parameters: battery current (I_b), battery voltage (V_b), battery power (P_b) and battery state of charge (S.O.C).
The negative value of battery current and power indicates that the battery is charged; the positive value indicates that the battery supply power. During acceleration and high-velocity driving, the battery supplies energy to the vehicle, while during braking, the battery is charged in the process of regenerative braking. Also when driving downhill, low-motion power is needed and the battery is charged by the engine.
Fuel consumption and emissions: Fuel consumption was measured together with the Internal Combustion Engines Laboratory, the Transportation Research Institute and the Faculty of Mechanical Engineering of the Technion – Israel Institute of Technology. The emissions and other parameters affecting fuel consumption were measured. The measurements were carried out on routes where the BRT can be implemented, intercity roads with and without stopping at the station, and with and without air-conditioning operation. Table 2 summarizes the energy flow parameters. Fuel consumption was established by connecting a spare gas tank to the vehicle that measured the weight difference before and after the test drive. Emissions were measured using dedicated equipment. Figure 19 shows average fuel consumption as a function of average velocity, and Figure 20 shows typical emissions results. The detailed results regarding fuel consumption and emissions are described in a report by the Internal Combustion Engines Laboratory, the Transportation Research Institute and the Faculty of Mechanical Engineering of the Technion – Israel Institute of Technology [17].
The main conclusions indicate correlation between fuel consumption and average velocity was found. Air-conditioning operation influences fuel consumption only at high ambient temperatures. Uphill driving causes an increase in fuel consumption. Emission levels of CO and HC per hour increase as with an increase in average velocity. On the other hand, No-x emissions are not influenced by average velocity. Air-conditioning causes an increase in emissions of CO by 11%, HC by 65% and No-x by 40%. Uphill driving causes an increase in emissions. The main advantage of the tested vehicle is low No-x emissions;

Hybrid drive energy flows: As previously mentioned, Table 3 presents selected data of the points at which fuel consumption and emissions tests were measured. The table contains route length, average velocity, change of kinetic energy (ΔE_k), regenerative energy (E_{reg}), regenerative energy per kilometer (E_{reg}/L, L- route length) and the ratio between regenerative energy and change of kinetic energy ($K = E_{reg}/\Delta E_k$) for different deceleration ranges. The conclusions regarding the results indicate that most of the decelerations exceed 0.8 m/s^2 and most of the regenerative energy is gained at decelerations of 1-4 m/s^2. However, the highest energy ratios (K) occur at low deceleration rates. Therefore, regenerative braking has the greatest effectivity at low deceleration rates.
Energy ratio (K) is influenced by various parameters, such as average velocity, driving style, road shape and conditions. In addition, values for city routes are between 0.1-0.26 K, and for intercity routes, between 0.02-0.1 K. The highest K values were obtained for "stop and go" driving that requires frequent use of brakes.
The regenerative energy per kilometer variation is from 13 KJ/km on intercity routes and up to 788 KJ/km on city roads. Figure 21 shows regenerative energy per kilometer as a function of deceleration range for various tested routes. The average velocity for the route is shown in brackets on the graph. The main increase in regenerative energy per kilometer is at deceleration ranges of 0.8-1 m/s^2 and 1.7-1.9 m/s^2. For higher decelerations, the regenerative energy per kilometer is almost constant.

6.5 The diagnostics and vehicle failures

During the test period, various faults and failures in the vehicle occurred. The vehicle's diagnostics level and documentation were not satisfactory or good enough to provide quick explanations as to the source of failure. The diagnostics were especially poor for hybrid drive troubles, and it took time to find and fix the failures. Most of the failures were associated with the hybrid drive. Some of the common failures were overheating of the electric invertors, the 400 V inverter stop of operation, battery connected failures, batteries being in too low a state of charge – often during uphill driving, uphill motion starting failures, uncontrolled height changes during driving, mechanic faults – starter, oil pump clutch, joint braking, speed sensors, and door opening faults – fuse burning and sudden power surge. Figure 22 shows the distribution of faults that occurred on flat and graded driving. The main conclusion is that vehicle reliability was poor during the test operation.

7. Summary and Conclusions

Several candidate vehicles can be considered in the future to be used in BRT systems.
During the test period, a number of transportation, technical and other types of tests were carried out on the selected vehicle "Phileas" in order to check the suitability of the vehicle for use as a BRT vehicle.
Positive impressions about the vehicle were exhibited due to its special attractive design, rail-like length and very good maneuverability and automatic driving, especially on turns. On the other hand, there were negative impressions regarding the faults.
The technical lectures and the drivers' training were successful, and Israeli drivers were able to drive the vehicle during the test period.
The vehicle could drive along all of the tested routes; in the automatic driving mode, the vehicle showed good results regarding the small gaps between the vehicle and the station. This enabled convenient accessibility for passengers, including wheelchair users. No problems of junction passing were noticed.
The maximum capacity was calculated for the current vehicle having 42 seats. The total capacity results are: maximum capacity according to eight standing passengers/m^2 – 212, according to six standing passengers/m^2 – 169 and according to four standing passengers/m^2 – 127.
Temperature distribution showed a reduction of 2-3^oC due to the air-conditioning system. This reduction is not acceptable for Israeli climate conditions.
Lateral acceleration values reached 0.17g. Vehicle behavior during turning was satisfactory and comfortable.
Gradability: the vehicle is not suitable for driving in mountainous areas.
Velocity, acceleration and braking: measured vehicle velocity and accelerations were acceptable (average acceleration was 0.18g). During a number of measurements, an exceptional deceleration of 0.52g was measured. Most of the decelerations were in the range of 0.2-0.3g.
On paved roads, the measured vibration level was low. On the other hand, on unpaved roads, high vibration amplitudes of up to 0.8g were measured.
Hybrid drive currents, voltages, fuel consumption and emissions were measured. The regenerative energy that was returned to the system during braking was calculated. The ratios between regenerative energy and change in kinetic energy were between 10-29%. The main advantage was the low No-x emissions.
Internal noise levels were about 70 dB, which were low compared to those of regular buses.
The vehicle's multiple failures, most of which were related to the hybrid drive, and the ineffective diagnostics resulted in poor reliability of the tested vehicle during operation. However, newer generation prototypes are being developed by the manufacturer using the parallel hybrid drive of the Allison Company. This change could improve the reliability and performance of the new vehicles.

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References

[1] U.S. Department of Transportation, Federal Transit Administration. *Characteristics of Bus Rapid Transit for Decision-Making*. Office of Research, Demonstration and Innovation, 2004.
[2] Bus Rapid Transit Policy Center website, http://www.gobrt.org.
[3] U.S. Department of Energy**,** Energy Efficiency and Renewable Energy website, http://www.eere.energy.gov/cleancities/hev/.
[4] Northeast Sustainable Energy Association (NESEA) website document**,** www.nesea.org/education/edmaterials/CARS_**FactSheets**_ResourceGuide.pdf.
[5] Friedman D*, A New Road.* Union of Concerned Scientists, U.S. Jan, 2003.
[6] Ciccarelli T. and Toossi R. Assessment of Hybrid Configuration and Control Strategies in Planning Future Metropolitan/Urban Transit Systems. Final report, California State University Long Beach. May 2002.
[7] Vehicle Technology Center website, http://www.gov.mb.ca/iedm/vtci/projects/nf_nr_0307.html.
[8] Van Hool website, http://www.vanhool.be.
[9] APTS website, www.apts-phileas.com.
[10] Irisbus website, http://www.irisbus.com.
[11] U.S. Department of Transportation, Federal Transit Administration. Vehicle Catalog. A Compendium of Vehicles and Powertrain Systems for Bus Rapid Transit Service 2006 Update, 2006.
[12] *Dopravní* website,.http://www.railvolution.net/dm.
[13] Website, http://www.bus-bild.de.
[14] Volvo Bus Corporation, *Bus Rapid Transit (BRT)*, 2006.
[15] Website, http://www.autokiste.de.
[16] Website, http://shanghaiist.com.
[17] Y. Zvirin, L. Tartakovsky, M. Gutman, M. Veinblat, V. Baibikov and Y. Aleinikov. *Road Tests of Phileas Hybrid Bus – Fuel Economy and Emissions Measurements*. Final report. Technion – Israel Institute of Technology, Faculty of Mechanical Engineering, Dec. 2006.

Table 1: Internal noise measurement results.

Area no.	1	2	3	4	5	6	7	8	9	10
	71.69	68.3	66	76	70	70	71.6	70	71	73
	61.73	71	70.1	78	64	72	90.6	72	72	68
	62.65	70.4	67.4	67	72	70	67	83	68	72
		69.5	68	63.65	84	66	66.3	66	69	74
		67	72.5	68	66	63	63.7	67	71	76
		71.7	70.1	67.6	74	68.8	67.68	70	72	74
		70.6	68	66.78	68	69	70	73.9	71.8	73
		66.7	70.3	65.71	70	66	85	90.2	69.1	75
		73.73	71.3	71.67	66	65.4	66	91.3	68.3	79
		78.19	71.68	64	63.9	65.2	90.6	69.5	70.2	71.3
		73.77	71.68	63.4	66.6	67.4	67.2	76	70.5	69.2
		60	68		65.2	86.6	67	73	74.4	68
		61.2	77.73		67.1	68	63.3	71	75	71
			68			72.3	65.4	72.5	74.3	82
			70			73.1	74.3	69.1		74
			70.1			69.3	75.6			76
			72.7			72.1	77.9			75.5
			66.1			73.6				76.6
			64.9							75
			65.2							
			73.3							
			70.4							
			69.9							
			68.1							
			69.5							
AVERAGE	65.36	69.39	69.64	68.35	68.98	69.88	72.30	74.30	71.19	73.82
MIN	61.73	60.00	64.90	63.40	63.90	63.00	63.30	66.00	68.00	68.00
MAX	71.69	78.19	77.73	78.00	84.00	86.60	90.60	91.30	75.00	82.00

Table 2: Regenerative energy, change of kinetic energy calculations and their ratio K ($E_{reg} / \Delta E_k$)

City driving							
L-Route length (km)	21.9						
Route average velocity (km/h)	20.9						
Decelerations range (m/s^2)	0-0.8	0-0.9	0-1.0	0-1.6	0-1.7	0-1.9	0-2.6
ΔE_k (KJ)	347.93	5579.78	9976.39	10292.13	12281.64	14247.375	14272.84
E_{reg} (KJ)	70.5	1183.76	1984.725	2033.44	2313.34	2621.69	2623.12
$E_{reg} / L (KJ / km)$	3.2	54.1	90.6	92.9	105.6	119.7	119.8
K	0.20	0.21	0.20	0.20	0.19	0.18	0.18

City driving with							
L-Route length (km)	7.5						
Route average velocity (km/h)	19.64						
Decelerations range m/s^2)	0-0.8	0-0.9	0-1.0	0-1.7	0-1.9	0-2.4	0-2.8
ΔE_k (KJ)	79.78	3471.45	6701	10771.68	14302.55	14381.48	15978
E_{reg} (KJ)	28.58	830.61	1582.53	2174.01	2733	2752.98	2888.38
$E_{reg} / L (KJ / km)$	3.8	110.7	211.0	289.9	364.4	367.1	385.1
K	0.36	0.24	0.24	0.20	0.19	0.19	0.18

Intercity highway uphill driving							
L-Route length (km)	26.3						
Route average velocity (km/h)	40.9						
Decelerations range (m/s^2)	0-0.8	0-1	0-1.7	0-1.9	0-2.6	0-2.8	0-3.4
ΔE_k (KJ)	274.15	11491.44	17616.13	22970.14	23894.458	24210.19	24345.99
E_{reg} (KJ)	15.74	1109.61	1801.22	2317.38	2417.34	2456.16	2467.58
$E_{reg} / L (KJ / km)$	0.6	42.2	68.5	88.1	91.9	93.4	93.8
K	0.06	0.10	0.10	0.10	0.10	0.10	0.10

Intercity highway down hill driving						
L-Route length (km)	14.9					
Route average velocity (km/h)	77.4					
Decelerations range (m/s^2)	0-0.8	0-0.9	0-1.0	0-1.7	0-1.9	0-2.8
ΔE_k (KJ)		4209	5769	8719.36	11601.77	12933.48
E_{reg} (KJ)		48.72	87.752	133.8	178.25	198.4
$E_{reg} / L (KJ / km)$		3.3	5.9	9.0	12.0	13.3
K		0.01	0.02	0.02	0.02	0.02

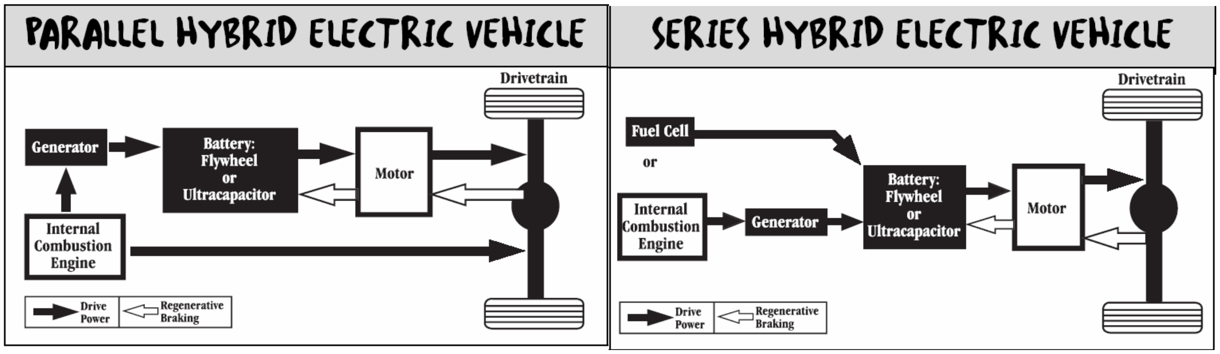
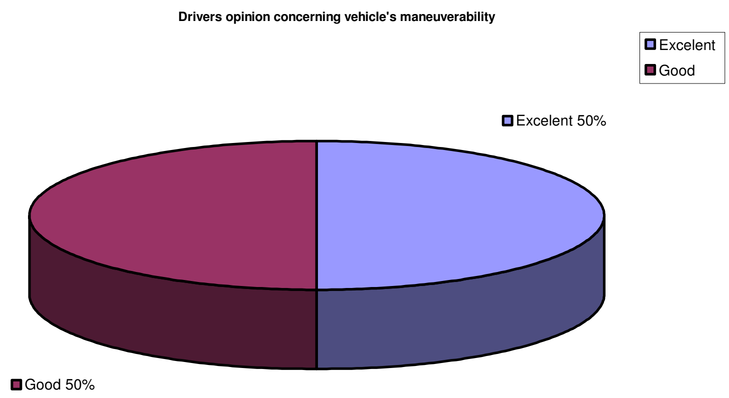


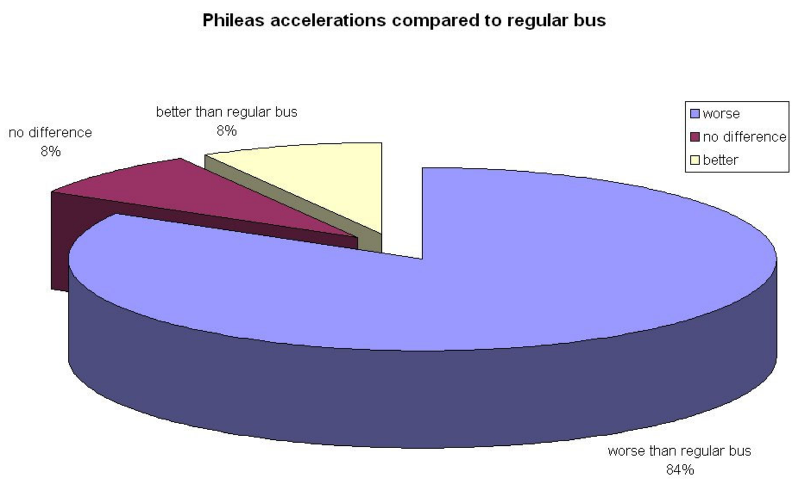
Figure 1: The hybrid drive configurations [4].

Figure 2: BRT vehicle candidates [6-12].

Figure 3: BRT vehicle candidates [13-16].

Figure 4: The vehicles demonstration to authorities and Haifa mayor





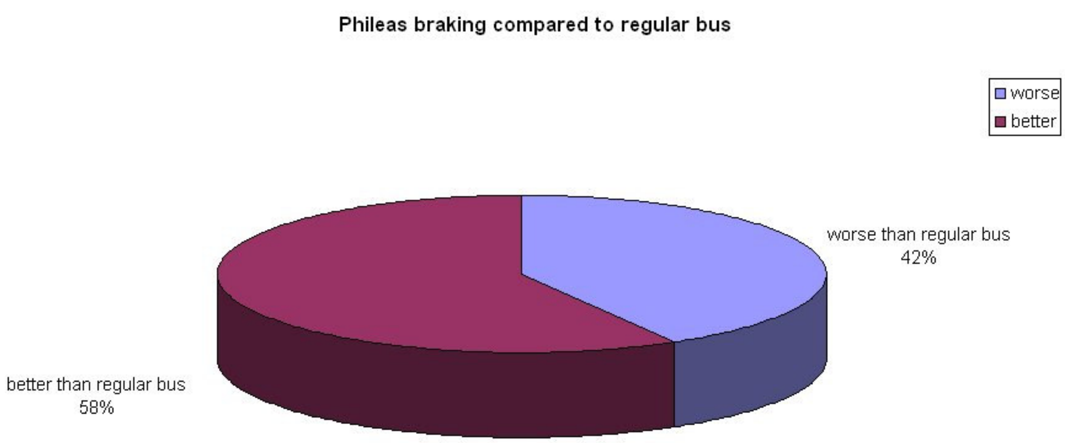


Figure 5: Selected survey of drivers' results.

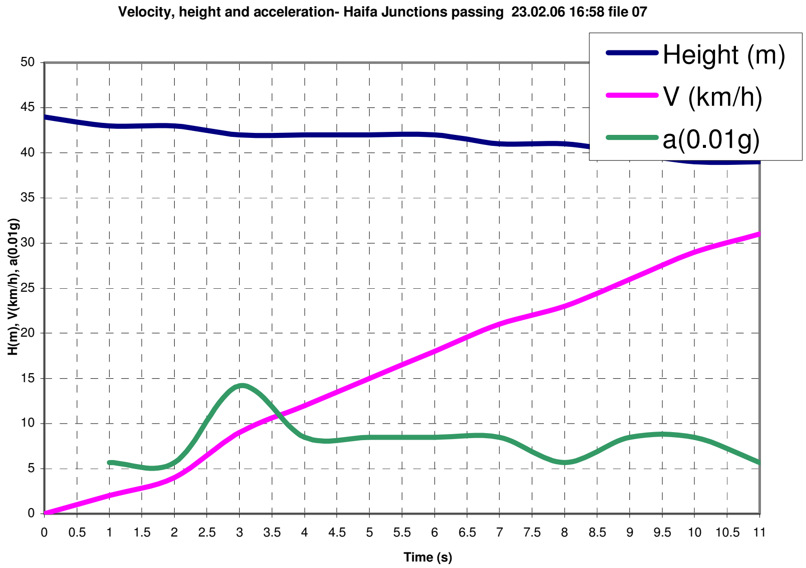
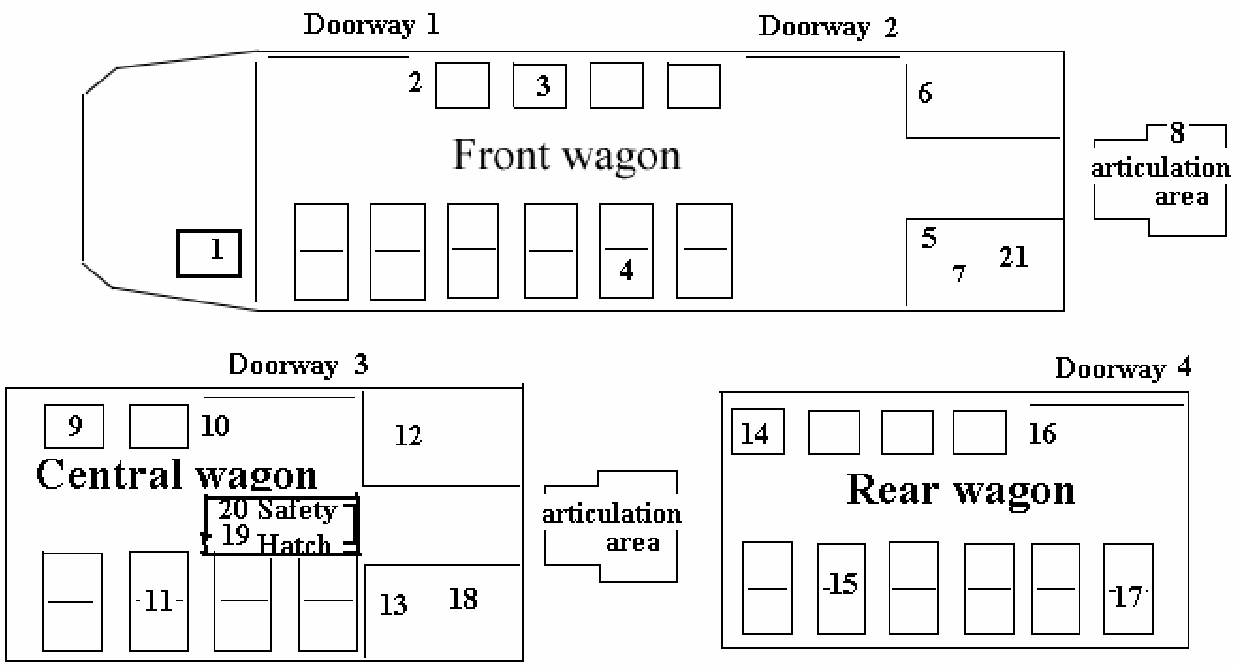


Figure 6: Example of measured junction passing parameters.



Thermocouples 19-20 measuring the ambient temperature are located outside the passenger compartment.
Figure 7: Location of thermocouples in the tested vehicle.

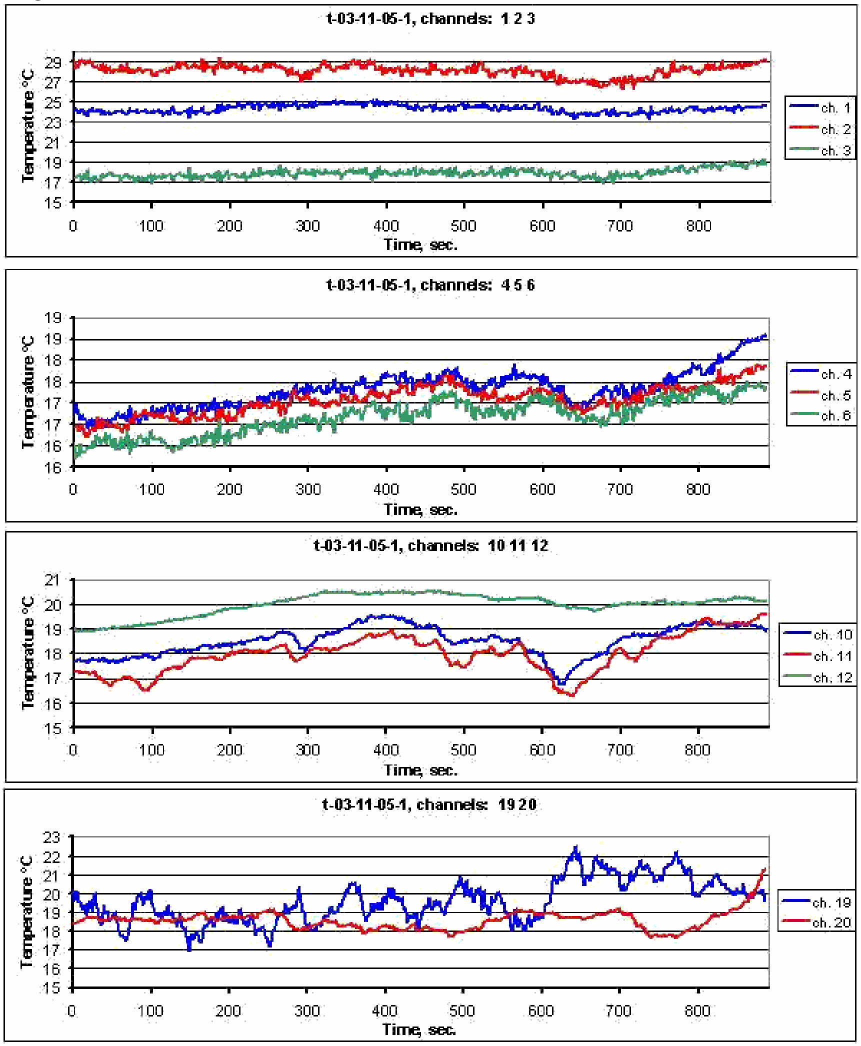


Figure 8: Selected thermocouples temperature distribution measurement results.

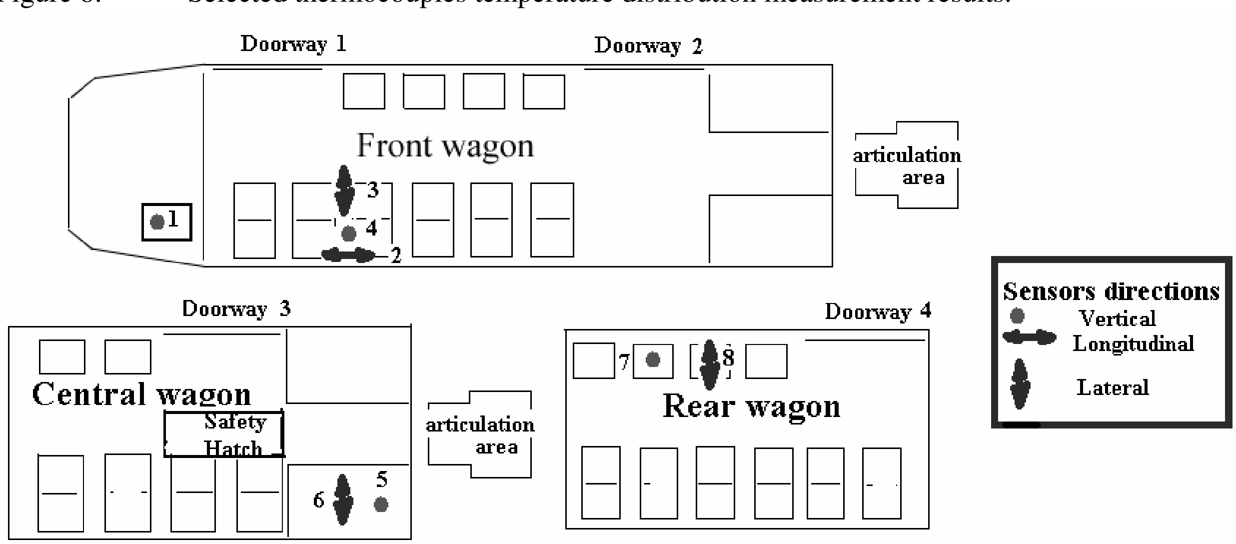


Figure 9: Location of the acceleration transducers.

The location of the vehicle on the map

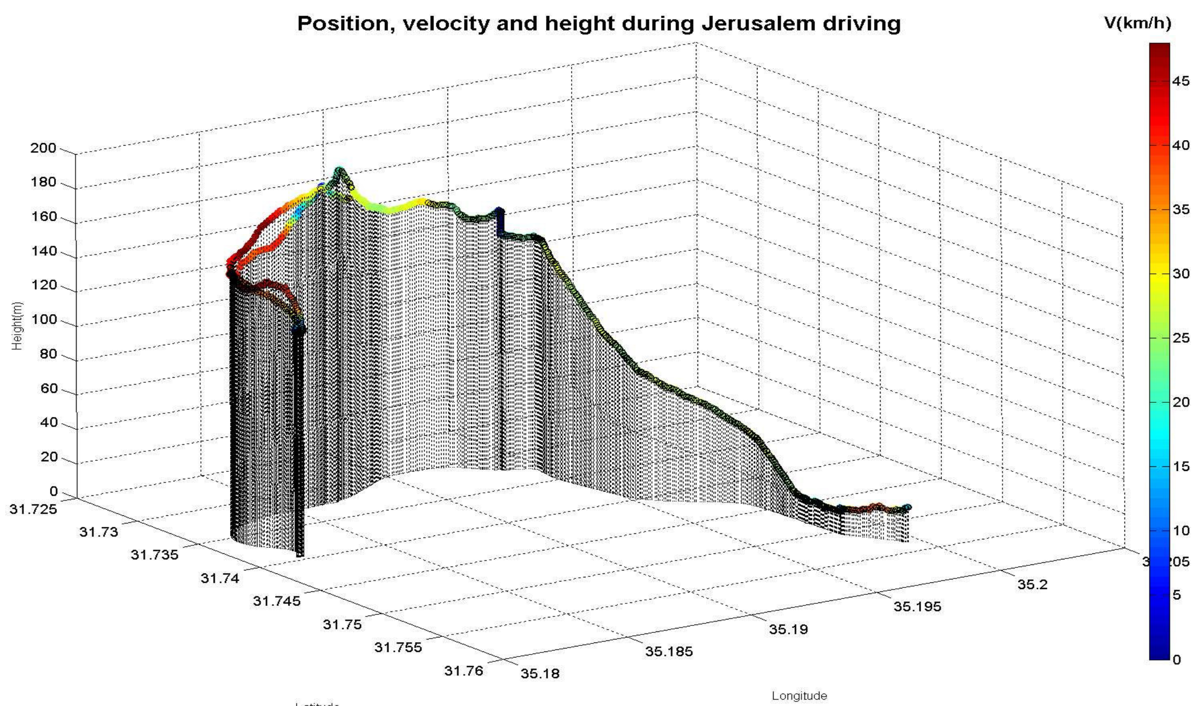


Figure 10: Vehicle's location (coordinates and map), velocity and relative height while driving in Jerusalem.

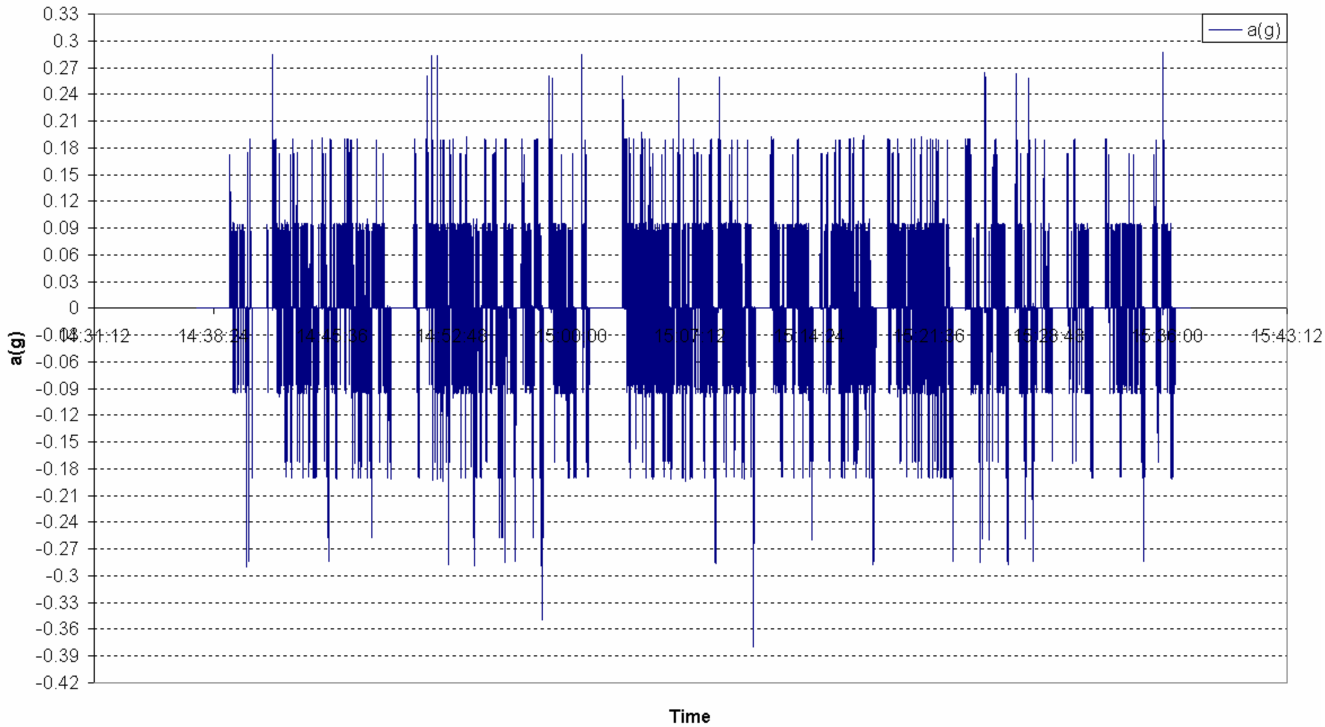


Figure 11: Typical longitudinal accelerations of the vehicle.

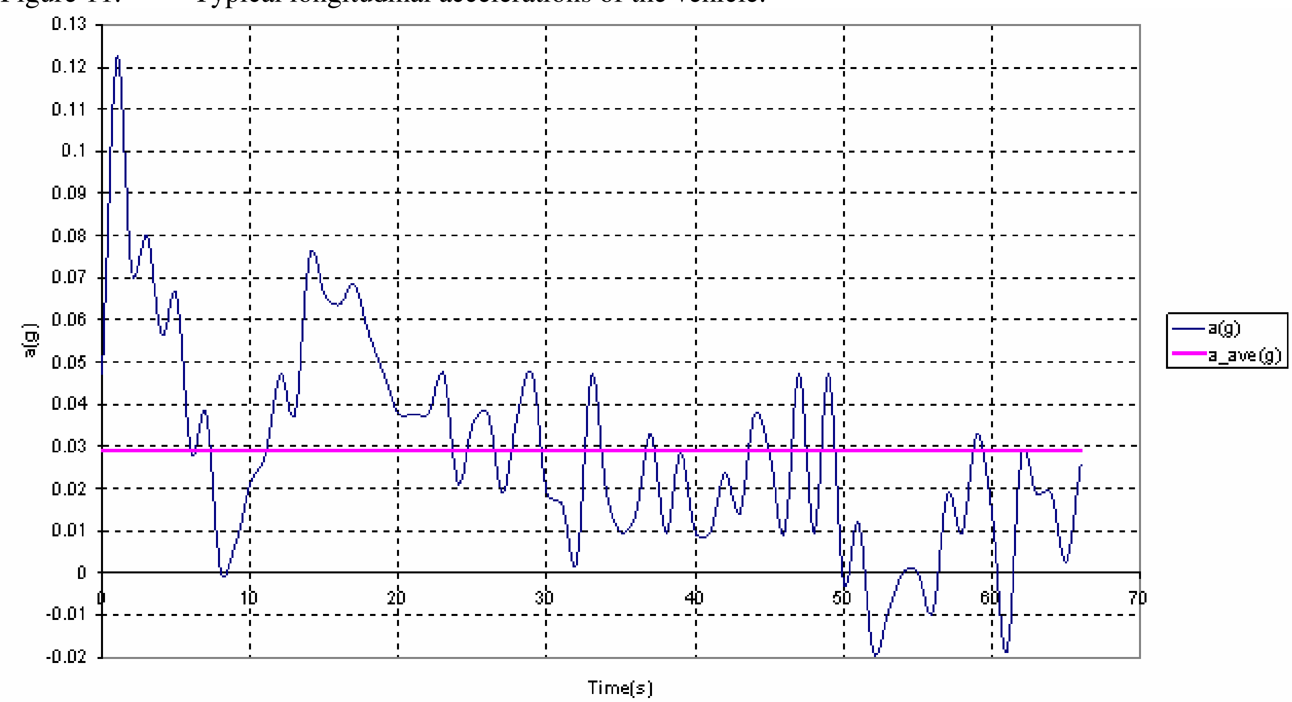


Figure 12: Measured instantaneous and average longitudinal acceleration profiles.

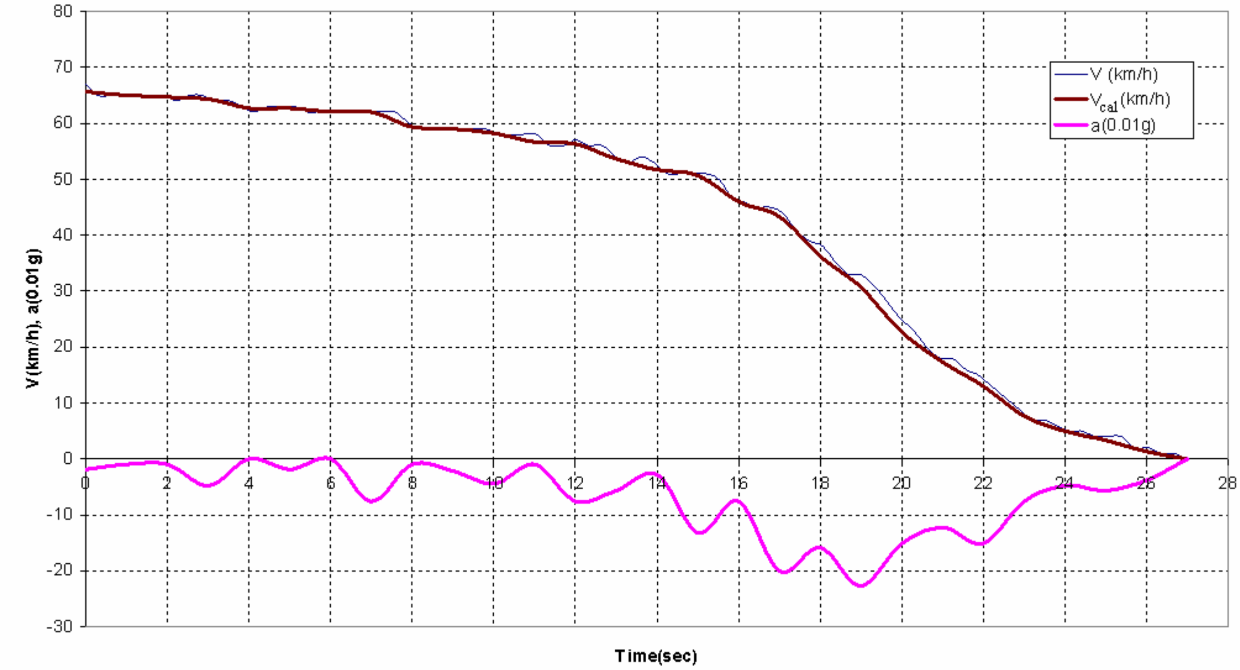


Figure 13: Measured braking deceleration and velocity profiles.

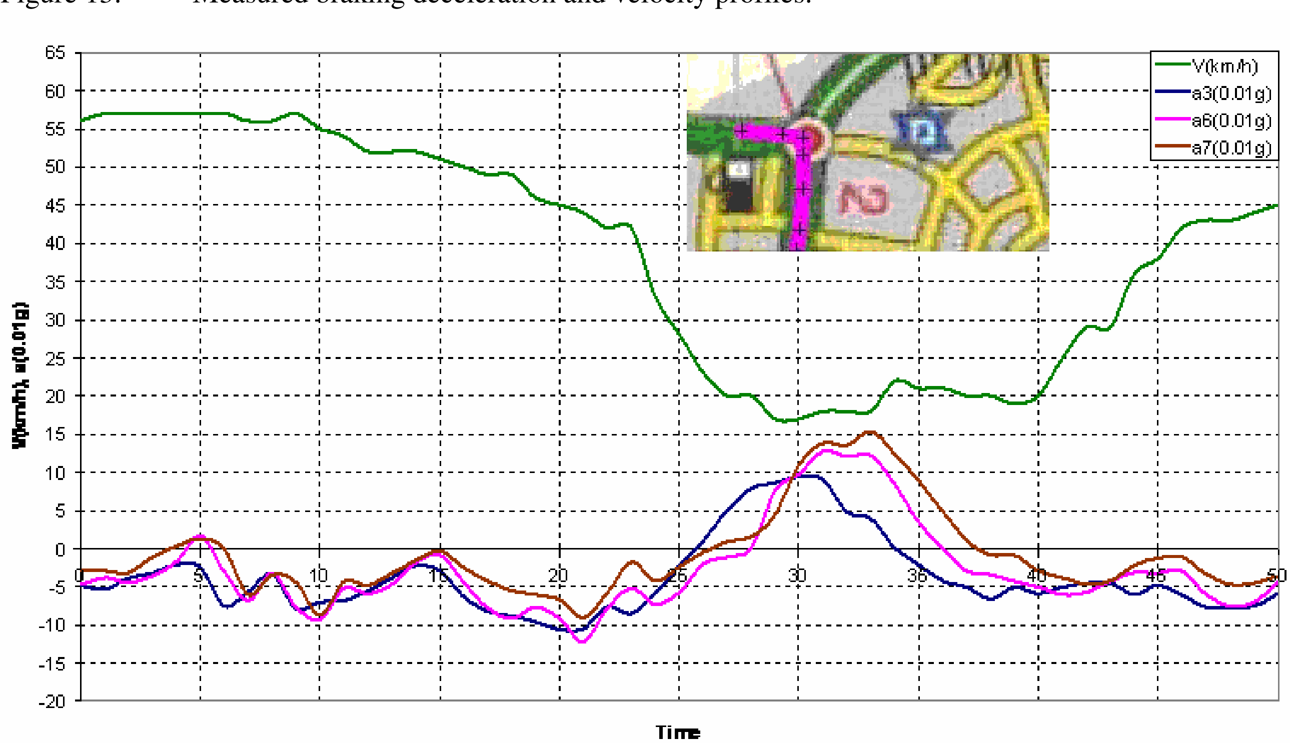


Figure 14: Velocity and lateral accelerations of the vehicle while turning at the junction shown on the map.

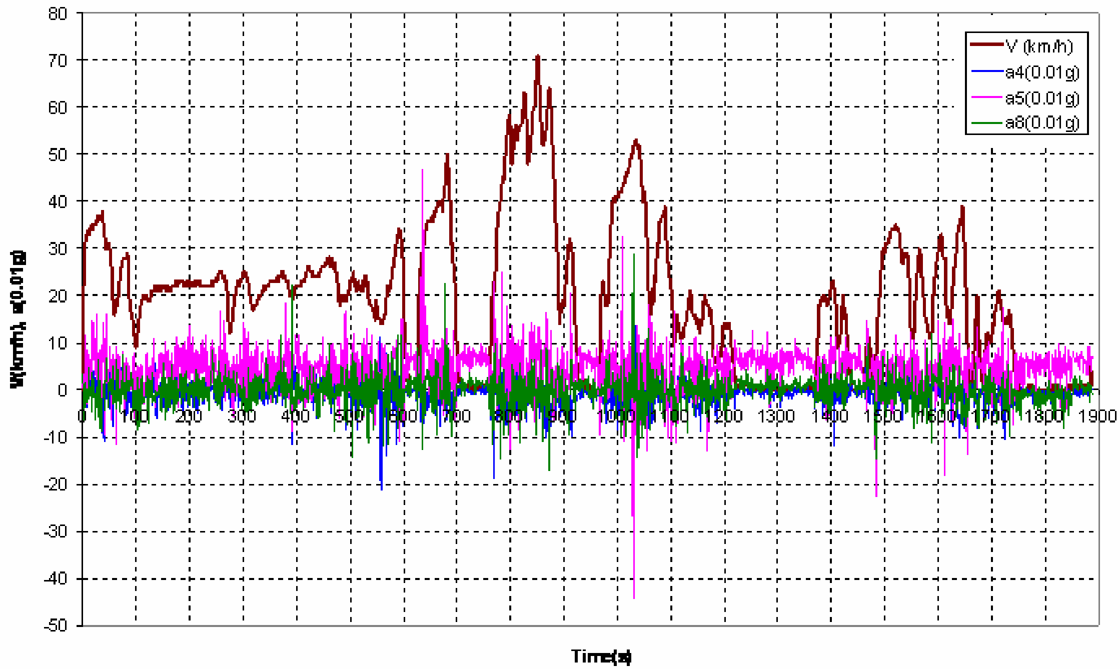


Figure 15: Velocity and vibration profiles.

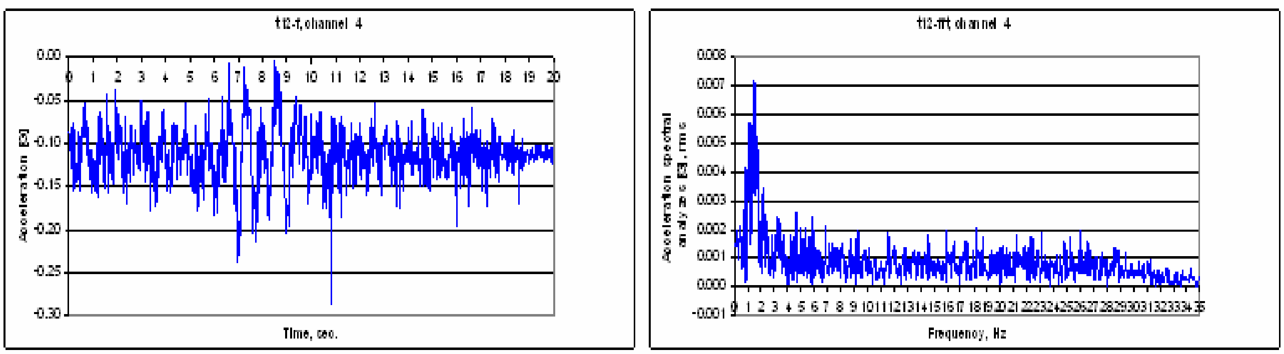


Figure 16: Vibration time and frequency domains.

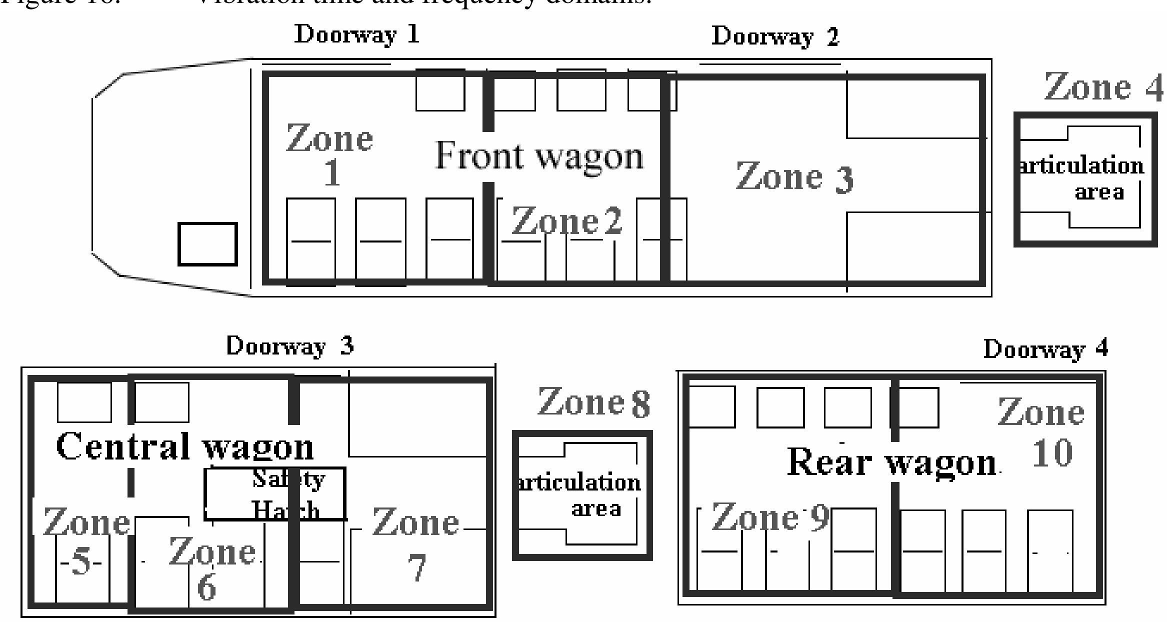


Figure 17: Internal noise measurement zones.

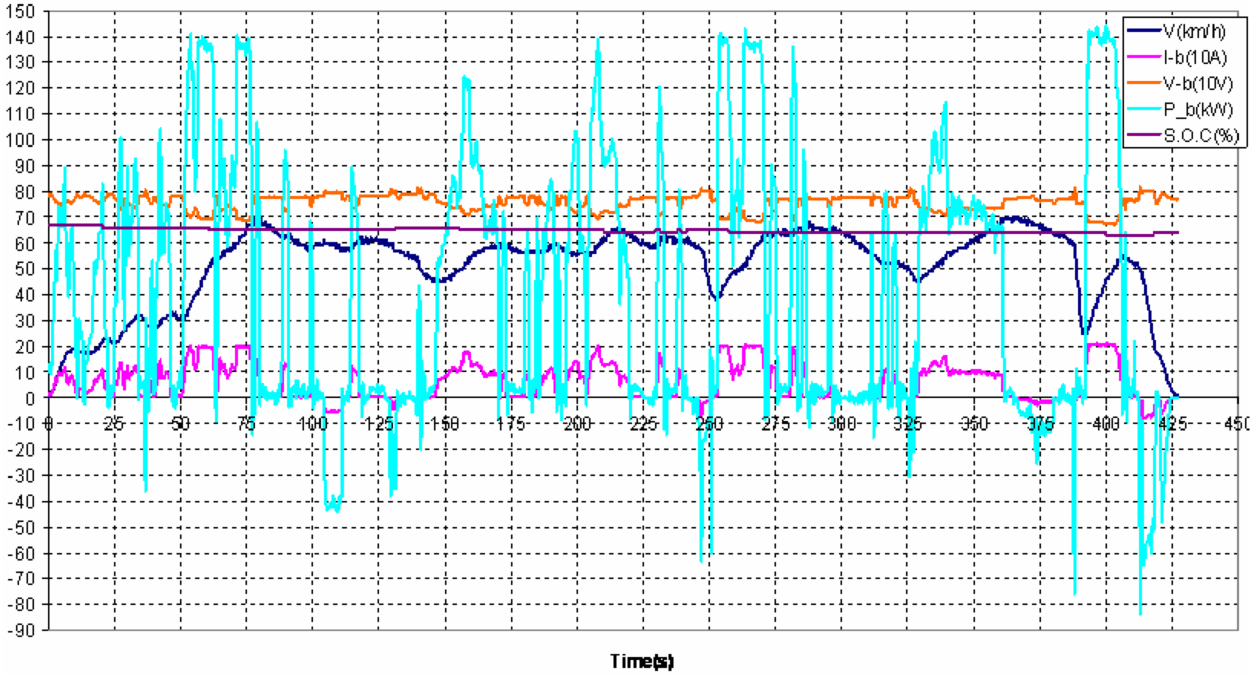


Figure 18: Velocity and battery parameter measurements.

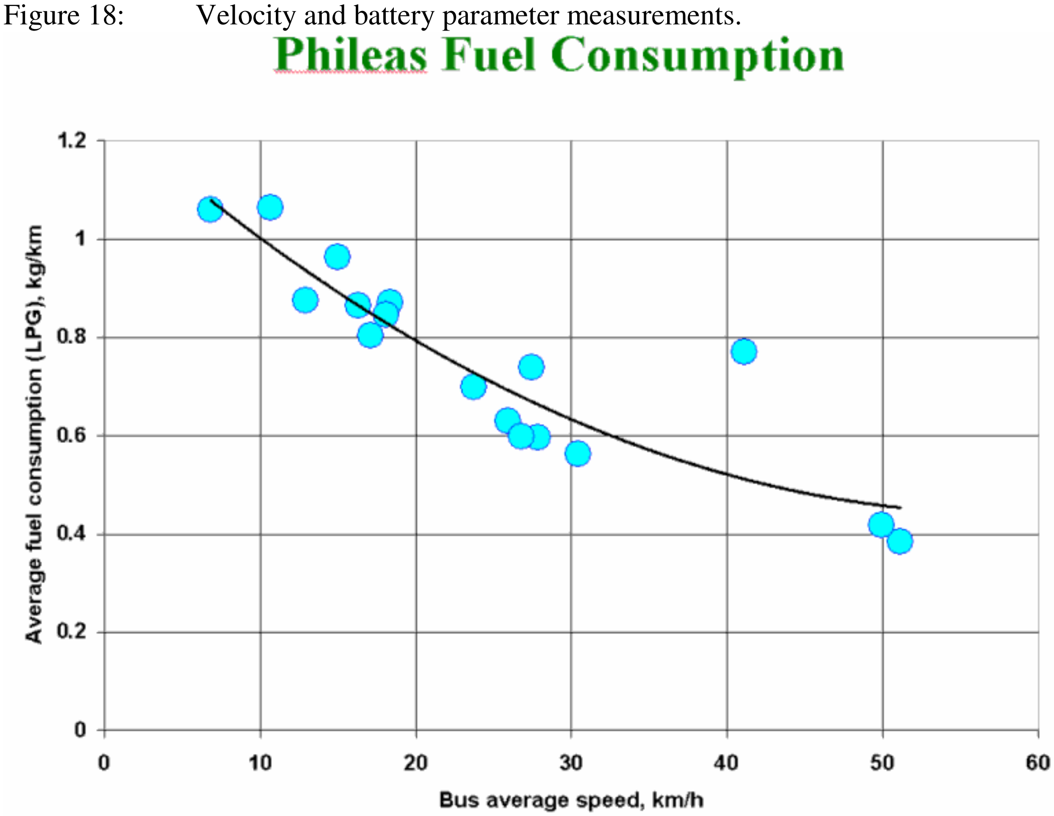


Figure 19: Average fuel consumption as a function of average vehicle velocity [17].

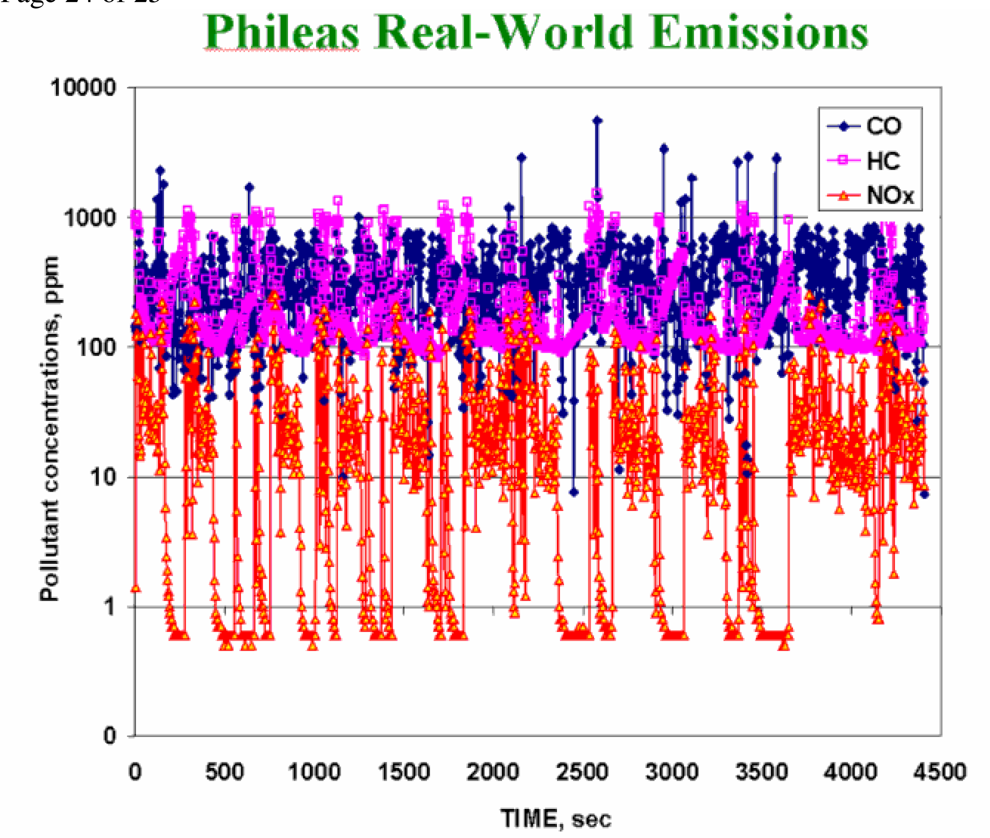


Figure 20: Emissions measurements on the city route [17].

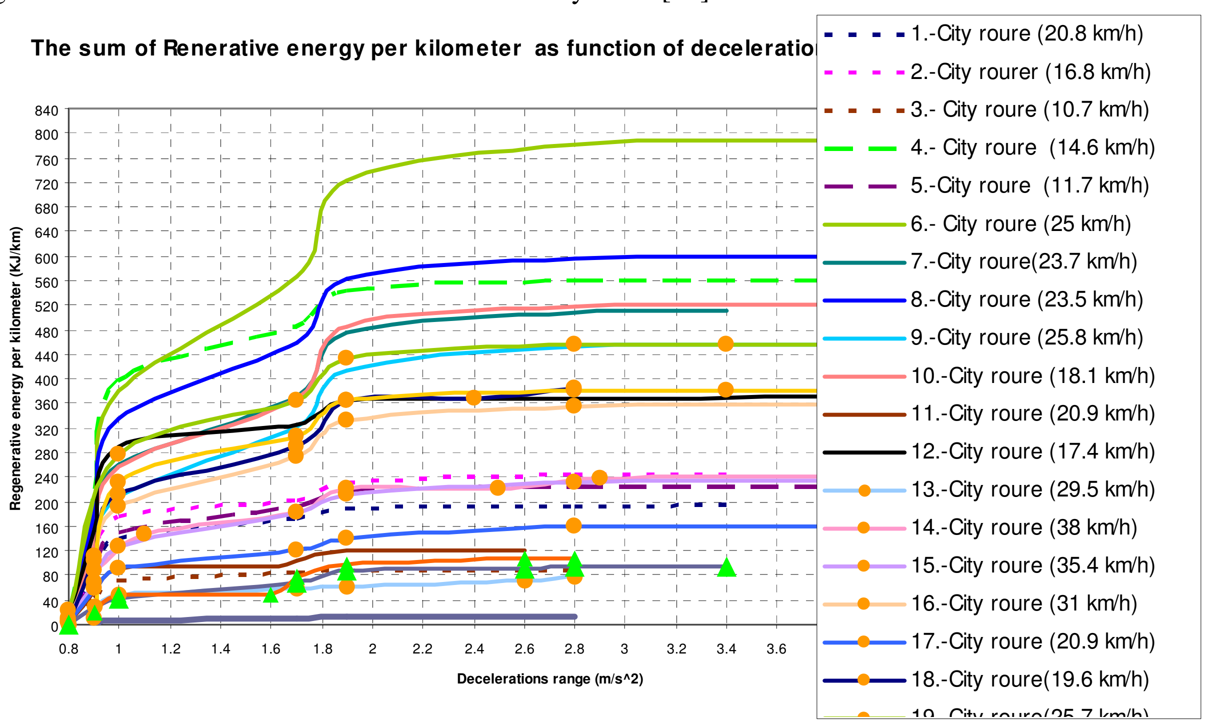


Figure 21: Regenerative energy per kilometer as a function of deceleration range.

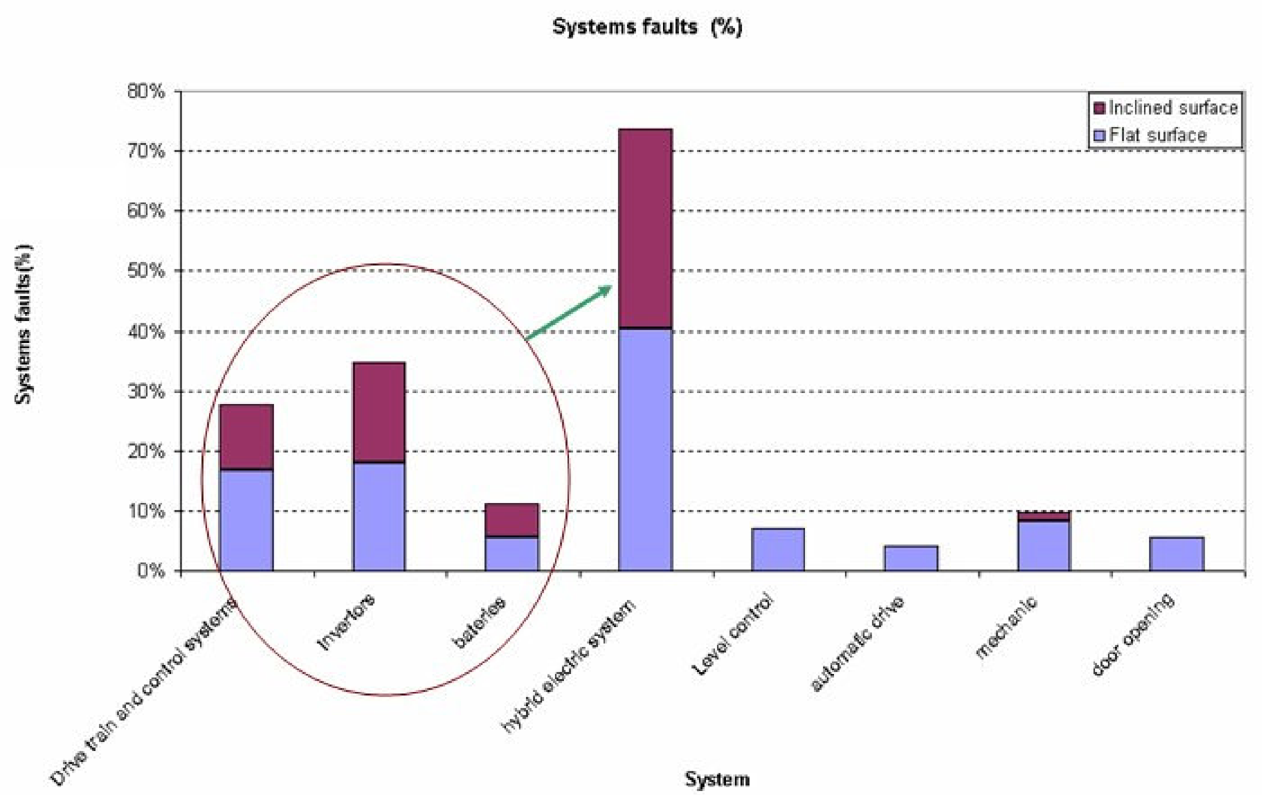


Figure 22: Failures distribution according to system type.