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FINAL REPORT

SCAQMD Contract 14062

Construction of a 1 Mile Catenary System and Develop & Demonstrate Catenary Hybrid Electric Trucks

eHighway SoCal

Final Report

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SCAQMD Contract 14062

Construction of a 1 Mile Catenary System and Develop & Demonstrate Catenary Electric Trucks

Final Test Results and Project Report

Project Period: 2014/7/14 - 2018/02/28

Provided by Siemens Industry INC

2018/Mar/12; Carson, CA and Erlangen, Germany

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Contents

1 Purpose and structure of the document

The aim of this document is to supply a final report of the SCAQMD Contract 14062. It is structured according to the contractual requirements of the statement of work [1] and complements the deliverables which were provided during project execution. The main focus is to summarize all tasks and specially concentrating on system performance and testing in course of the EHWY SoCal project on Alameda Street in Carson, CA.

The project focused on erection of 1 mile catenary bi-directional infrastructure, a power supply substation and integration of pantograph type current collectors into three different trucks which were intensely tested, see Figure 1 and Figure 2. Details on testing and results are given in [2].

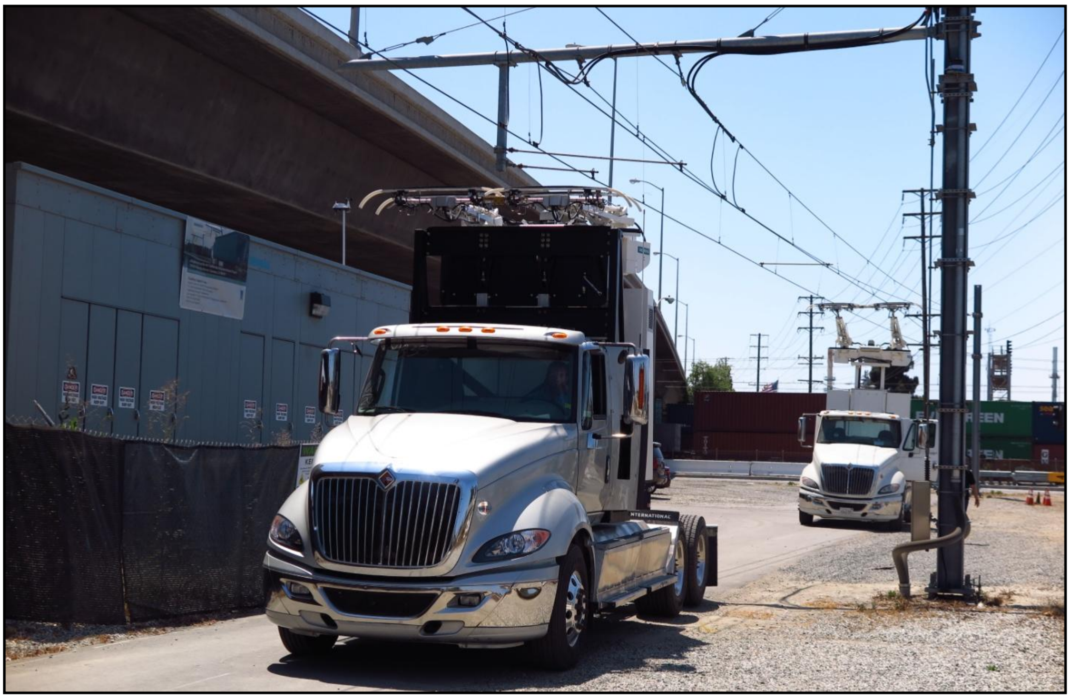


Figure 1 TransPower CCAT (front) and ECAT (behind) at test track next to substation

Figure 2 MACK Truck (Volvo Group) with trailer on Alameda Street

2 Project background and objectives

Air quality remains a major challenge for Southern California. According to the 2016 Air Quality Management Plan (AQMP) “the most significant air quality challenge in the Basin is to reduce nitrogen oxides (NO_x) emissions sufficiently to meet the upcoming ozone standard deadlines.”[A1] The AQMP further states that 552 tons NO_x is emitted each year and that 56% of this stems from on-road mobile sources. The largest segment of mobile sources causing these emissions is heavy-duty trucks, which emit 147 tons of NO_x each year. Forecasts point to significant NO_x reductions across all segments, but NO_x emissions will remain a challenge and heavy-duty trucks will remain the leading emitter of NO_x for as long as the forecasts have been modeled (year 2031). As the 2015 AQMD White Paper on Goods Movement states, “the analysis for the goods movement sector shows a need for greater penetration of zero- and near-zero-emission technologies in order to attain air quality standards” [A2].

The AQMP also highlights the importance of co-benefits, for instance from state level plans to reduce greenhouse gas (GHG) emissions. Transportation has become the by far biggest source and is currently estimated to emit 39% of all California’s GHG. This is partly because of the strong decarbonization achievements on the power generation side, but it is also due to the growth in transportation activity as well as slow progress in making vehicles (such as heavy-duty trucks) emit less. In fact, the forecast for freight related GHG emissions shows that trucks constitute the biggest source and are forecasted to grow strongly up to 2050, the year by which California should have reduced all its GHG emissions by 80% compared to 1990 levels, see following Figure 3.

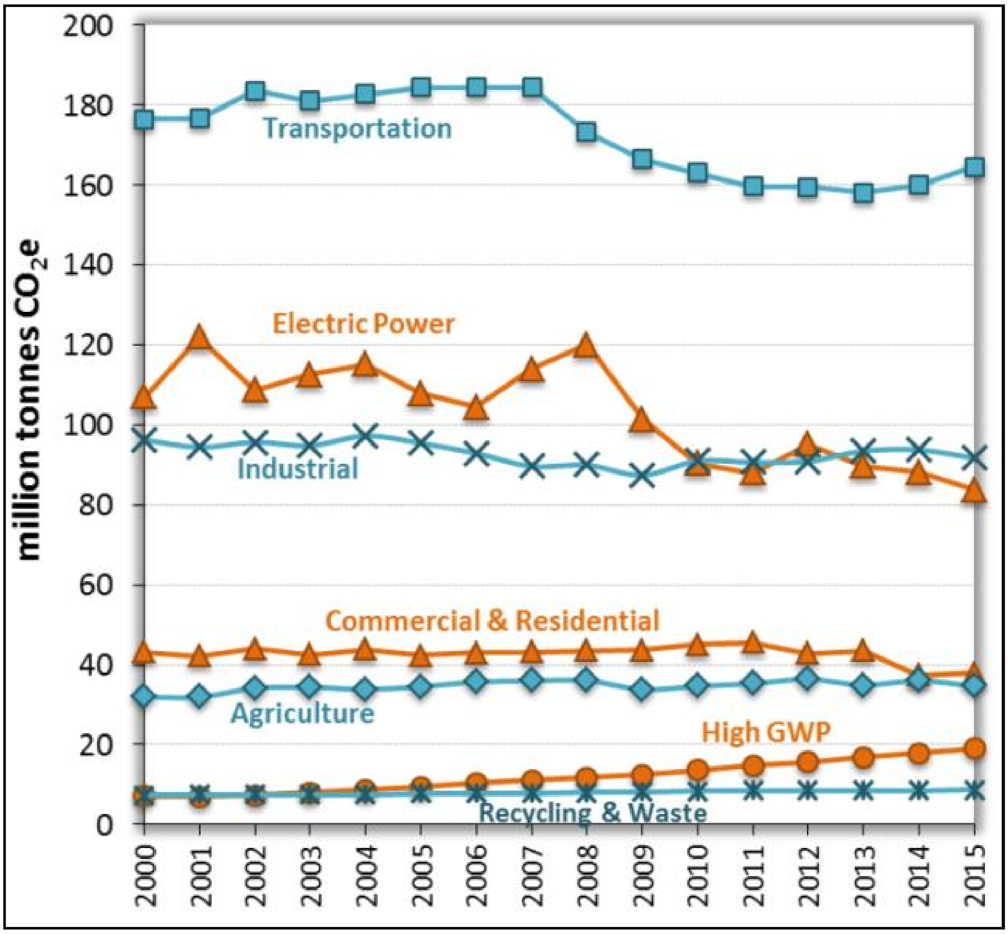
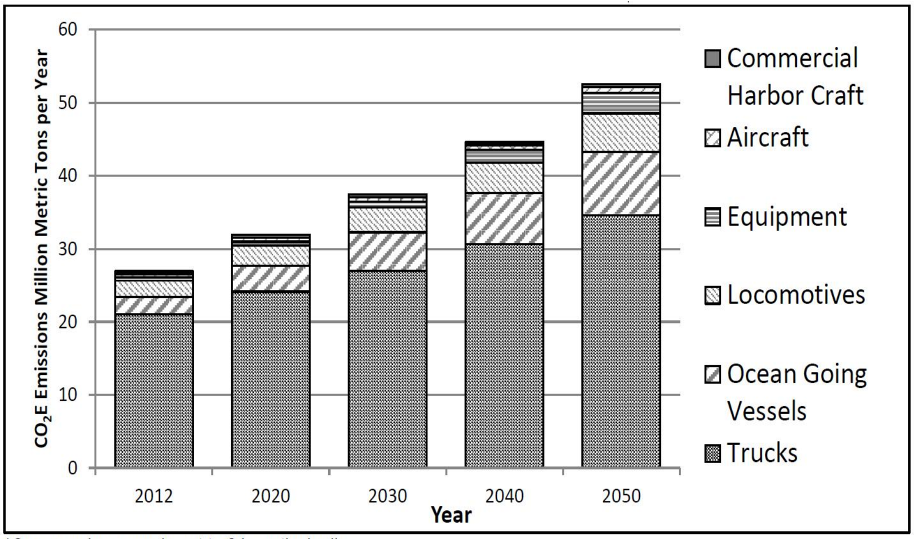


Figure 3 Trends in California GHG Emissions [A3]

In accordance with State Bill (SB) 375 ARB sets goals for Metropolitan Planning Organizations (MPOs) such as Southern California Association of Governments

(SCAG) to reduce emissions from cars and light vans [A4]. As of the 2017 update the SCAG was expected to achieve GHG reductions of 21% by 2035. Truck emissions (and other goods movement) falls under the California Sustainable Freight Action Plan (CSFAP) [A5]. It “*establishes clear targets to improve freight efficiency, transition to zero-emission technologies, and increase competitiveness of California's freight system”.* One such target is to “*deploy over 100,000 freight vehicles and equipment capable of zero emission operation.”* The California Air Resources Board (CARB) estimates there to be around US $53 billion over the next 10 years to address GHG emissions from transportation [A6]. Alone in 2018/2019 $398 million is available for clean trucks [A7]. There are also examples of funding being available to infrastructure for those vehicles [A8].



*Ocean-going vessels out to 24 nautical miles.

Figure 4 Statewide GHG Emissions from Freight Sources [A9]

To a significant extent both air quality issues and GHG emissions stem from truck operations. Therefore SCAQMD decided to road test that zero emission technology in the port drayage operations.

Taking the increasing demand for renewable electrical energy in all sectors into account it will be essential to apply solutions with maximum efficiency, as shown in Figure 5.

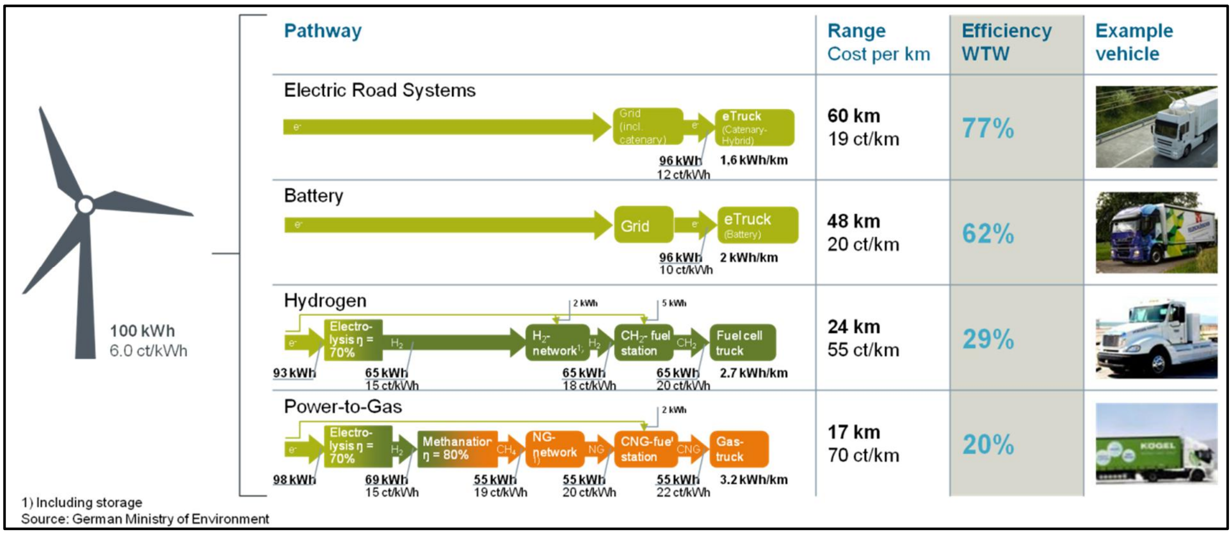


Figure 5 WTW (well to wheel) efficiencies of decarbonized road freight options

3 Executive summary

3.1 Statement of project

For heavy-duty vehicles, the diesel engine is used almost exclusively as the method of propulsion. Since the end of the 1960s, the fuel consumption of a 40-ton truck trailer was reduced by around a third. By 2030, a further increase in engine efficiency from 20 to 30 % is forecasted. While the innovations and the developments for traditional combustion trucks to lower emissions are progressing, the increasing road traffic volume caused by a demanding transport sector is compensating those improvements.

Thus there is the need of a rapid and practicable solution to freeze and sustainably lower all emissions - locally harmful exhausts and greenhouse gases. Renewably generated electrical energy will play a significant role in achieving these targets. At the same time the technical and operational limitations of energy storage systems (such as batteries) must be overcome. This can be best achieved by supplying the electrical energy to propell a heavy truck over long distances by means of an electric road system (ERS). ERS with external power supply make it possible to upgrade existing road infrastructure and thus avoid the need to develop new costly routes including their long planning and approval procedures. To realize emission reduced transport the provision of zero emission corridors based on an electric road system is an option. Those corridors could provide a major contribution to the targeted emission goals. For non-electrified sections the use of complementary technologies, i.e. batteries, fuel cells, or range extenders with compressed natural gas (CNG) or synthetic fuels may be added.

The key purpose of the project is to demonstrate the viability of such a zero emission corridor with catenary supply combined with a variety of low- or zero- emission trucks.

3.2 Project objectives

Heavy-duty trucks are the number one source of smog-forming emissions in Southern California. Developing a zero- or near-zero emission goods transport system at the ports will reduce smog-forming, toxic and greenhouse gas emissions in communities around the ports, which are heavily impacted by air pollution.

The primary goal of this project was to promote the implementation of zero emission goods movement technologies, and the secondary goal was to demonstrate the most viable technology to be adopted for a future, regional zero-emissions corridor. This was done by combining an overhead contact line based electric road system with trucks from different OEM suppliers utilizing three different drive technologies. Key to success and major objectives of the project was the integration of an advanced pantograph into three class 8 trucks to allow full electric operation on the catenary infrastructure built for this project. The catenary system was built in both directions on a 1 mile stretch of Alameda Street in Carson, CA, which is a major truck route heavily used by trucks serving the ports of Long Beach and Los Angeles.

After integration of hybrid drivetrains and pantographs into the trucks and following the construction of the catenary infrastructure, the project was completed by comprehensive tests under real traffic conditions on a public road. This testing was meant to measure the required parameters, to check the operational procedures and to demonstrate maturity of the solution. The outcomes of those tests are outlined in [2].

Further objectives of the project are the assessment of the environmental benefits and the determination of key financial indicators of the zero emission technology.

3.3 The eHighway as a zero emission road freight technology

In order to achieve the project objectives it was necessary to design, build and commission a catenary infrastructure consisting of a bipolar overhead catenary system supported by poles located on the median, a DC (direct current) traction power substation and an operation and control center. Together with the two hybrid and one full electric truck, these subsystems form the eHighway system as shown in Figure 6.

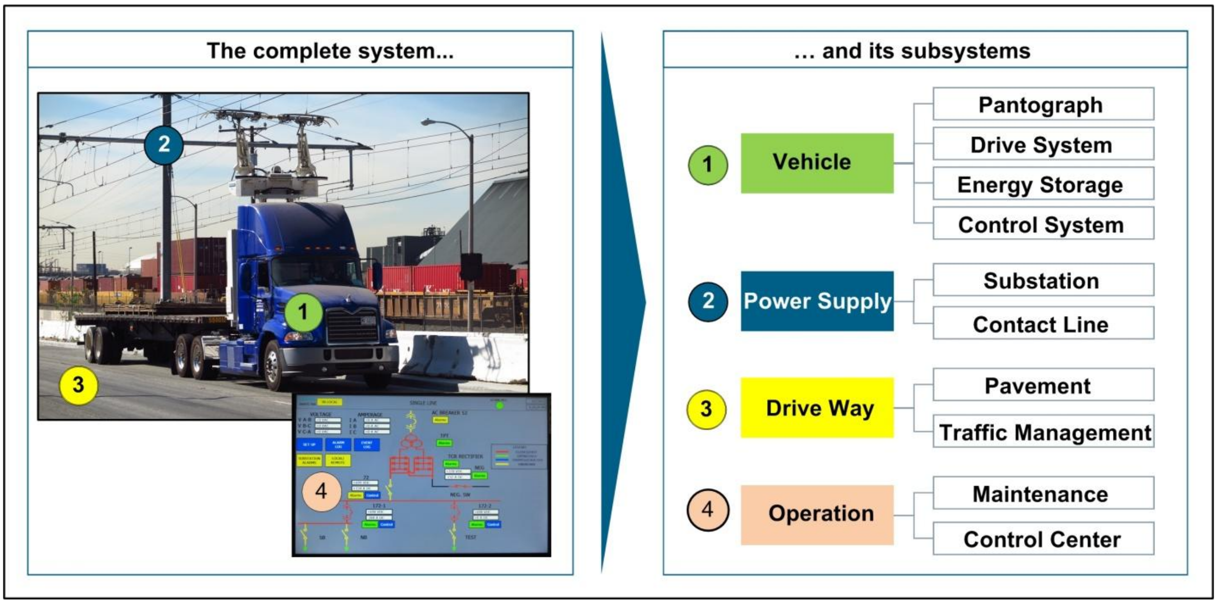


Figure 6 Subsystems and components of the eHighway system

The road testing of the catenary type zero emission technology required two interrelated work strings. On the one hand all planning, design and implementation works of the subsystems with their technical interfaces had to be carried out including their adaption to the local requirements. On the other hand external stakeholders and technical interfaces (e.g. to energy suppliers and road administration) required intense collaboration. Consequently a major subject as well as a key outcome of the project is an improved understanding of all interfaces that need to be considered for a wider implementation of the technology.

3.4 Project conclusions

The project has shown that the eHighway system can be implemented in an existing road infrastructure as a potential zero emission goods transport technology. During demonstration the eHighway system proved to be a viable technology suitable for e.g. regional zero criteria pollutant emission corridors. On the one mile demonstration track and beyond – depending on the capacity of the onboard energy storage – the class 8 trucks were able to operate without any tailpipe emissions. Based on the demonstration results the eHighway system may be considered as one of the valid options for zero emission road freight transports. Provided that renewable electrical energy is used, significant additional CO_2 reductions can also be realized.

Implementing the eHighway system requires investments in both, the road side electrification infrastructure and the eHighway adapted trucks. However, such capital expenditure can generate a return on investment as evaluated in the provided business cases. These are influenced by a multitude of factors such as technology costs, efficiency rates, energy pricing, utilization, transport density, and local infrastructure installation conditions. A general business case was developed and submited [14]. Nevertheless for individual projects detailed business evaluations are recommended.

Taking into consideration that the system tested was still in a R&D phase and had not reached product maturity in all subsystems yet the performance of the demonstration on Alameda Street is a successful proof of concept in a representative application environment, but certain externalities resulting from a heavily industrialized and urbanized area need further study on potential costs. Future steps for industrialization of pantograph and hybrid drive technologies were derived from this milestone project.

While underway with the execution of the engineering of the OCS foundations undocumented utilties were uncovered in the median of Alameda Street. A new foundation type had to be designed for installation above ground. This design change required new engineering designs, permits, approvals, safety barrier design, and isolation of the foundations from traffic - both motorized combustion and motorized electrification. In addition, after the execution of the contract documents the State of California enacted a law which required the offsetting of a structure from a high pressure gas line. Although SOCAL Gas frequently visited on-site works at all design and construction stages and after the system had been employed for 14 months SOCAL Gas required the movement of the substation.

After negotiations between SOCAL Gas and AQMD the gas utility allowed for the testing to run from July 1 of 2017 to December 28 of 2017 or a total data testing period of six months. The above mentiones tasks increased the project duration by one year.

3.5 Recommendations and future work

This project demonstrated, that different drive configurations can be used in combination with the eHighway system. Future work should concentrate on:

- Additional cost/schedule considerations of externalities of urban/industrial environments.
- Intensified cooperation with truck OEMs to allow for truck and pantograph industrialization. The prototyped trucks used in the demonstration had inherent limitations such as extended wheelbase and slightly reduced payloads, and thus are not yet ready to be directly industrialized.
- Elaborating further the interfaces towards energy suppliers with regards to market roles as infrastructure providers and operators (incl. energy billing).

Since the feasibility of the catenary technology as a highly efficient continuous power supply backbone is demonstrated, and since the eHighway system can be combined with the other technologies for decarbonized zero emission transport, an option for future decisions is provided. Parallel developments in energy storages (e.g. batteries) or alternate on-board supplies (e.g. fuel cells) will not deteriorate the eHighway concept but increase the overall efficiency on non-electrified sections, whereas reducing costs may impact the overall economic feasibility.

3.6 Acknowledgment of all project sponsors

The eHighway demonstration project was funded by the following parties:

- SCAQMD – South Coast Air Quality Management District
- China Shipping Fund
- California Energy Commission
- Port of Long Beach
- L. A. Metro
- Siemens INC (in-kind contributions)

We as Siemens INC. are deeply grateful for having had the opportunity to demonstrate the viability of this zero emission technology in a challenging public surrounding.

4 eHighway – ZE technology essentials

To realize the project objectives it was necessary to design, build and commission the corresponding infrastructure consisting of a two pole overhead catenary system supported by masts, a traction power substation and an operation and control center. A second string of work packages was related to the trucks including their hybridization and the integration of pantographs. While a complete review of the assigned project tasks is given in Chapter 5 this short chapter is meant to provide key information on the technology.

The basic idea of the eHighway technology is depicted in Figure 7:

a) after entering an electrified section the pantograph equipped truck detects an overhead contact line so that a connection can be established while driving
b) once the pantograph is raised and electric contacts in the truck are closed, the external power flow can start via the substation components and the catenary
c) within the truck the electric drive is powered directly from the catenary and a battery may be charged in parallel for off-line sections

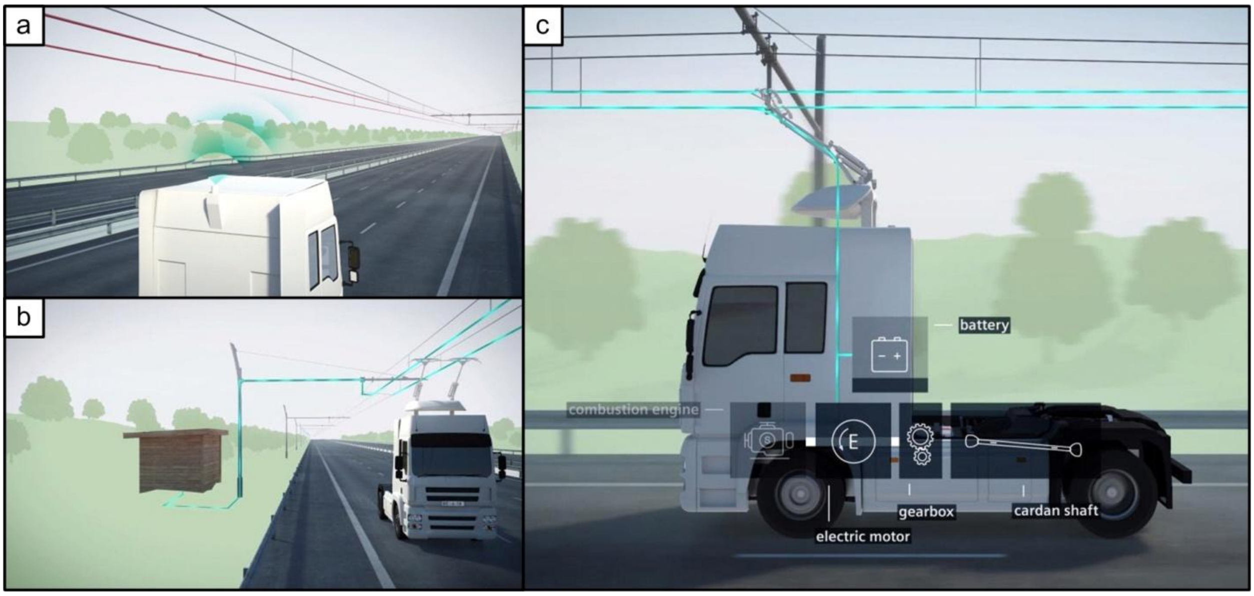


Figure 7 eHighway core functionalities - (a) contact line detection, (b) external power supply and (c) power flow in the hybrid truck

4.1 Substation and catenary for external power supply

The electrical infrastructure system mainly consist of two parts: the substations and the overhead contact line system. Both are based on mature rail electrification technology.

The traction power supply substations have a modular set-up according Figure 8. These substations are designed as containers or precast concrete buildings which are prefabricated and tested at the factory to allow for a fast and relatively simple placement and commissioning at site. They provide fundamental safety features which, amongst others, allow for safe power turn off in case of any irregularities.

The overhead contact line system consist of a bi-polar catenary sytem suspended by cantilever arms which are attached to poles that are placed alongside the road or on the median. The system therefore can be installed without modifications/interference to the road surface whereas crash protection must be individually assessed. The overhead contact line system can be addepted to curves, bridges and highway entries or exits. The main components of a straight layout are shown in Figure 9.

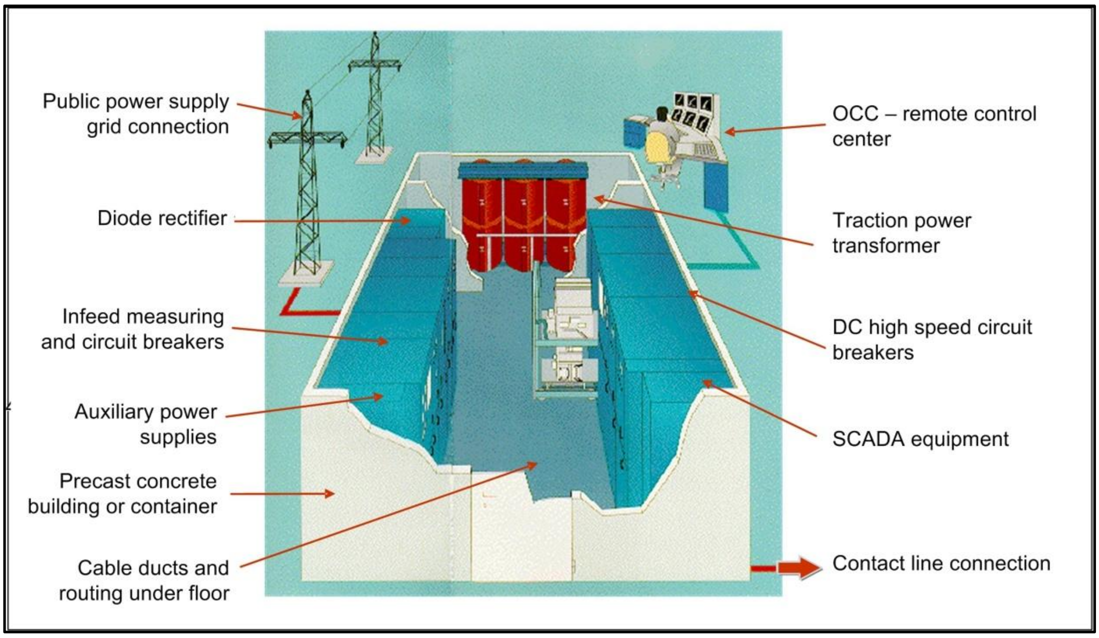


Figure 8 Modular setup of a DC traction power supply substation (TPSS)

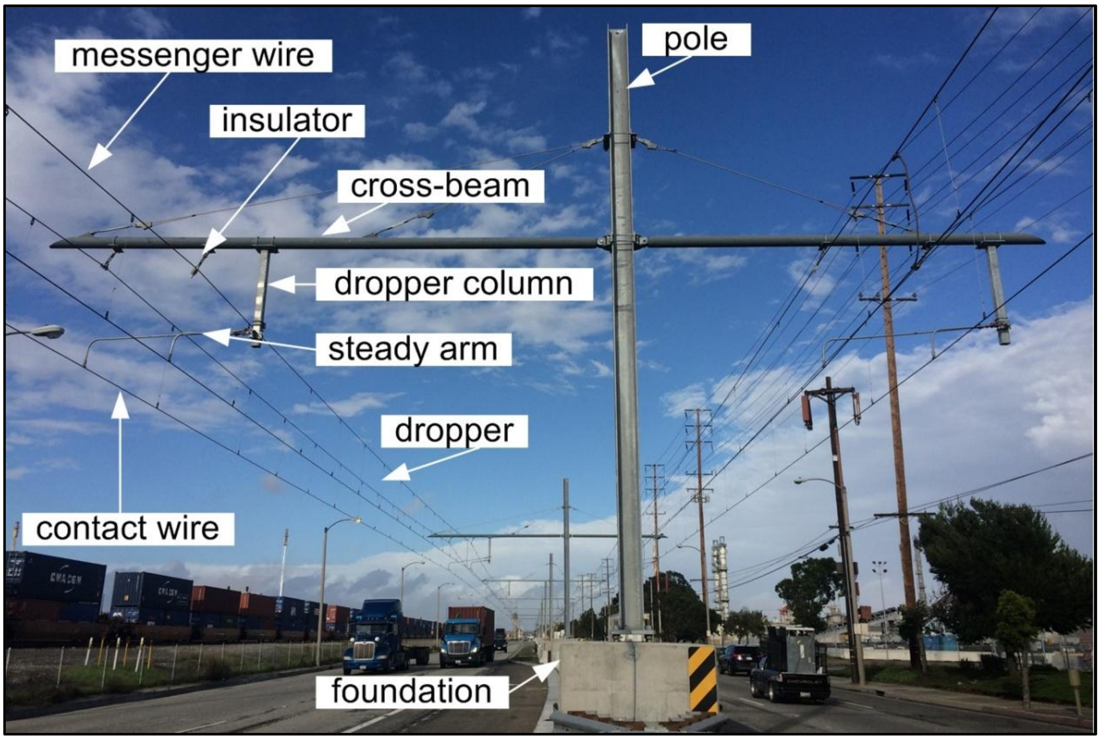


Figure 9 Main components of the overhead contact line system (OCS)

4.2 The eHighway hybrid trucks and pantographs

The hybrid configuration of the eHighway addapted trucks allows for contact line interruptions whenenever necessary. This may happen when adaptation to the adjacent infrastrucutre becomes to complex, cost intensive or the infrastructure is not wanted (e.g. for optical reasons). The trucks would then disconnect from the catenary wire, proceed their journey based on their alternative drive system and reconnect to the catenary system as soon as they reach the next equipped road section. The hybrid trucks for contact line operation consist of two key subsystems - the hybridized or full-electric truck and the pantograph system.

Hybrid trucks for catenary operation

The trucks are based on standard semi trailer trucks which were modified to enable the utilization of the overhead catenary system. These modifications include adaptations of the drive system and the integration of a pantograph, control system and energy storage. Three different drive concepts have been realized in this project:

- CCAT: a serial hybrid with a CNG range extender integrated into a Navistar truck
- ECAT: a full electric configuration with batteries integrated into a Navistar truck
- a parallel hybrid with diesel combustion engine by MACK

The test trucks named CCAT and ECAT where retrofitted and operated by Transpower. The MACK truck was designed, integrated and operated by Volvo. A serial hybrid configuration (see Figure 10, left) is until now most commonly used for heavy duty vehicles, especially in bus applications. The electric engine replaces the manual or automatic transmission of the vehicle and the combustion motor is connected to a generator. Via an electric link (DC link) the power is transferred to the drive engines. The main purpose of the diesel engine is to act as a range extender by loading the onboard energy storage system (battery) while driving without connection to the overhead catenary system. A serial hybrid configuration allows for operating the combustion engine with maximum efficiency within the optimal rotational-speed range. The connection between the electric traction motor and the energy storage (e. g. a battery) enables a good recuperation performance when the vehicle is braking. In catenary operation the power is fed directly to the DC link.

In comparison to that the parallel hybrid configuration (see Figure 10, right) more commonly used for heavy duty trucks. The electric engine is integrated into the mechanic transmission (gear box) and drives the axles in parallel to the combustion engine. Depending on the application the electric engine and the energy storage is designed for average power in cruising modes to provide higher efficiency in most of the usage time. Nevertheless the combustion engine must be designed for accelerations and higher power demands. In catenary operation the power infeed is the link between battery and electric drive.

Besides these two basic principles a number of bridge concepts has been developed that form mixtures between the topologies.

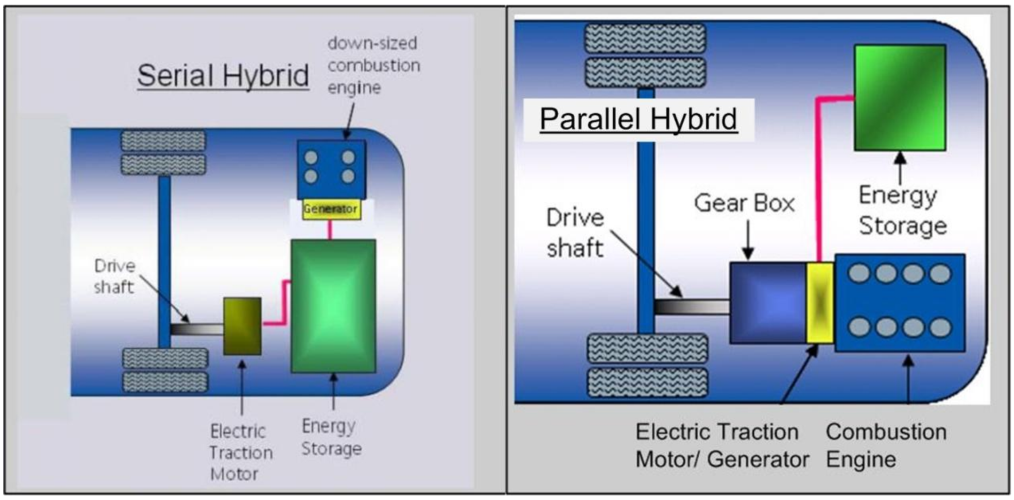


Figure 10 Block diagrams of a serial (left) and parallel (right) hybrid drive system

Over the past several years, hybridization has made significant gains even for long-distance trucks. Major truck manufacturers have announced that they will be introducing hybrid vehicles onto the market in the coming years. Figure 11 provides an overview on drive technologies and independent energy supply options for heavy-duty vehicles. The developments in the heavy-duty vehicle sector show that hybridization also represents a decisive component for more sustainable road freight transportation. In a modular hybrid concept, different combinations of drive modules (electric engine or combustion engine) and systems of energy supply or storage (batteries, fuel cells, overhead line, conventional or synthetic fuels) are possible depending on the development status and infrastructure. The applications used in the SoCal project are marked green. The individual vehicle configurations are summarized in chapter 5.8 and in [12].

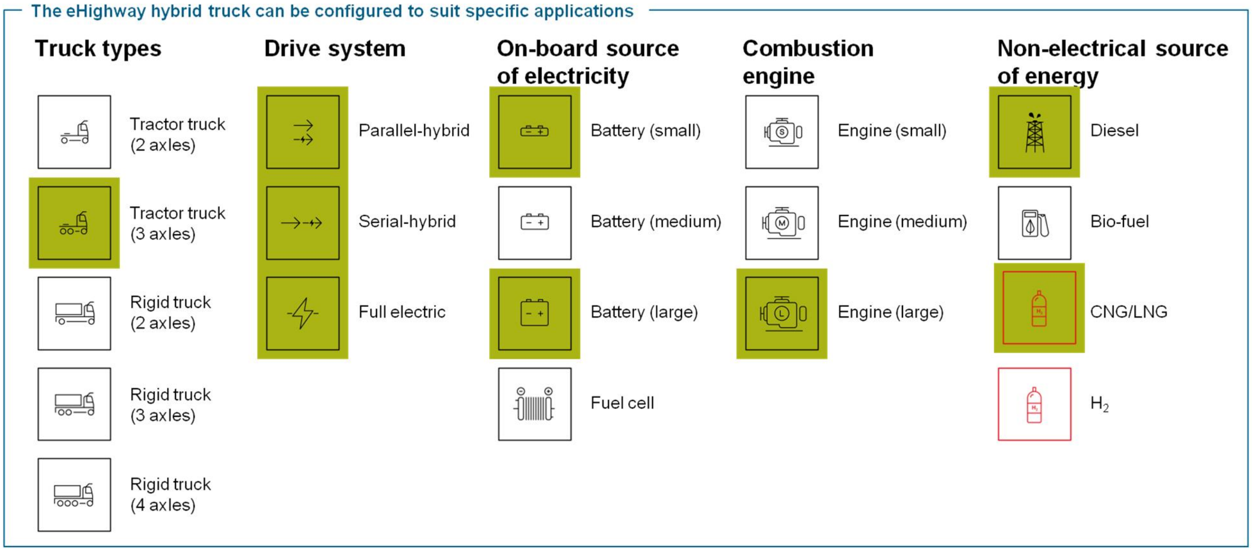


Figure 11 Architectures for catenary supplied trucks (green options were realized in project)

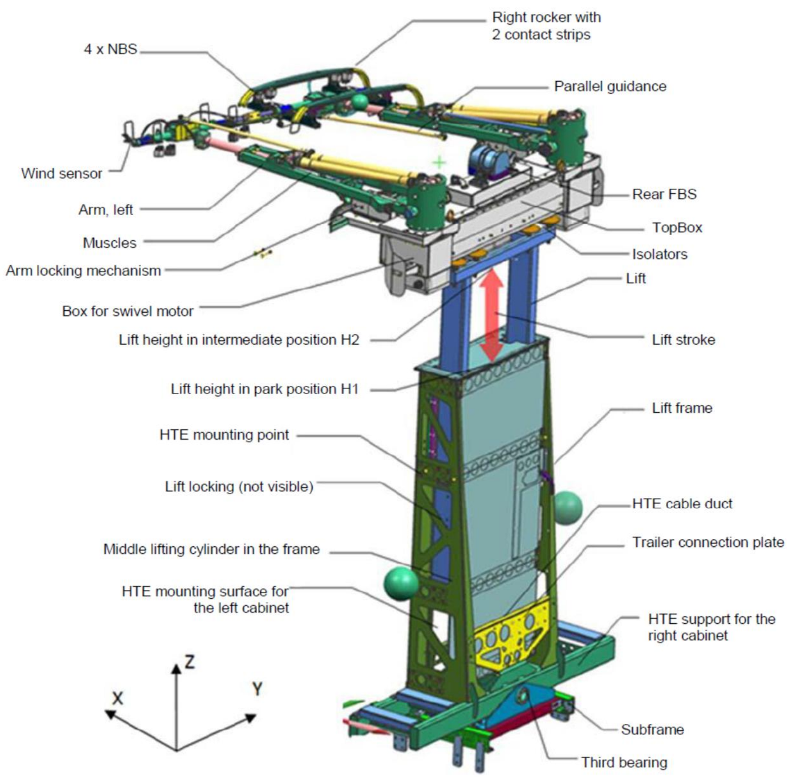
Pantograph system

The central innovation of the system is an intelligent pantograph which transfers the electrical energy from the eHighway overhead contact line system to the electric traction motor and the onboard energy storage system. Compared to panthographs used for railbound vehicles the eHighway pantograph has to comply with several additional requirements. In railways the return current can flow back to the substation via the steel wheels and rails. In road applications the return current cannot flow back via the rubber tires and road surface, so the eHighway system requires a bi-polar overhead contact line system. The pantograph has thus to be able to connected and disconnect with two overhead wires simultaneously. Moreover and unlike trolley busses connection must be done while driving as the trucks are not supposed to stop the traffic flow when entering electrified sections.

Road based vehicles are not rail-guided. An active control of the pantograph is required to compensate for the irregular lateral movements of the trucks within their lane. At the same time a controlled vertical movement of the pantograph has to ensure that the right contact force with the overhead wires is maintained during operation. In order to maintain the flexibility of the trucks and limit their dependence on the overhead contact line system a safe retraction mechanism is required in case the driver wants to change lane, overtake other vehicles or needs to perform an evasive maneuver.

When installed on the truck the pantograph system may neither limit the loading volume of the truck nor the loading and off-loading operation of goods. Finally the pantograph system had to be designed in a way that it can be used by different truck manufacturers and a wide range of truck types.

The basic mechatronic system is shown in Figure 12. Amongst other items it depicts the connector frame to the base vehicle, the different sensor systems NBS (near field) and FBS (far field) and the two lift positions. Each pantograph head comprises of the carbon contact strips and four near field sensors to detect out of range use so that a lowering procedure can be triggered.



Legend / explanations:

FBS – long-range sensor technology

H1 – lower, locked park position

H2 – upper, locked work position

HTE – Hybrid Truck Equipment (cover and power electronics for connection to hybrid trucks)

NBS – short-range sensor technology

Rear FBS – rear installation position of the laser scanner

Subframe - support for connection to the vehicle frame

Figure 12 Mechatronic concept of pantograph system including main components

4.3 Driveway

The drive way is formed by the road which usually already exists. Additional provisions have to be considered for a reliable and safe operation of the entire system such as crash protection for poles and substations or additional or modified traffic signs. A traffic management system controls the overall traffic by i.e. checking the vehicle density and supervising the individual lanes in case of maintenance works.

Special care must be taken for existing roadside installation such as traffic light, overhead road signs and bridges. Depending on the specific situation additional insulation layers, protective elements or adjustments of the existing infrastructure need to be designed and installed.

4.4 Operation and maintenance

Similar to rail electrification system the eHighway system has an operation and control center (OCC). Via a SCADA (Supervisory Control and Data Aquisition) system the status of the road electricfication infrastructure can be monitored and, in case necessary, modified. From within the OCC it is possible to e.g. de-energize specific sections in order to allow for maintenance work. The collection of data from the power substations or optionally from trucks operating in the relevant area, is beneficial to gain a high availability of the entire system. Additional functions may be the collection of pantograph status information to determine correct system properties or to initiate maintenance activities.

Further tasks of an OCC or a control center at a higher level may be the measuring and billing of the energy used. This function is optional and depends of the operational model used.

5 Scope of work according contract

The overall scope of the project comprised of development and demonstration of an overhead catenary system (infrastructure) and corresponding pantographs to power various OEM class 8 trucks with different hybrid propulsion systems.

The interfaces of the pantographs to the trucks were to be defined by Siemens. Further work items included the testing and commissioning of the pantographs at the truck manufacturing and laboratory sites. In total four adaptable pantograph systems were manufactured to be installed and integrated on the trucks.

The bipolar DC catenary system was designed and installed in both directions along Alameda Street. The approximate one mile segment extends north to south from E. Lomita Blvd to the Dominguez Channel. At the middle, underneath Sepulveda Blvd. overpass, a containerized traction power rectifying substation and a control centre had to be installed.

The project had to be completed by a 12 month testing and demonstration phase, which was agreed to be reduced to 6 month. This reduction was necessary since the operational license could not be extended. The individual test items and results of the test phase are documented in [2].

The project was split into twelve individual tasks as listed in Table 1. It reflects the contractual requirements and sequence of the tasks according to the statement of work.

As all tasks were to be reported in detail with individual deliverables, this final project report concentrates on brief summaries of the individual tasks in the following sub-chapters.

Table 1 Project tasks and assignment of report chapters

Task	Title	Chapter
Task 1	Basic Infrastructure System Design	5.1
Task 2	CEQA and Construction Permitting	5.2
Task 3	Infrastructure System Detailed Design	5.3
Task 4	Procurement and Manufacturing - Infrastructure	5.4
Task 5	Installation and Commissioning of Infrastructure	5.5
Task 6	Pantograph System Definition and Interface Identification	5.6
Task 7	Pantograph Engineering Integration and Certification	5.7
Task 8	Pantograph Production, Assembly and Integration into Each Vehicle	5.8
Task 9	Catenary Truck and Infrastructure Demonstration	5.9
Task 10	Determine Owner and Operator of System	5.10
Task 11	Project Management and Reporting	5.11
Task 12	System Decommissioning and Site Restoration	5.12

5.1 Task 1 - Basic Infrastructure System Design

Task 1 - Basic Infrastructure System Design comprised a package of engineering and planning documents mainly to illustrate and outline, how the stationary infrastructure was planned to be realized. The documents served as a basis for a detailed engineering and the application and approval for construction and operational permits.

The submission of this package did include the following documents:

- site evaluation and report
- single line diagram of the substation
- layout plan of the overhead contact line
- building layout and a site power and signals cabling plan

Except the site evaluation report all other documents were updated and summarized in two documents later on and can be found under Task 3 - Infrastructure System Detailed Design, see chapter 5.3.

For the erection of the catenary infrastructure a section of CA Highway 47 named Alameda Street was chosen. It is a truck route running parallel to Interstate 710 and Terminal Island Freeway. These truck routes connect the harbors of Long Beach and Los Angeles to a number of inland cargo distribution and container handling facilities. The chosen section of Alameda Street belongs to the city of Carson, CA. Figure 13 shows the localization of the chosen section in large scale and in a street map.

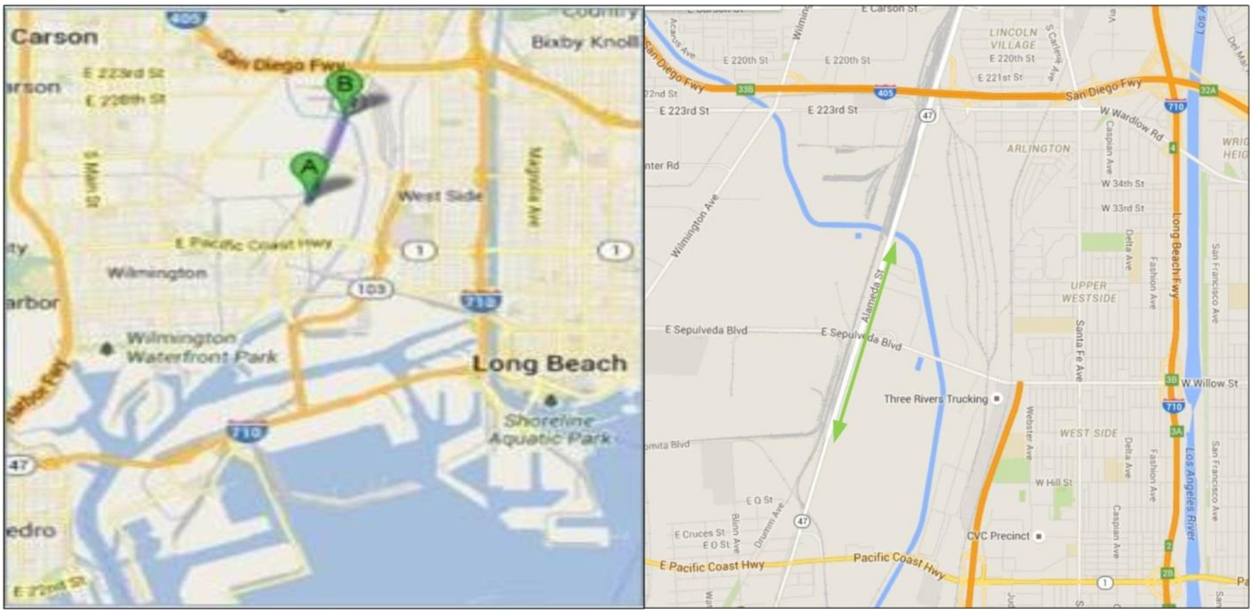


Figure 13 Localization of the eHighway site in Carson, CA

Visual impressions of the site prior to infrastructure construction are given Figure 14. Image a was taken looking southbound, image b looking northbound.

The section south of Sepulveda Boulevard overpass was characterized by a very small media and no sidewalks as it directly neighbors a railway yard and a fuel depot. For the section north of Sepulveda Blvd. overpass a number of left turn lanes and varying median widths and layouts are characteristic.

In order to simplify construction of the overhead contact line system the installation of the poles on the median between the northbound and southbound roadway was a project prerequisite by the customer and carried out accordingly.

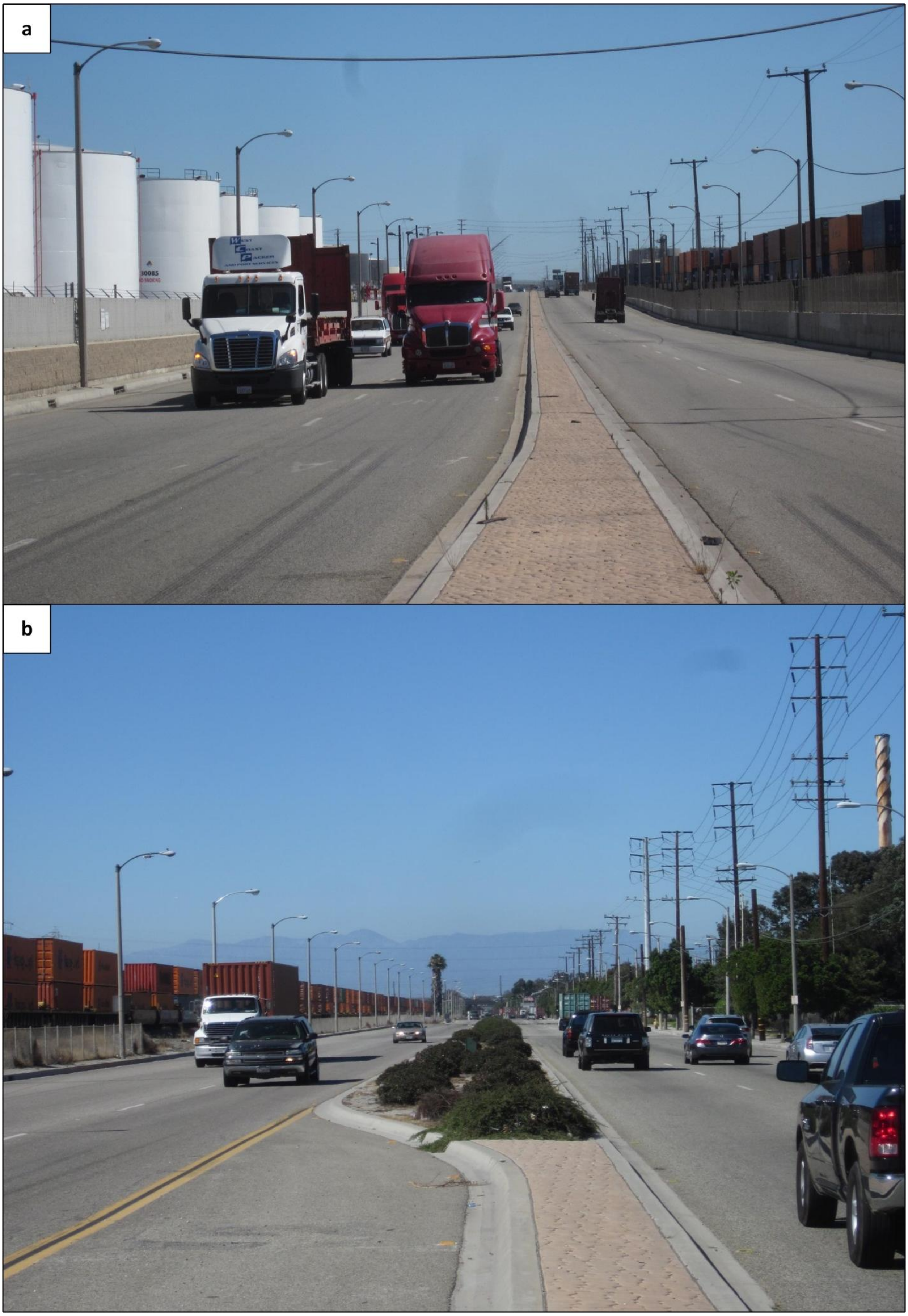


Figure 14 Alameda Street at Carson, CA prior to infrastructure construction (a – southbound, b – northbound)

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5.2 Task 2 - CEQA and Construction Permitting

A CEQA (California Environmental Quality Act) self-assessment for the application of the construction permission was prepared. Furthermore the following documents were submitted to the city of Carson to complete the application.

- Cover and Vicinity Map
- General Symbols and Abbreviations; Legend and Symbols Sheet
- Structural General Notes
- Civil Plans, Plan and Profile
- Maintenance Facilities and Test Track
- Civil Plans Sections and Details
- Overhead Contact System – Assembly, Foundation and conduit mounting
- Building Structural Plans, e. g. TPSS Foundation
- Low Voltage Single Line Diagram
- Power and Signals Overall Site Plan
- Grounding Plan and Details

Based on the application and documents handed in a permission was issued by the City of Carson which granted the installation and construction activities of the catenary system. During the early construction phase that started with the drilling of the originally planned steel pipe foundations unexpected additional underground facilities were found. Those led to a complete redesign of all pole foundations with then above ground precast gravity concrete foundations as shown in Figure 15.

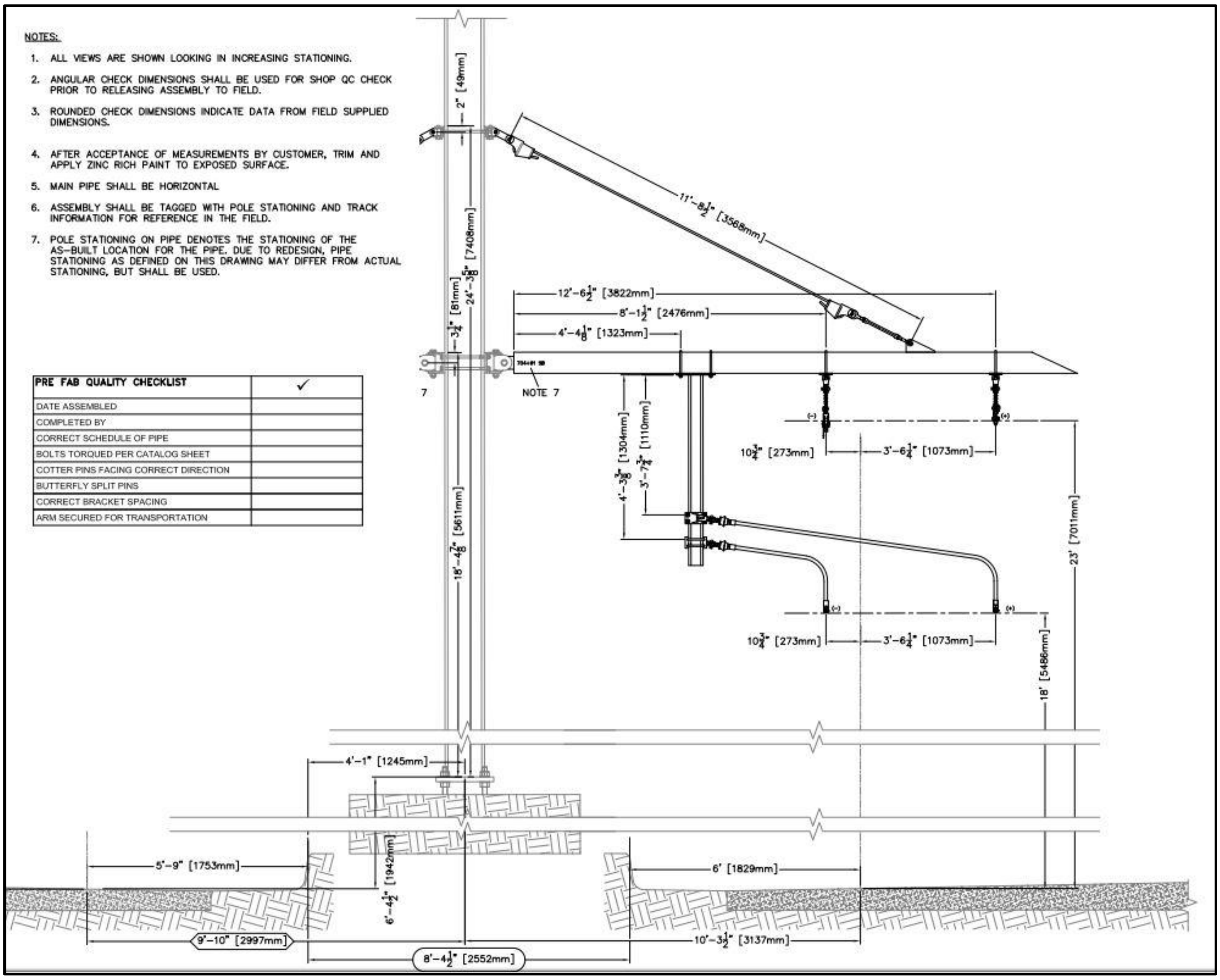


Figure 15 Cross section of a standard pole with precast concrete foundation

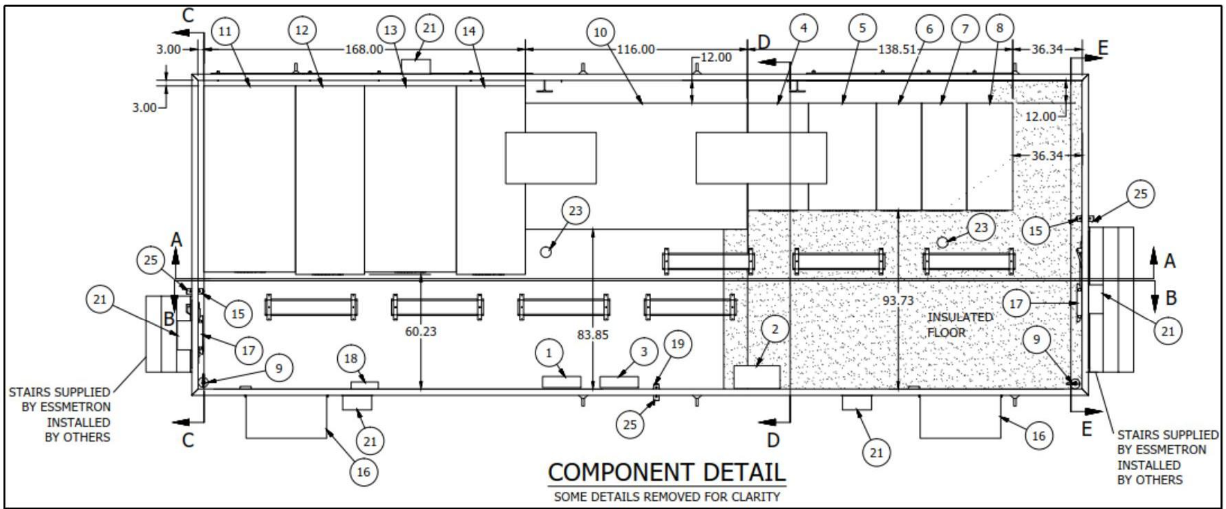
5.3 Task 3 - Infrastructure System Detailed Design

Task 3 focused on the detailed design of the infrastructure system and comprised following sub-tasks:

- detailed design of the traction power supply station
- detailed design of the overhead contact line system
- description of the test procedures

Traction power supply station TPSS (substation)

The design is based on standard components for electrical railways and tramways. For the planned operation of a maximum of four trucks the rating of the power transformer was set to 1 MVA with a correspondent 12-pulse-diode rectifier. The operating voltages are 3~AC 12 kV medium voltage for the infeed and DC 600 V nominal traction voltage for the OCL to feed the trucks. The substation auxiliary supplies run at AC 120 V. An overview of the substation layout and the main components is shown in Figure 16.



Main components:	- 4-8 DC traction power section (rectifier and switchgears) - 10 (main) power transformer - 11-14 AC medium voltage section (switchgears and measuring)

Figure 16 Traction power substation layout drawing with main components

Overhead contact line system (OCS)

As part of this sub task an updated site plan was provided. Further documents included details about installation methodology and standards which have to be considered for materials and the processing of those. The engineering submission also contained parts lists and drawings lists for the poles and the catenary. The overhead contact line system consists of catenary type contact lines for both electric poles and for both directions. Each catenary consists of a steel rope messenger wire with a cross section of 70 mm² that support a copper magnesia alloy as contact wire with a cross-section of 150 mm². The choice of the conductors is subject of a power flow study considering variables like traffic assumptions, power demand, substation spacing.

The catenaries of the poles a laterally spaced at 1.35 m (53'') at a nominal height of 5.48 m (18 ft) above ground. A cross-section is shown in Figure 15.

The contact and messenger wire are tensioned with concrete weights via suspension wheels that are located at beginning and end of the electrified section. The tension wheels serve to keep a continuous tensile strength within the conductors while mitigating the thermal length deviations according to varying outside temperatures.

As a road specific adaption one of the messenger wires had to be insulated as it can possibly get to close to the existing traffic light signal unit. Figure 17 shows that detail.

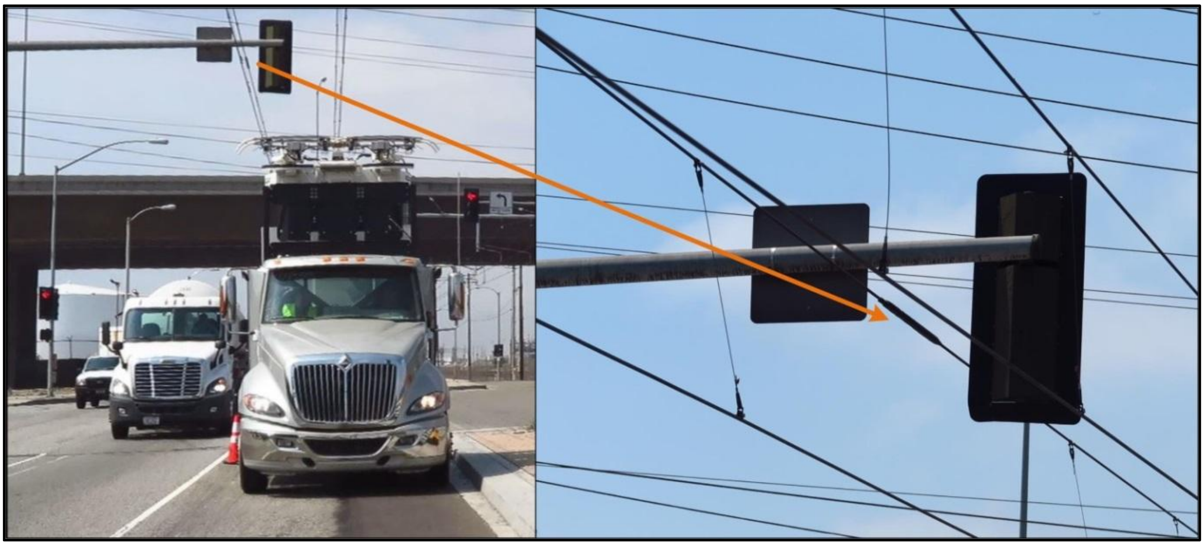


Figure 17 Messenger wire insulation at traffic light signal unit

Above ground foundation requirements

Due to the poorly documented underground utilities in the City of Carson, a pressurized gas line was uncovered on Alameda Street median during the first construction phase which caused the stoppage of work in constructing the originally planned underground foundation. This lead to the redesign, re-permitting, purchasing and installation of an above ground foundation not unlike a trust block system, see Figure 18 b (page 26).

From this came the requirement for a traffic abutment system in the median as well as various traffic safety systems to be employed, such as crash attenuators see Figure 18 c.

Infrastructure test procedures and descriptions

Tests are crucial for the proper and reliable functionality of a system. For this sub task test procedures were submitted, that were also used to perform testing of the project infrastructure, including traction power substation, overhead contact line, and the general site. This comprehensive collection of test procedures includes production (factory) testing, field testing, and commissioning as applicable to this subsystem.

A test matrix excel sheet was attached. The matrix described which test procedures are for production, field, or commissioning tests. Although all test procedures were submitted under Task 3 the performance of the individual tests was part of later tasks.

5.4 Task 4 - Procurement and Manufacturing – Infrastructure

The test descriptions introduced in the previous chapter form the basis for the requirements of Task 4. It is separated in 3 different subtasks comprising factory acceptance tests (FAT) for the traction power supply station (TPSS), the overhead contact line systems (OCS) and the auxiliary infrastructure.

Traction power supply station TPSS (substation)

Comprehensive technical and functional tests of the AC high voltage cabinets and the DC units were conducted for the TPS including:

- DC Breaker truck production test
- DC Incoming/Feeder cubicle production test
- Negative cubicle production test
- Rectifier production test
- TPSS Field test (same procedure as used for field commissioning)
- AC Switchgear production test

The DC Feeder breaker functional tests included preliminary settings and functionality checks of the protection relays. The most important functions tested were:

- Maximum current tripping
- Relative current rise function
- Absolute current step function
- Transformer temperature warning and tripping
- Maximum and minimum voltage tripping

For the transformer a separate FAT was issued by the manufacturer SchaffnerMTC Transformers. The different losses for magnetization and caused by the current flow in the winding systems under load were measured. Over a wide load range the transformer efficiency is at about 98.8 %, so even moderate loads do not cause increased losses. The transformer has one primary high voltage winding system and two secondary winding systems using a star-delta configuration to reduce harmonic distortion in combination with the 12 pulse diode rectifier. A detailed analysis of the grid impact was done by SCE – Southern California Edison proving no negative effects of the eHighway power supply [10].

All tests for all substation components were passed without any objections. After the FAT the TPSS was ready for the shipment to the construction site at Carson, CA.

TPSS (substation) - localization

After the execution of the contract documents the State of California enacted a law which required the offsetting of a structure from a high pressure gas Line. During the construction period SOCAL Gas visited the foundation of the substation and witnessed the following construction works: excavation, placement of the grounding grid, construction of the foundation and finally the setting of the substation container.

This intern, i. e. the law changes, lead to internal reviews by SOCAL Gas as to the location of the Substaion which caused the project to stall on the testing of the vehicles for over six months. Once the added duration fo the testing was negotiated said testing resumed.

Overhead contact line system (OCS)

This subtask comprised a documentation of testing results as applicable for production requirements of each product supplied by Siemens for the OCL or purchased by vendors. The production tests have been conducted in the Tualatin, OR warehouse (unless stated otherwise on the test reports) and followed Siemens quality guidelines. The tests required for release to construction site depend on the properties of each product and were defined and implemented to provide a consistent quality of goods.

For the different parts and groups the following tests are applicable:

- Fittings and hardware (visual and dimensional tests; sample galvanizing)
- Insulators:
  - Visual and dimensional tests
  - Dielectric insulation test
  - Mechanical load proof test
- Wires:
  - Visual and dimensional tests
  - Mechanical tension and elongation tests
  - Electrical resistance test
  - Twist test
- Poles (Certified material test, welder certificate)

Auxiliary infrastructure

A FAT was done for the temporary office for site and control room. Other facilities i.e. CCTV, fences etc. were tested under Task 5.4 auxiliary infrastructure field acceptance test report.

5.5 Task 5 - Installation and Commissioning of Infrastructure

All site installation works were finalized with extensive tests to proof the reliability and safety of all components and subsystems. They were conducted by qualified personal, witnessed and documented.

Overhead contact line system (OCS)

For the OCS a mechanical acceptance test was done, comprising foundations of the poles, cantilevers and head spans, contact wires and droppers, messenger wires, insulators, pole mounted disconnectors. The disconnector was tested electrically. The test was successful and minor irregularities could be fixed on short notice. The tests included:

- OCS Electrical test, including high potential and isolation testing
- OCS Energization test
- OCS Mechanical Inspection, including height control

Traction power supply station (substation - TPSS)

This test is to prove that all of the connections are correct and that no shipping damage has occurred to the insulators or other components. Since those tests are an important safety feature for the entire system they were quite comprehensive and took several days. Beside visual inspections, measurements, functional tests and readjustments to the settings were done.

- TPSS Field function test
- TPSS Energization test
- TPSS Short circuit test
- AC Main breaker Siprotec relay settings
- Transformer temperature monitor settings
- DC Positive switch settings
- DC Feeder breaker Sitras Pro relay settings

After these tests were completed for both subsystems the eHighway demo track was ready to start the system integration with the modified hybrid trucks along the Alameda Street.

The pictures on the following two pages illustrate the construction process:

- Figure 18 a – delivery of the TPSS and unloading by crane
- Figure 18 b – all concrete foundations placed, median widening completed
- Figure 18 c – all poles placed, begin of route with crash attenuators
- Figure 18 d – catenary works with fork lifts

Figure 18 Construction phase – setting of foundations and poles

5.6 Task 6 - Pantograph system definition and interface Identification

During the design process for the different hybrid trucks, a comprehensive interface synchronization between the Siemens pantograph system and the different OEMs and integrators was necessary. For identifcation and definition the interfaces were structured in different categories based on developments over several years. This structure was also used as a basis for the integration tests at the OEMs test sites. Moreover this structure is transferrable to other hybrid trucks and helps to standardize and optimize pantograph integration as individually customized solutions are limited.

All interfaces were successfully implemented during the project together with the OEM partners Volvo and Transpower. Figure 19 gives an overview about the infaces followed by a brief characterization of the interface contents.

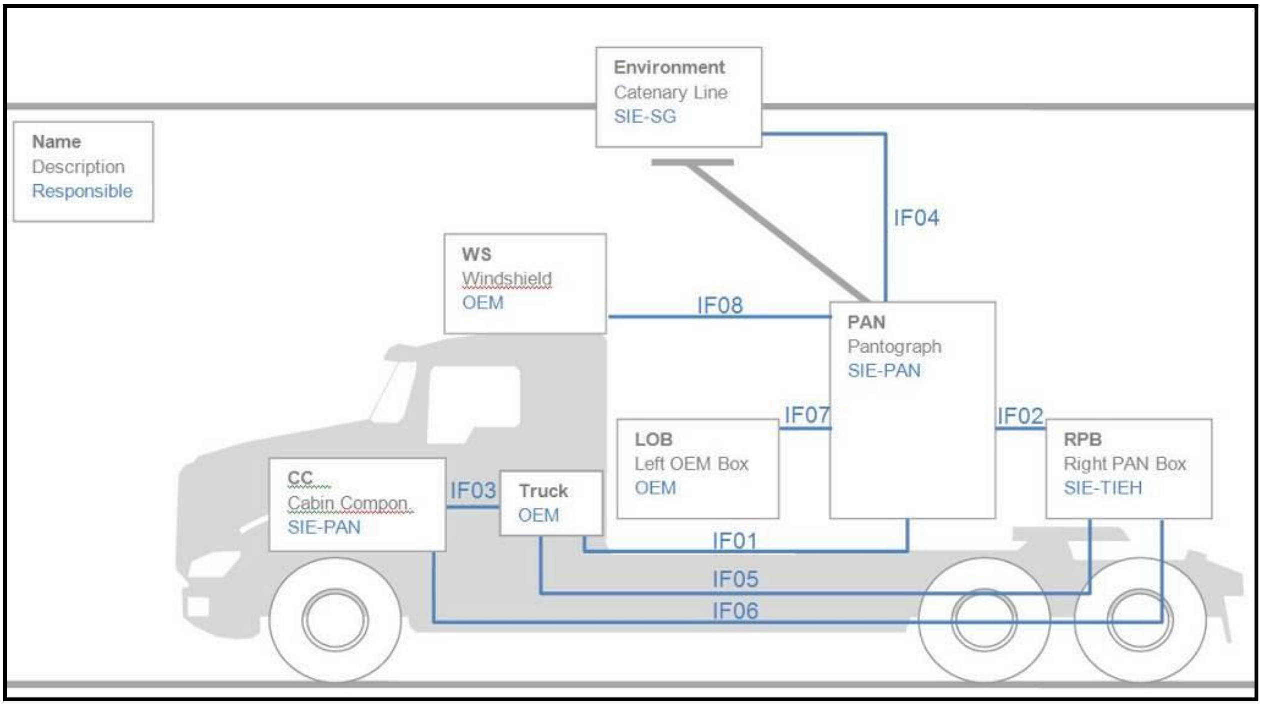


Figure 19 Pantograph interface overview

IF01 – Mechanical interface: PAN – Truck

This interface defines the mechanical interaction between the truck and the pantograph. Dimensions, weight and speeds are settled in this interface. The mechanical mounting to the base frame with an adaptable sub-frame lies in the responsibility of the truck supplier.

IF02 – Right PAN Box (RPB) – pantograph

The right PAN Box contains all electrical and pneumatic elements to control the pantograph. It serves also as main interface enclosure for signals, electrical power, and pneumatics necessary to control the pantograph.

IF03 – Truck – Cabin Components (CC)

For the communication between the truck cabin and pantograph a touch screen and additional dashboard buttons are installed as human machine interface (HMI). This interface defines communication with the CAN-Bus of the truck and contains message definitions.

IF04 – SIE-SG – OEM

This interface outlines the electrical parameters for the power consumption of the electrical drive system. It defines performance ranges the power supply, the pantograph, and the electric hybrid drive are designed for. The voltage range definitions used for the EHWY SoCal project were according to Figure 20. For the demo project on Alameda Street no inverter was installed at the substation.

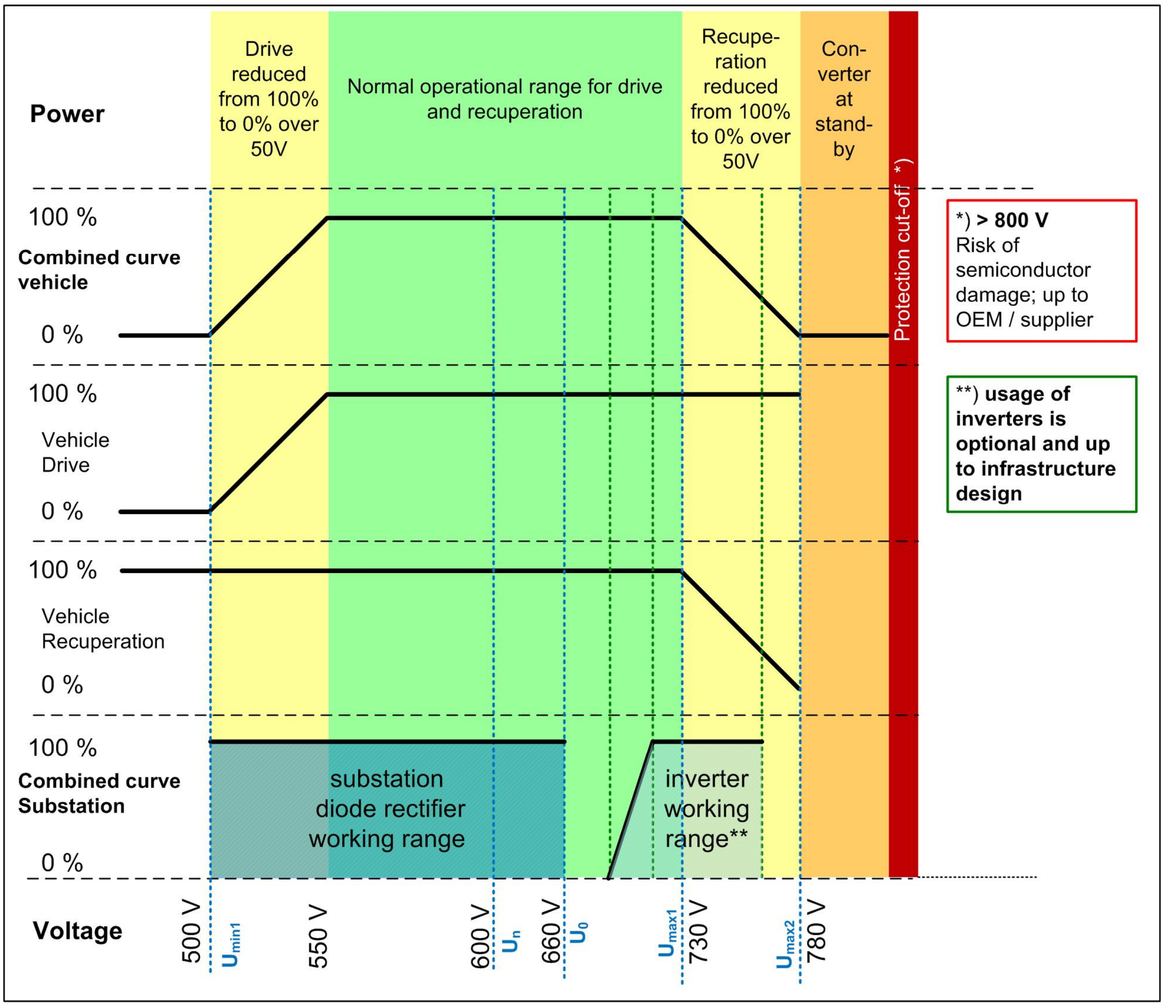


Figure 20 Voltage range definitions for the demo project

IF05 – Truck – Right PAN Box

This interface defines the pneumatic and electrical requirements between the truck and the pantograph. Cables and hoses are determined and responsibility for the supply.

IF06 – RPB – CC

This interface defines the signal characteristic requirements for the communication between the truck and the RPB i.e. via Ethernet or Profinet.

IF07 – Truck – LOB

The LOB (left OEM box) provides an installation space for interface components of the OEM truck. Mechanical data and dimensions are defined in this interface.

IF08 – PAN – windshield (WS)

This interface defines the mechanical space requirements for a windshield (WS) which is part of the truck equipment. A 3-D model was provided to the truck manufacturer considering the needed ranges for movements of the pantograph.

5.7 Task 7 - Pantograph engineering integration and certification

There were in total four pantographs manufactured and tested at the workshops. After the pantographs have left the assembly line they were tested and certified in a test field. All four pantographs had the same technical design, but were fabricated in sequence. In parallel the integration planning into the individual trucks started. For the mechanical integration 3D-Models were used, as shown in Figure 21 for Volvo [11] and Transpower trucks [12].

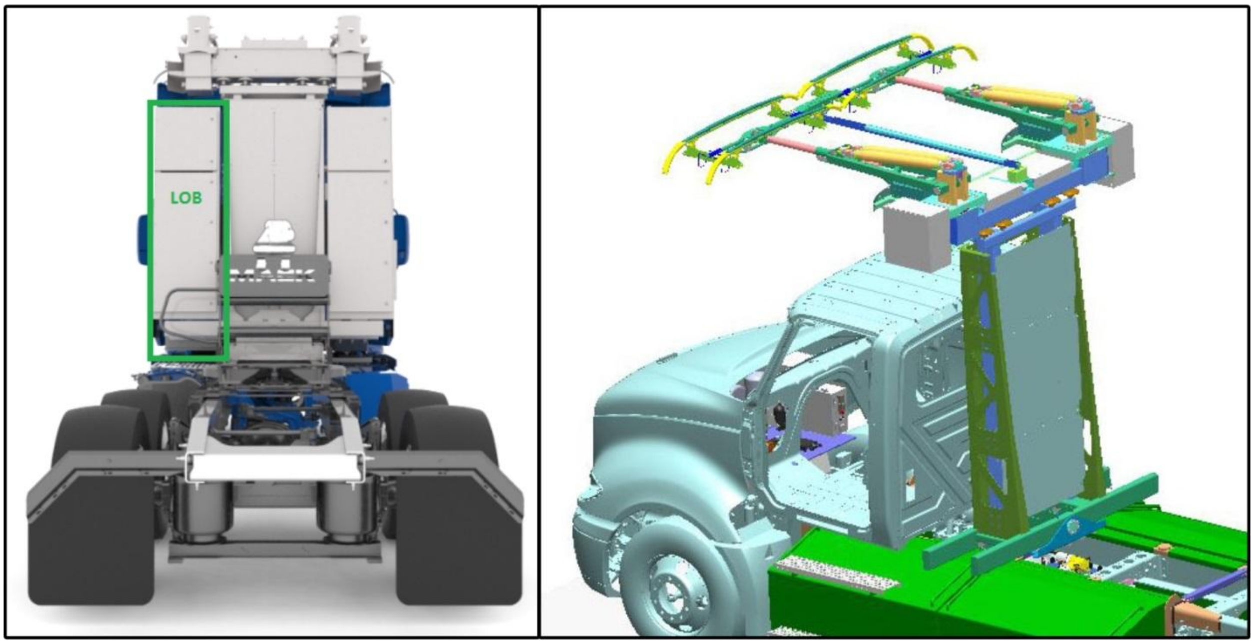


Figure 21 3D-Model of pantograph integration into Volvo (left) and Transpower truck (right)

The factory acceptance tests were performed individually at the manufacturing site in Berlin. For the FATs the pantographs were connected to the operation panel (HMI) which was supposed to be installed in the truck cabin later on (see Figure 22). The right PAN Box (RPB) containing several control elements for the pantograph was pre-tested in the assembly factory in Chemnitz/Germany. The FAT configuration consists of the pantograph system incl. external compressed air supply, an external DC 600 V power supply and the cabin components with related software licenses. Open issues were listed at the end of the FAT report.

In particular the following tests were conducted:

- Visual Inspection:
    - Pantograph arms
    - Topbox lift
    - Right PAN box (RPB)
- Functional Tests:
    - Startup and shutdown
    - Operational functions
    - Safety functions including automated dropping device (ADD) to detect broken carbon contact strips
    - Graphical user interface, operating messages

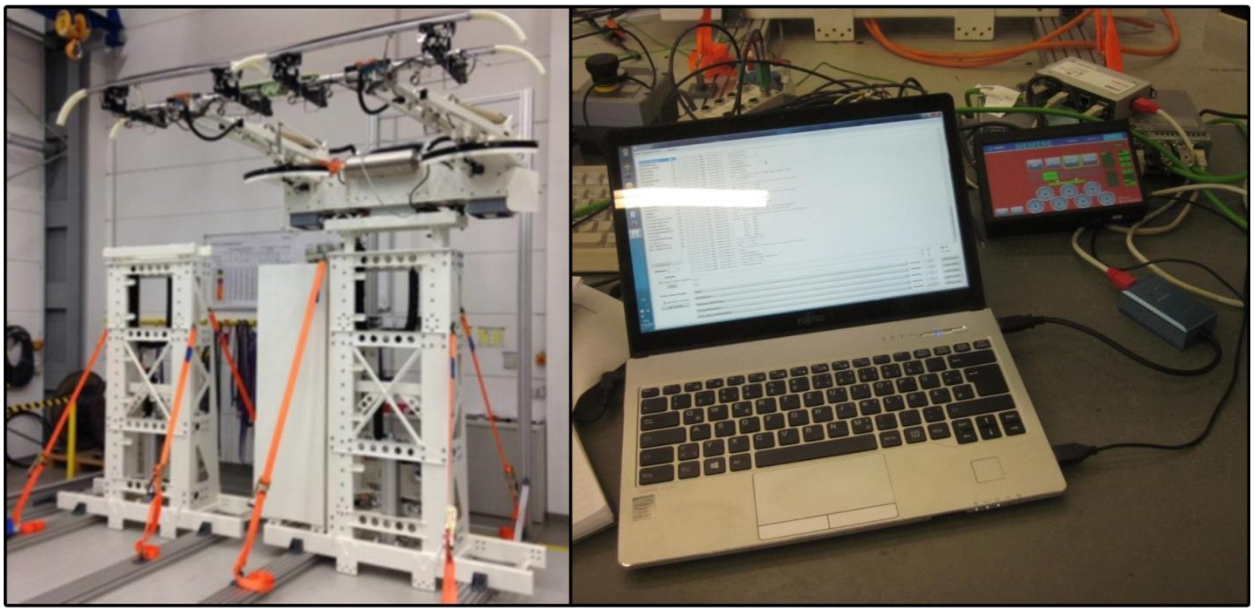


Figure 22 Arrangement for pantograph FAT at Berlin

A key test refers to the pantograph control and lateral working range. Figure 23 shows this test with the ultimate horizontal arm positions. Proper functionality of the lateral arm movement was a pre-requisite for the planned tests with trucks operating at the edge of lane to determine usability over the full lane width.

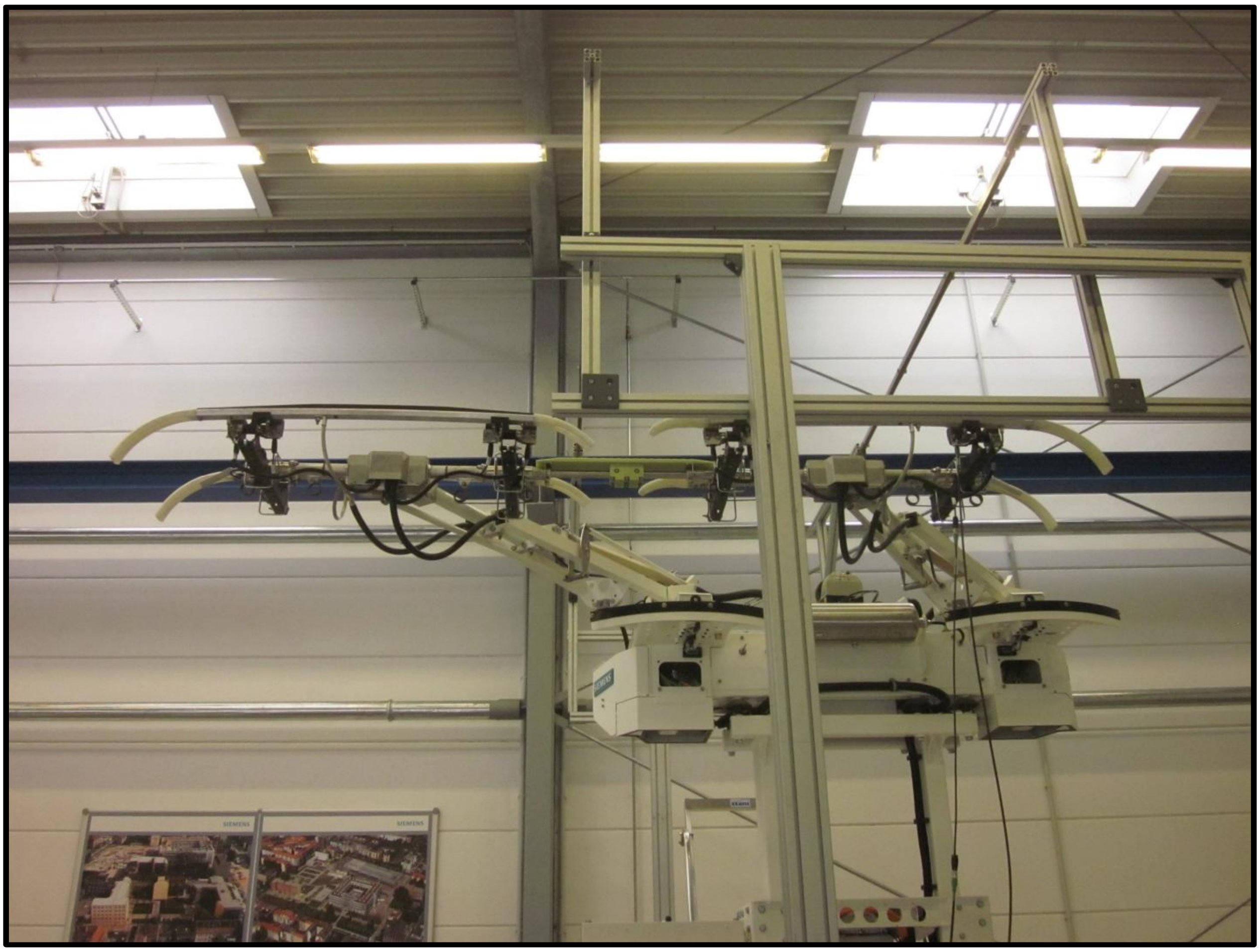


Figure 23 Pantograph horizontal working range test during FAT at Berlin

5.8 Task 8 - Pantograph production, assembly and integration into the hybrid trucks

After the manufacturing the pantographs were packed and sent to Poway, CA (Transpower facility) and to Gothenburg (Volvo plant). At these plants the pantographs were integrated into the trucks. Figure 24 shows the hybrid drive topology of Volvo and their pantograph - driveline interface. Integration was completed with further interface tests and ultimately with a site acceptance test.

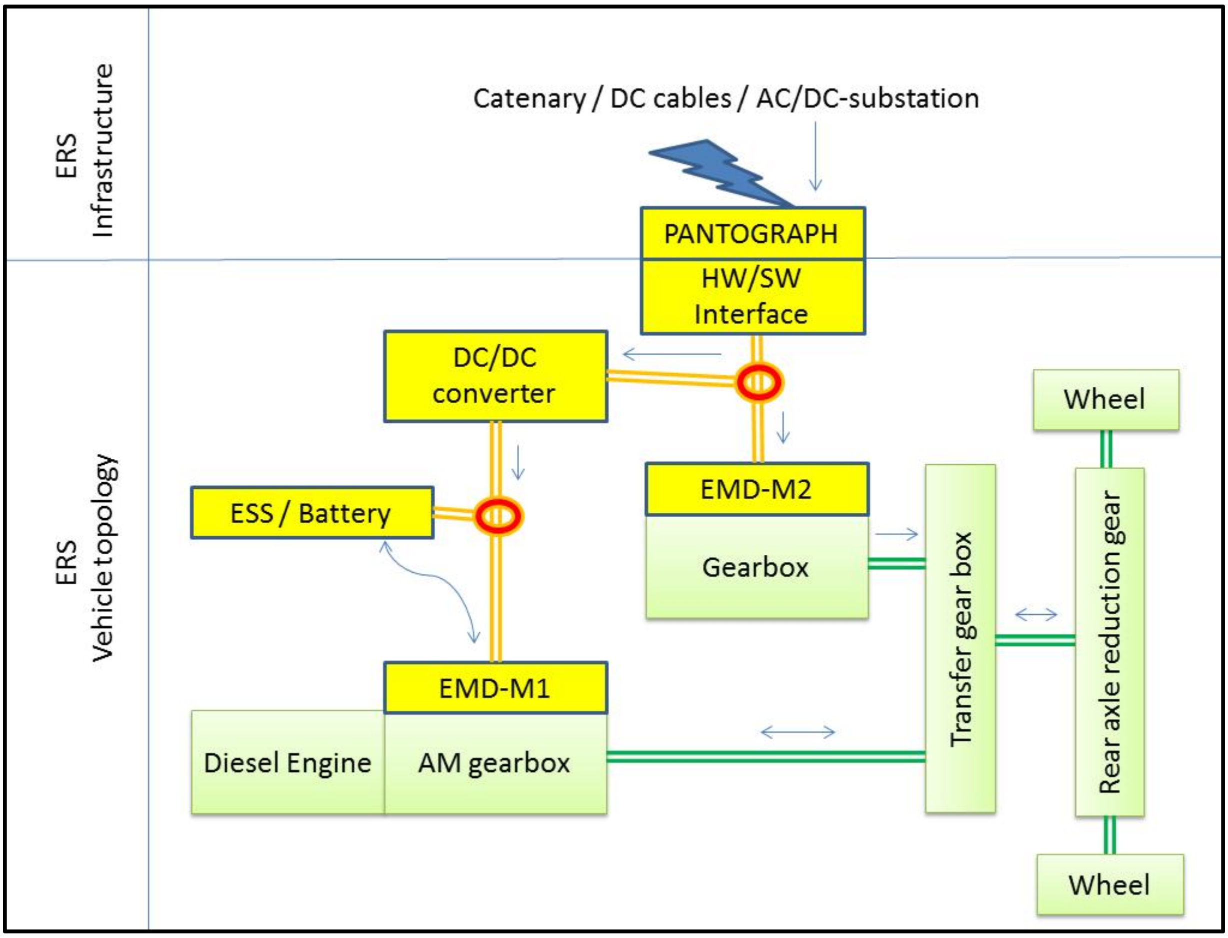


Figure 24 Integration of external powers supply into Volvo hybrid driveline [11]

The final integration tests were performed at the test track on the Alameda Street for the Transpower trucks. Those comprised checks of mechanic and electric functions as well as functionality of the safety features. Figure 25 shows the CNG truck CCAT during site acceptance test.

The system configuration of the site acceptance tests consisted of:

- the pre-tested pantograph system on the Transpower trucks
- the pre-tested hybrid drives and batteries on the Transpower trucks
- the pre-tested and commissioned external DC 600 V power supply as substation
- the commissioned overhead contact line on the test track

The corresponding Volvo tests were performed at the German eHighway test site at Gross Doelln, prior to an initial testing phase for the hybrid drive system (cf. chapter 5.9).

After the site acceptance tests were successfully closed for three different types of hybrid electric trucks and the catenary, the whole system was ready to demonstrate a zero emission corridor along the Alameda Street.

Figure 25 Transpower CNG truck CCAT during site acceptance test

5.9 Task 9 - Catenary truck and infrastructure demonstration

This task can be considered as the technical core of the project as it serves to study and demonstrate maturity and reliability of the electric power supply of hybrid trucks via a catenary system. The task is subdivided in three main topics:

- Component integration testing of the MACK truck in Germany (cf. chapter 5.9.1)
- System integration and performance testing on Alameda Street with all hybridized trucks (cf. chapter 5.9.2)
- Catenary system safety analysis to evaluate potential hazards and mitigation measures related to the catenary system (cf. chapter 5.9.3)

5.9.1 Component Integration Testing in Germany (Task 9.1)

After the factory acceptance test (FAT) in Gothenburg/Sweden the MACK truck was transported to the e-Highway test site in Gross Doelln/Germany before it was shipped to Los Angeles. Thus the first dynamic functions of the truck were tested, and it was possible to prove that the pantograph system can operate on different catenary system as long as their key parameters are in the interoperability range.

The integration and optimization works comprised the following aspects:

- site acceptance test including safety functions and proof of correct integration
- evaluation of vertical and horizontal working ranges
- power transfer to hybrid drive system including optimization of the power split between the two electric driveline that form a combination of a parallel and serial hybrid drive (cf. Figure 10, Figure 24)
- evaluation of acoustic emissions at different speeds (cf. [2])

Figure 26 shows the MACK truck at the non-public eHighway test track at Gross Doelln north of Berlin. The substation is situated in the side margin.

Figure 26 Test of MACK truck at Gross Doelln site 2016

5.9.2 Testing on site Alameda Street - Demonstration phase and testing

The system integration and performance testing was carried out during a 6 month period from June to December 2017. While specific integration and optimization task of the different trucks dominated the first months later test weeks concentrated on the performance testing that followed the required test items according to the statement of work [1]. Table 2 lists the required test items. Results are discussed in [2].

Table 2 Test items and assignment of report chapters

Item	Test description
A1	Infrastructure commissioning tests
A2	Energy efficiency testing
A3	General truck performance testing
A4	Pantograph performance and contact quality
A5	Drive in / drive out testing
A6	Overtaking testing
A7	Emergency braking testing
A8	Operating at the edge testing
A9	Proof of fail-safe pantograph design
A10	Ergonomics testing
A11	Weather and ambient condition test
A12	New algorithm testing*

Test planning and actual execution had to consider specifics of a heavily used truck route. For a number of integration and performance tests the electrified lanes had to be reserved and closed by traffic management see (Figure 27), which turned out to be hard to enforce. Moreover at different times testing had to be coordinated with road works by third parties, which occasionally limited availability of the mainline infrastructure.

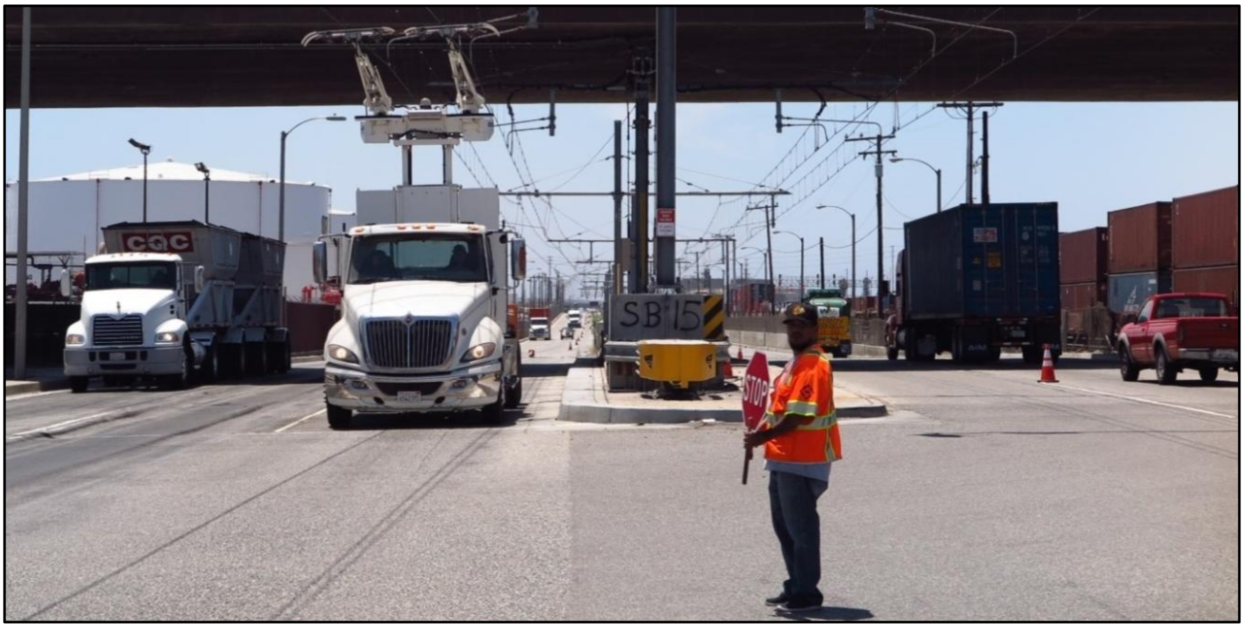


Figure 27 Traffic management in place in both directions

5.9.3 Catenary system safety analysis (Task 9.4)

The introduction of a catenary system into public road infrastructures for tramway, trolleybus and electric truck applications raises a number of safety related concerns. While all safety rules, standards and project specific safety procedures could be transferred from existing electric public transport applications further topics were studied in detail in the related research projects in Germany. Hence the catenary system safety analysis can be derived in a three-step approach:

- Review of existing catenary system safety engineering methods and adaption of the overhead contact line design for road and highway applications
- Performance of an Operating and Support Hazard Analysis (OSHA) considering the project specifics for the 1 mile stretch on Alameda Street corridor
- Review and provision of discussion regarding process and results of the technical assessment of the integration of the catenary system by the German Federal Highway Research Institute (BASt – Bundesanstalt für Straßenwesen) [13]

The key aspects of these work streams are explained in the following sub-chapters.

Review of existing catenary system safety engineering methods

Design, construction and operation of catenary systems are very mature and based on vast experience of more than 100 years of expertise. The experience made contributed to a wide set of system, product, component, material and testing standards that are likewise applicable for rail and road applications. In the course of eHighway related research projects delta analysis were performed to identify additional risks and mitigation measures that result specifically from the highway application context.

One key finding was the mitigation of risks related to broken contact wires. In railway applications the broken contact wire falls to the ground and triggers a short circuit which is then detected by the substation and triggers the switch to interrupt power supply immediately. As road surfaces are not conductive enough this procedure is not applicable. Moreover the coiling wire forms a mechanic obstacle. As a mitigation measure the dropper spacing was revised to 3 meters to prevent the contact wire from falling down. This measure was tested by cutting the wire, as shown in Figure 28.

Figure 28 Reduced dropper spacing prevent broken wires from falling to ground

To prevent further trucks from running into the defect section with raised pantographs an optional broken wire detection system can be used. This is installed at the tensioning devices and can detect broken wires. This signal can then be transferred to the substation and triggers the switch to de-energize power supply.

Operating and Support Hazard Analysis (OSHA)

In the course of the Alameda Street demo project a mandatory OSHA (operating and support hazard analysis) was performed and discussed with the stakeholders. Besides the inherent safety related design methods already observed in the design of the catenary system project specifics hazards were identified and mitigated by technical or organizational measures. Technical measures included the application of crash barriers and absorbers along the median to reduce the severity of potential vehicle crashes into the foundations of the poles, as shown in Figure 29. Further topics included operational measures like coordination with third parties when road works are necessary and involve the usage of machinery in the vicinity of the catenary system (see Figure 30).

Figure 29 Crash absorbers at beginning of electrified section (left) and guard rails (right)

Figure 30 Road works with machinery in the vicinity of the contact line

5.10 Task 10 - Determine owner and operator of system

Despite intense stakeholder dialogue and high public attention during the demonstration phase, cf. chapter 8 – Public relation, it was not possible to determine ways for uninterrupted ownership and operation of the demonstration site along Alameda Street. Therefore the decommissioning according task 12 (see chapter 5.12) was carried out.

Nevertheless the discussion of and with relevant stakeholders revealed a lot of insights that form an integral part for further system applications. The related findings are integrated into [14] that deals with the economic assessment and implications of the eHighway system. A survey of potential owner operators of an eHighway system was conducted by SCAQMD's consultant and will be presented as a separate document along with this report.

5.11 Task 11 - Project management and reporting

During construction and commissioning all required reporting was provided up to the stoppage of work as stated below and in chapter 6.1. Once truck testing was underway reporting was provided as required.

General adherence to schedule can be summarized as follows:

- The schedule was kept up until local utility SOCal Gas required the TPSS to be moved due to California State law enacted January of 2016 wherein encroachment with in an easement of a high pressure gas line was illegal. This caused a stop in the work for six months until the SCAQMD negotiated a six month period for testing of the pantograph equipped trucks on the OCS System on Alameda Street.
- Once the test period was granted the trucks were tested from July 1, 2017 through January 3, 2018 with the outcome as previously noted.
- Upon completion of the six month test period the contract was changed to reflect the test period as defined.
- Due to AQMD's negotiation process for the furtherance of testing of the tucks AQMD did not advise or include Siemens in the negotiation. Therefore Siemens was directed to stop further execution of the work until AQMD and SOCAL Gas came to the agreement of the testing duration and test start date and test end date. This in turn presented little to no data to report back to AQMD on a monthly basis.
- Once testing was underway on July 1, 2017 AQMD was notified via letter of the testing start date.
- AQMD was henceforth presented with the required quarterly reports for the testing submittals.
- Through this testing process Siemens advised AQMD of the resource loading schedule and the resource requirements schedule for the duration of the project.

5.12 Task 12 - System decommissioning and site restoration

While evaluation of the project results and compilation of the final report this task was still ongoing.

The Decommissioning of the site is currently underway. The requests for proposals (RFP) have been provided to three thus contractors with work instructions and site review. Answers to these RFPs are currently being entertained.

Permits are currently being sought for the scope of work through the City of Carson and provisions are being made for the offloading and disposition of the site equipment.

6 Challenges, findings, recommendations

Proving technical maturity and technological supremacy compared to other electric road systems for freight haulage was one key goal of the project. The second one was to actually see and learn about catenary infrastructure installation in an industrial public environment, pantograph integration into different hybrid vehicles and endured testing under real traffic conditions.

This chapter deals with the challenges, that occurred during project execution, major findings related to the testing operations, and recommendations to be drawn to foster the implementation and development of catenary type truck haulage.

6.1 Challenges during project execution

Underground infrastructures – gas pipelines

During the project execution it turned out that foundations for the poles which are supporting the catenary cannot be piled with steel tubes as this is common practise for catenaries. Further investigations surrendered that a gas pipeline was running embedded in the central reserve / median. This did not allow to pile the poles as this was intended. The solution to overcome this challenge was to install the poles on pre-cast concrete foundations to get permission from the gas pipeline operator company. The necessary redesign did involve the contact line system as well as further median and road works. Redesign and re-approval of the foundations caused a project delay of several months. Later on another gas pipeline underneath the substation was found to be critical for an extension of the testing phase as it limits accessibilty to the pipelines for maintanance. To adjust for both challenges it was mutually decided to intensify the testing phase and to shorten it to a 6 month period. This reduction was necessary since the operational license for the substation could not be extended.

Interface to truck supplier

Integration of the pantographs into common class 8 trucks requires a comprehensive interface clarification. Also the challenge to adapt the combustion motor technology and to propel a truck with electric motors was underestimated. Although Siemens made experiences with other suppliers to integrate catenary power supply on heavy duty trucks, additional efforts and clarifications were necessary to reach project goals. Finally and during system integration testing individual minor adaptions in all subsystems including protection settings at the infrastructure could be found to stabilize truck performances. Future applications and efforts should strive to standardize that interface further and to generalize findings from integration and testing.

Truck #4

Contrary to original planning no agreements to purchase and hybridize a fourth class 8 truck from another truck OEM could be achieved. While negotiations took very long a positive agreement seemed certain. Therefore it was mutually decided to purchase and manufacture all four pantographs in a row to benefit from ressource synergies. After FAT the fourth pantograph was stored in Germany and is now being shipped to be used as a spare part.

Incorporation of parallel research work in Germany

In parallel to the execution of the demonstration project on Alameda Street research and development projects continued in Germany. As already discussed in chapter 5.9.3 safety related findings were incorporated in design and construction of the catenary system. Minor adaptions to the pantograph control, e. g. optimized lowering procedure, were realized as well without influence on project schedule.

6.2 Findings during testing phase

Test operation related findings

- Achieving and maintaining a sufficient level of stability for the entire system - substation, prototype vehicles, and pantographs - was a challenge during system integration and parts of the paralleled testing time. It required quick support from specialists as well as securing availability of special spare parts.
- The combination of the relatively short electrified track with the heavy traffic conditions made it hard for the drivers to accomplish specific test routines like full overtaking maneuvers or edge of lane testing without traffic interference.
- All trucks feature battery buffered electric drives that charge in parallel to driving. Given the traffic conditions and short electric run time in each drive it was very hard to repeatedly reach cruising speeds and steady states for the drivetrains.
- The sharp turns (U-turns) at Alameda Street were leading to increased trailer tires degradation and eventually stop of trailer operations in early December.

Truck related findings

While the reliability of the prototype trucks has been well sufficient to support the data collection and performance testing activities, the following observations are worth highlighting:

- Electrified truck auxiliaries (24 V/12 V batteries, air compressors) remain key assets of vehicles without auxiliaries powered permanently by diesel engines. This accounts especially for the air compressor given the higher air supply needs due to the higher contact line height and the rough road. More powerful compressors would be helpful to avoid overload the auxiliaries.
- The main battery systems of contact line powered vehicles show significant differences in the use cases and electric cycling, calling for increased maintenance time for battery balancing. Future designs should include other cell types specifically designed for static and dynamic charging.
- Maintaining proper alignment of the vehicle with the infrastructure at all times to prevent loss of contact has proven to be challenging in certain driving situations. Therefore further deployment of electrified roadways along freight corridors should consider integration of vehicle automation technologies to assist the driver, e. g. assisted steering, automated positioning in lane center.
- The cycle times of pantographs – especially for connection – are relatively long and should be optimized in future designs.
- Studying driver ergonomics revealed that positioning of the displays and necessary involvement of the drivers to operate the pantograph can be optimized. In the mid-term automatic pantograph operation should be considered.

Infrastructure related findings

- With the current pantograph design and the given legislative framework (contact line height at 18 ft nominal) the pantographs operate at the vertical edge of their working range. Potential optimizations for future operation have been derived.
- Integration (esp. substation relay setting) of different vehicle types call for close cooperation of all subsystem specialists. The system integration findings have to be generalized as further detailed interface specifications towards the truck drivetrain integrators and the substation designers.
- Turn-outs and variable street layouts demand more complex catenary constructions and increase testing impact when closed lanes are required.

6.3 Recommendations for research and improvement

The eHighway is based on proven and mature technology, especially on infrastructure side. Nevertheless, compared with other transport systems, the eHighway is still a rather young concept with further development plans regarding system optimization. Further R&D works and steps towards higher TRL (technology readiness level) must be taken and are already planned. This is most important for industrialization and robustness of the pantographs and electric hybrid drivetrains optimized for heavy truck applications. Based on the challenges overcome, findings made, and discussions started with stakeholder the following recommendations can be derived:

Regulatory framework

After the successful demonstration of the technical feasibility of the eHighway system the regulatory framework will need to be evaluated in further detail as it has a major impact on the commercial viability of future projects. The major aspects include taxation, emission charging, billing and accounting, infrastructure design and approval guidelines.

Power supply and generation

The interfaces towards energy suppliers should be elaborated further with regards to market roles as infrastructure providers and operators as well as to further analyze and specify technical aspect. The topics to be considered comprise the shift to increase regenerative power generation, technical network connections aspect, power flow estimations and optimized system designs, energy metering and billing, and system operation and maintenance.

Others use cases

Beside the use of overhead lines by truck it could be also considered to adapt this technology to propel electric buses in private or public sector. This could increase the number of vehicles on electrified sections and open up synergies for design and production of electric drivetrains for commercial vehicles.

Truck technology

The catenary technology can serve as an electric backbone for dynamic supply and additional charging of vehicle storages. To extend ranges beyond electrified sections for complete ZE cycles supplementary systems like on-board batteries, fuel cells, or PtG/PtL combustion engines will be needed. Future work should simplify drivetrain combinations and head for mutual optimization of energy storages to gain vehicle designs matching the designated applications.

The vehicle built by Volvo for this project was a technology demonstrator intended to represent an eHighway enabled vehicle. The vehicle included several technologies not ready for commercialization and was optimized for maximum flexibility with regards to operating modes.

With the experience gained both in terms of technology and operating conditions during this demonstration, substantial design improvements were identified with regards to complexity, weight and reliability for this specific application.

The primary areas to be addressed in future works include:

- Vehicle power distribution system where number of energy conversion steps can be greatly reduced.
  - This would lead to a less complex electric mechanical propulsion topology.
- Joint optimization of vehicle and pantograph design aimed to reach a globally optimal design.
  - This would lead to a less complex interface and control of connection / disconnection of pantograph.

Endurance tests and increased testing conditions

During the development of the eHighway components and products comprehensive tests were conducted and proved road stability adequately matching the development stages.

Nevertheless the existing contact line sections in demonstration projects are too short to gain endurance test results. Future field trials already feature longer electrified sections and increased truck operations to achieve more mileage as a better base to evaluate and improve robustness.

In order to further increase the maturity of the concept, future testing should include a broader operating context where both dynamic events such as entry/exit of the eHighway at higher speeds as well as steady state conditions can be studied in more detail.

This would require an enhanced test track setup which should preferably be defined jointly by infrastructure, vehicle provider and local authorities. Some desired characteristics of such test tracks known from vehicle providers include at least above 40 km as well as variation in road grades (+/- 3-5%) to better represent long haul vehicle operation.

7 Assessment of project goals

7.1 Zero emission goods movement technologies

Zero emission freight haulage techonologies comprise solutions with on-board energy storages based on alternative fuels or electricity and solutions with external power supply, see Figure 31.

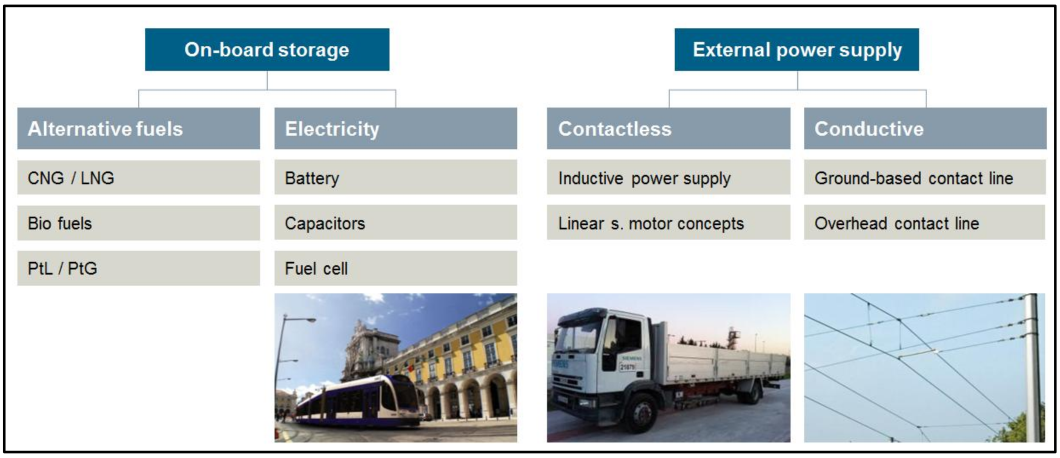


Figure 31 Zero emission technology matrix for road freight applications

A key driver to determine applicability and to differentiate the solutions is a closer examination of the overall efficiencies according Figure 32.

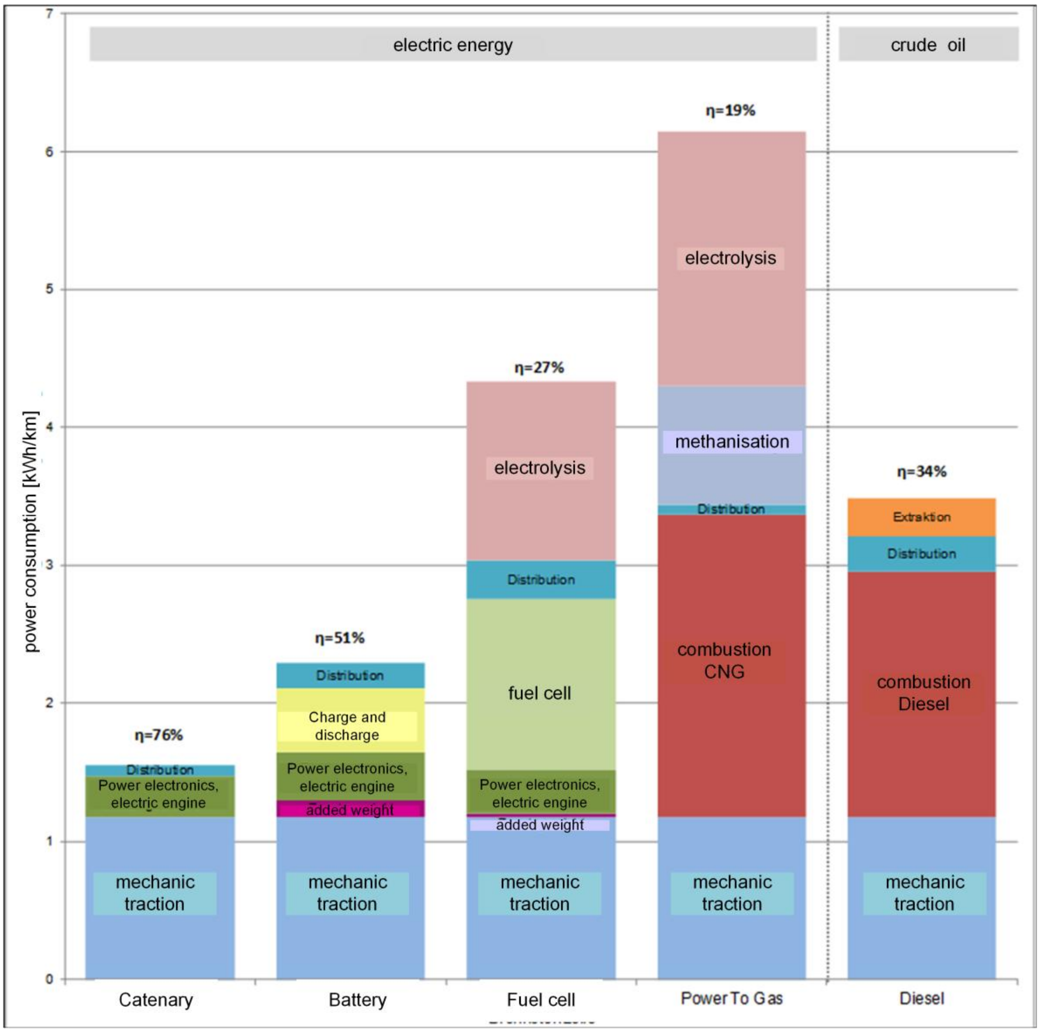


Figure 32 WTW efficiencies as specific power consumptions of different ZE technologies

Analysis of Figure 32 allows the following conclusions:

- External power supplies by means of catenary systems are by far the most efficient technology.
- Batteries are still more efficient than conventional diesel traction, but will always be limited by ranges, additional weights and production and lifecycle related emissions.
- Hydrogene fuel cell systems and synthetic fuels (e-fuels) are characterized by unduly low efficiencies, see also Figure 5 and Figure 32, leading to drawbacks as core decarbonization technologies.
- To achieve an acceptable efficiency level compared to conventional diesel traction a blend of technologies is necessary with highly efficient direct electricity use on electrified core network sections and extension of electric range by batteries or synthetic fuels.

Electrifying core corridors and heavily used truck routes can be a catalyst towards environmental friendly but still economically feasible ZE freight system.

7.2 Most viable technology

As shown in the overview in Figure 31 different external power supplies can be discussed. Typically they are summarized with the term ERS – electric road systems and comprise the following technologies:

- Power supply via overhead contact line systems (catenary)
- Inductive energy transmission
- Power supply via a ground-based (earth) conductor rail

Figure 34 characterizes these different technologies by explaining power transmission principles and a short discussion of advantages and disadvantages. Further state-of-art information on all types of ERS is assembled in [15]. Based on the scale of the existing public demonstrations on Alameda Street corridor and E16 highway in Sweden as well as the planned field trials in Germany the catenary type power supply can be considered as the most mature ERS technology. Moreover transmission efficiency on the contact point between infrastructure and vehicle reaches 99 % [16] and is much higher than the inevitable transmission losses in inductive solutions.

With specific consideration of the heavy truck volumes that are discussed for ZE corridors ground-based conductor rails must be questioned regarding their integration into the road surface. While lane grooves can be compensated by vehicle suspensions and the pneumatic pantograph mechatronics in overhead contact line applications such distortions (see Figure 33) cannot be handled by integrated conductor rails.

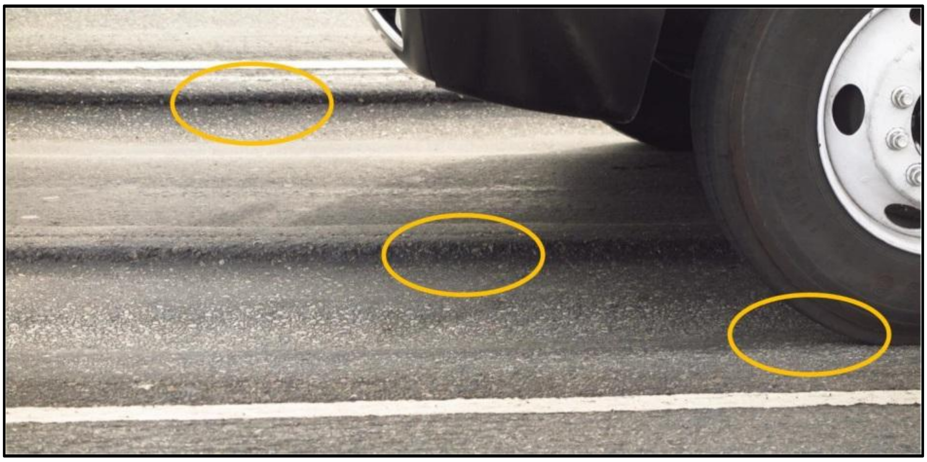


Figure 33 Lane grooves on Alameda Street at intersection

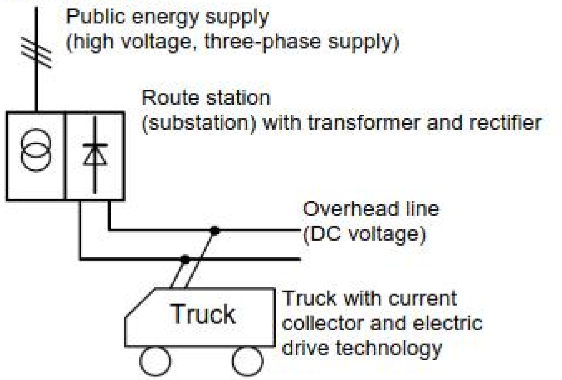
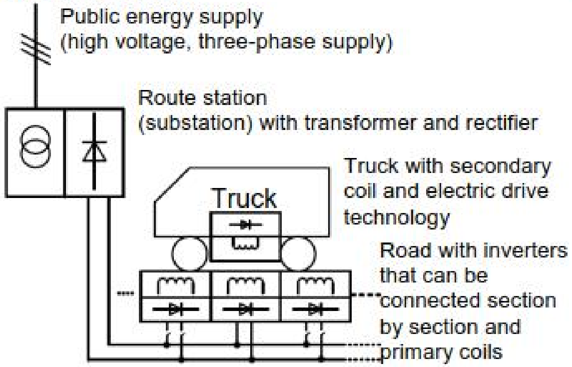
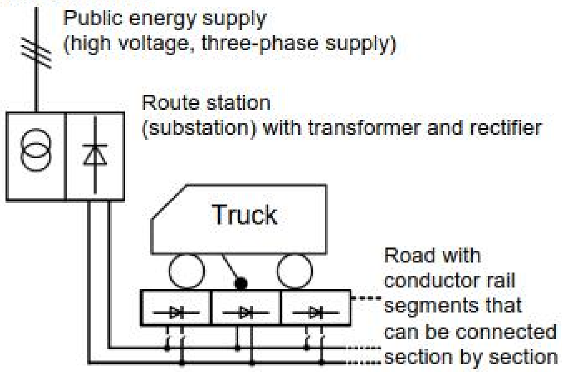
<table>
<tr>
<th>Overhead line
Grid-bound transmission of electr. energy with an overhead line</th>
<th>Inductive energy transmission
Transmission of electrical energy through induction of electrical voltage</th>
<th>Earth conductor rail
Transmission of electrical energy through a rail beneath the vehicle</th>
</tr>
<tr>
<td>Schematic sketch
</td>
<td>Schematic sketch
</td>
<td>Schematic sketch
</td>
</tr>
<tr>
<td>Operating principle
- from power supplies in substations, DC voltage is generated for feed into overhead line
- Trucks are equipped with current collectors and transmit current from the overhead line to the drive system
- Trucks are equipped with power electronics, an electric motor and energy storage system
- Vehicles can exchange energy gained via the overhead line when braking or feed it back into the upstream grid</td>
<td>Operating principle
- from power supplies in the substations, DC voltage is generated for feed into the supply line
- Route is divided up into segments that can be connected section by section
- Trucks are equipped with coil systems (secondary coils) in which electr. voltage is induced and energy is transferred when overlapped with the road coil
- The trucks are equipped with power electronics, an electric motor and energy storage system</td>
<td>Operating principle
- from power supplies in substations, DC voltage is generated for feed into conductor rails
- Route is divided up into segments that can be connected section by section
- Trucks are equipped with current collectors and transmit current from rails to the drive system
- Trucks are equipped with power electronics, an electric motor and energy storage system</td>
</tr>
<tr>
<td>Advantages
- Easy to integrate current collector/drive technology
- DC or AC voltage possible
- No notable electromagnetic influence with DC systems
- proven technology, 120 years of experience
- no direct intervention into the route required
- mobile current collector can offset vehicle movements in the lane without any energy loss
- distance of the substations approx. 1-4 km (no additional switches and route installations required)
Disadvantages
- visible overhead line above the electrified lane</td>
<td>Advantages
- no visible overhead line, road transport remains virtually unchanged visually
Disadvantages
- extensive installations in the road per segment
- EMV critical, given the alternating field
- coil systems must be traversable by trucks (mechanically heavily loaded lane)
- the top/base layer required for this increases the distance between the road and vehicle coil and lowers efficiency
- longer road segments that are not completely overlaid by vehicles have poor efficiency</td>
<td>Advantages
- no visible overhead line, road transport remains virtually unchanged visually
- good efficiency due to conductive energy transmission
Disadvantages
- extensive installations in the road per segment
- rail systems must be traversable by trucks (mechanically heavily loaded lane)
- weather conditions such as snow and ice or contamination can significantly worsen the electrical conductivity
- individual vehicle movement on a stabilization level is either difficult or impossible to achieve without subsequent damage due to rigid current collector coupling</td>
</tr>
</table>

Figure 34 Comparison of technical features of ERS power transfer technologies

7.3 Conclusions and perspectives

The project has demonstrated that the eHighway system can be implemented in an existing road infrastructure as a potential zero emission goods transport technology. During the testing phase the eHighway system proved to be a viable technology suitable for e.g. regional zero-emissions corridors. The whole project and the testing gained wide interest by stakeholders and potential users, see Figure 35.

Figure 35 Catenary supplied hybrid trucks raise attention of key stakeholders for ZE transport

Lessons learned from this project and from the eHighway related activities of Siemens and its cooperations partners are being implemented in the ongoing development and improvement. A strong focus will be put on a new generation of the pantograph system which is to be released for the field trials on German highways in 2019. The modifications are targeting at reducing the weight and complexity of the pantographs in order to increase the availability while at the same time reduce the costs.

During the recent years the eHighway system is increasingly being considered as the backbone technology - not only for shuttle applications in ports and mines, but although as core solution to reach ambitious climate protection and emission reduction targets.

When larger distances of highways are being electrified with overhead contact lines, there will remain a share of the routes where the vehicles have to utilize their alternative drive system. Besides batteries and synthetic fuels used in conventional or down-sized combustion engines small fuel cell systems may be used, if this technology proves out feasible and cost-compatible in the future. The adaptation of the trucks to the specific needs of the logistics companies offers great potential to achieve ZE road freight transport while at the same time foster the development of these technologies.

Larger scale projects also offer potential to reduce infrastructure costs significantly as discussed in the business cases for further applications in Southern California.

8 Public relations and communication

8.1 Press and media releases

The feedback from public media, internet platforms and TV stations on the project were positive. The TV report from Discovery Canada has given a comprehensive overview of the goals and targets which were achieved during the project duration. The following Internet Links have been published after the opening of the eHighway on the Alameda Street.
All press and media releases can be found in the attachments under the chapter 10.2:

- SoCal Siemens Inc Newsroom (November 8, 2017)
- Siemens eHighway Runs for SoCal, Fleets & Fuels (November 17, 2017)
- How about electric semis that draw power from overhead wires?, Green Car Reports (November 20, 2017)
- Siemens Begins Zero-Emissions Highway Testing in California, Heavy Duty Trucking (November 13, 2017)
- First 'eHighway' Demonstration Project Under Way, Environmental Protection (November 20, 2017)
- California's First Electric Highway Is Finally Open, Green Matters (November 13, 2017)
- Siemens Begins Zero-Emissions Highway Testing in California, Trucking Info (November 13, 2017)
- Today’s Pickup: California ports become testing ground for electrified highway, Freight Waves (November 13, 2017)
- One way to curb freight emissions: Put trucks on an electric catenary system, Ars Technica (November 10, 2017)
- Never Mind Electric Cars: Why Electric Roads are the Real Key to the Future, Inverse (November 10, 2017)
- Trucks start rolling down California eHighway, New Atlas (November 10, 2017)
- Siemens eHighway Heavy-Duty Trucks Continue In California, Clean Technica (November 12, 2017)
- Siemens debuts first electrified eHighway in the US, Gears of Biz (November 10, 2017)
- When overhead wires feed energy to trucks in California demo, Tech Xplore (November 10, 2017)
- Ports of LA and Long Beach Debut Hybrid Trolley-Trucks, The Maritime Executive (November 9, 2017)
- Siemens Unveils California’s New Electric Highway, The News Wheel (November 12, 2017)
- This Week in Tech: An Electric Highway for Green Transportation, Architect Magazine (November 10, 2017)
- Today’s Pickup: California ports become testing ground for electrified highway, Freight Waves (November 10, 2017)
- First US eHighway demonstration in California, Energy News Live (November 10, 2017)
- California Builds First Electric Highway, For Construction Pros (November 9, 2017)
- First U.S. eHighway Electrified Trucks Running in California, Construction Equipment (November 9, 2017)
- Syndication: America’s first eHighway goes live in California, Blouin News (November 10, 2017)
- Hybrid 'trolley trucks' debut in Port of LA, Long Beach, Fox 11 Los Angeles (November 9, 2017)
- This Electric Highway Powers Trucks Without Recharging
- Fast Company, November 9, 2017
- There's Now An Electric Highway In California Forbes, November 8, 2017

- eHighway broadcast coverage-ABC, CBS November 8, 2017
- Trolly-like system for heavy-duty trucks tested near the ports of LA, Long Beach Daily Breeze (LA local), November 8, 2017
- Siemens debuts first electrified eHighway in the US Inhabitat, November 9, 2017
- Siemens Tests Novel eHighway for Heavy-Duty Trucks in California Next-Gen Transportation News, November 8, 2017
- California Builds First Electric Highway
- Forconstructionpros.com, November 9, 2017
- First U.S. eHighway Demonstration Running in California, Mass Transit, November 8, 2017
- Siemens To Conduct eHighway Trials With Electric Volvo Trucks In California Inside EVs, November 9, 2017
- Electrified 'eHighway' demonstration running in California Utility Products, November 8, 2017
- Siemens Tram-Trucks Cruise Near LA Port, Port Technology, November 9, 2017
- Siemens launches the first eHighway demonstration in the US

TV Reports

- Discovery Channel Canada 12-01-2018

8.2 Presentations to Customers and Stakeholders

During the construction and testing phases a number of technical presentations were held at site. Table 3 lists these dates. For the press and media event an information package was provided, cf. chapter 10.2.

Table 3 Date and topic of customer and stakeholder presentations

Date	Topic
2015-12-22	Funding partners demonstration at substation and test track
2017-07-18	Port of Long Beach
2017-07-18	SCE – Technical Group 1
2017-09-07	AQMD Board Meeting
2017-10-14	4th International Moving Forward Network Conference
2017-11-08	Press and Media Event
2017-11-30	Discovery Channel Canada
2017-12-12	SCE – Technical Group 2

9 Abbreviations, literature and Indices

9.1 Abbreviations

Abbreviation	Explanation
BEV	Battery Electric Vehicle
CC	Cabin Components
CCAT	CNG CAtenary Truck
CEQA	California Environmental Quality Act
CNG	Compressed Natural Gas
EBIT	Earnings Before Interest and Taxes
ECAT	Electric CAtenary Truck
ENUBA	Elektromobilität bei schweren Nutzfahrzeugen zur Umweltentlastung von Ballungsräumen
ESS	Energy storage system
FAT	Factory Acceptance Test
FBS	Far range Sensor (Translated)
GFD	Ground Fault Detection
HMI	Human Machine Interface
HEV	Hybrid Electric Vehicle
ICTF	Intermodal Container Transfer Facility
NB	Northbound
NBS	Near range Sensor (Translated)
OCS/ OCL	Overhead Contact Line
OEM	Original Equipment Manufacturer
OSHA	Operating and Support Hazard Analysis
PAN	Pantograph
PCC	Pantograph control computer
PPP	Public Private Partnership
RPB	Right Pantograph Box
ROI	Return on invest
SB	Southbound
SCADA	Supervisory Control and Data Acquisition
SCAQMD	South Coast Air Quality Management District
SCIG	Southern California International Gateway
SoCal	South California
SOW	Scope of Work
TES	Traction Electrification System
TPSS	Traction Power Supply Station
TRL	Technology Readiness Level
TSP	Transport Service Providers
UBA	Umweltbundesamt (Federal Environment Agency)
UP	Union Pacific
WTW	Well to Wheel (eco balance from oil-well to powered wheel)
ZETECH	Zero Emission Truck & Electric Catenary Highway (by Transpower)

SIEMENS

9.2 Literature

[1] *SCAQMD:* Contract No. 14062 incl. Statement of Work. Diamond Bar, 2014

[2] *Siemens AG [Hrsg.]:* SCAQMD Contract 14062. Q4 Testing Report, 22 Feb 2018.

[3] *UNFCC United Nations Framework Convention on Climate Change:* Paris Agreement. Paris, 12.12.2015. Link: https://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf

[4] *EPA - United States Environmental Protection Agency:* Sources of Greenhouse Gas Emissions for 2015. Link: https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions

[5] *ITF - International Transport Forum:* Outlook 2017. Link: http://www.keepeek.com/Digital-Asset-Management/oecd/transport/itf-transport-outlook-2017/summary/english_e979b24d-en#.Wo2GapiWwu4#page1

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[7] *CALSTART:* I-710 Project Zero-Emission Truck Commercialization Study Final Report. November 2013. Link: http://www.calstart.org/Libraries/I-710_Project/I-710_Project_Zero-Emission_Truck_Commercialization_Study_Final_Report.sflb.ashx

[8] *Siemens AG [Hrsg.]:* ENUBA – Elektromobilität bei schweren Nutzfahrzeugen zur Umweltentlastung von Ballungsräumen (FKZ: 16EM0077). Abschlussbericht. München, 2012. Link: http://www.erneuerbar-mobil.de/sites/default/files/publications/abschlussbericht-enuba_1.pdf

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[10] *SCE - Southern California Edison:* Grid Technology and Modernization File, eHighway Grid Impact Assessment. Memorandum by Ioan, A. and Smith, J. Record No.: TC-15-027-TR06. Pomona, CA, February 2018. (internal report)

[11] *Volvo Group:* Demonstration of Siemens Electric Road System on Diesel Electric Hybrid Truck - eHighway Vehicle Test Report. Report by Amar, P. and Larsson, B. Record No.: P4348. Gothenburg, January 2018. (internal report)

[12] *TransPower:* Electric and CNG Hybrid Trucks for the Zero Emission Truck & Electric Catenary Highway (ECHT-ZETECH). Final Report. Escondido, CA, December 2017. (internal report)

[13] *Siemens AG [Hrsg.]:* ENUBA 2 - Technical assessment, Result report (TB-E). Presented to German Federal Highway Research Institute (BASt – Bundesanstalt für Straßenwesen). Erlangen, August 2015. (non-public report)

[14] *Siemens AG:* Business cases for future catenary projects in the South Coast Air Basin. Report to SCAQMD, February 2018. (internal report)

[15] *SINTEF Energy Research:* Technology for dynamic on-road power transfer to electric vehicles – Overview and electro-technical evaluation of state-of-the-art for conductive and inductive power transfer technologies. Project: ELinGO – Electric infrastructure for Goods Transport. Project report 1.2, Oslo, January 2018.

[16] *Lehmann, M. et. al.:* Untersuchung eines Stromabnehmers für schwere Nutzfahrzeuge. In: eb - Elektrische Bahnen, Jg. 111 (2013) H. 11, S. 657ff

Additional literature sources for project background

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[A2] http://www.aqmd.gov/docs/default-source/Agendas/aqmp/white-paper-working-groups/wp-goodsmvmt-final.pdf?sfvrsn=2

[A3] https://www.arb.ca.gov/cc/inventory/pubs/reports/2000_2015/ghg_inventory_trends_00-15.pdf

[A4] http://www.ca-ilg.org/post/basics-sb-375

[A5] http://www.casustainablefreight.org/documents/PlanElements/AppendixB_FINAL_07272016.pdf

[A6] https://www.arb.ca.gov/cc/sb375/sb375_workshop%20presentation_los_angeles.pdf slide 21

[A7] https://www.trucks.com/2017/12/11/california-green-truck-incentive-package/

[A8] http://www.energy.ca.gov/contracts/GFO-17-603/

[A9] https://www.arb.ca.gov/gmp/sfti/Sustainable_Freight_Draft_4-3-2015.pdf pages 13 & 24

9.3 Figures

9.4 Tables

10 Appendices

10.1 Project Synopsis

Provided as PDF: SCAQMD Contract 14062_synopsis.pdf

10.2 Information package I – Press & Media event

Provided as Zip-File: SCAQMD_14062_MediaPackage.zip

10.3 Information package II – Press Releases

Provided as Zip-File: SCAQMD_14062_PressReleases.zip

10.4 Photo documentation

The photograph documentation contains the following aspects:

- Construction: SCAQMD_14062_Construction.zip
- Testing: SCAQMD_14062_Testing.zip
- Miscellaneous: SCAQMD_14062__Miscellaneous.zip
- Graphics used in the report: SCAQMD_14062__ReportGraphics.zip

10.5 Vehicle data sheets and key facts

General Information

Vehicle ECAT is equipped with the 2nd generation pantograph in cooperation with Transportation Power Inc. The ECAT truck is designed as a pure electrical vehicle and the internal combustion engine has been removed. It will start to perform on a public eHighway application in Los Angeles early 2017 to be one of the first eHighway vehicles to run in the USA on public roads.

Data Sheet

Base Vehicle:	Navistar International Prostar
Vehicle Modification by:	Transportation Power Inc.
In Operation since:	2017
Vehicle Length:	8,4 m (20,50 m incl. trailer)
Vehicle Weight:	9,8 t
Gross Vehicle Weight:	40 t
Drive System:	Full Electric
Power Electric Machine:	300 kW
Type of Energy Storage:	Battery
Capacity of Energy Storage:	115 kWh
Range from On-board Energy Storage:	65-130 km
Type of Pantograph:	Active Pantograph (2nd Gen.)

Figure 36 Data sheet Transpower ECAT truck

General Information

Vehicle CCAT is equipped with the 2nd generation pantograph in cooperation with Transportation Power Inc. The CCAT truck is designed as a serial hybrid vehicle and the combustion engine runs on compressed natural gas. It will start to perform on a public eHighway application in Los Angeles early 2017 to be one of the first eHighway vehicles to run in the USA on public roads.

Data Sheet

Base Vehicle:	Navistar International Prostar
Vehicle Modification by:	Transportation Power Inc.
In Operation since:	2017
Vehicle Length:	8,4 m (20,50 m incl. trailer)
Vehicle Weight:	10,7 t
Gross Vehicle Weight:	40 t
Drive System:	Serial Hybrid
Power Electric Machine:	300 kW
Type of Energy Storage:	Battery + CNG
Capacity of Energy Storage:	115kWh
Range from On-board Energy Storage:	160-305km
Type of Pantograph:	Active Pantograph (2nd Gen.)

Figure 37 Data sheet Transpower CCAT truck

General Information

Vehicle Mack is equipped with the 2nd generation pantograph. It was modified by Volvo/Sweden to interface with the Siemens pantograph.

Data Sheet

Base Vehicle:	Mack Pinnacle Daycab
Vehicle Modification by:	Volvo Group
In Operation since:	2017
Vehicle Length:	8,5 m
Vehicle Weight:	9,1 t
Gross Vehicle Weight:	40 t
Drive System:	Parallel Hybrid
Power Electric Machine:	120 kW
Type of Energy Storage:	Battery
Capacity of Energy Storage:	1,2 kWh
Range from On-board Energy Storage:	1-4 km
Type of Pantograph:	Active Pantograph (2nd Gen.)

Figure 38 Data sheet MACK truck

RICARDO

South Coast AQMD

TCO of Overhead Catenary System power port drayage trucks

Final Report

16 February 2018

Delivering Excellence Through Innovation & Technology

www.ricardo.com

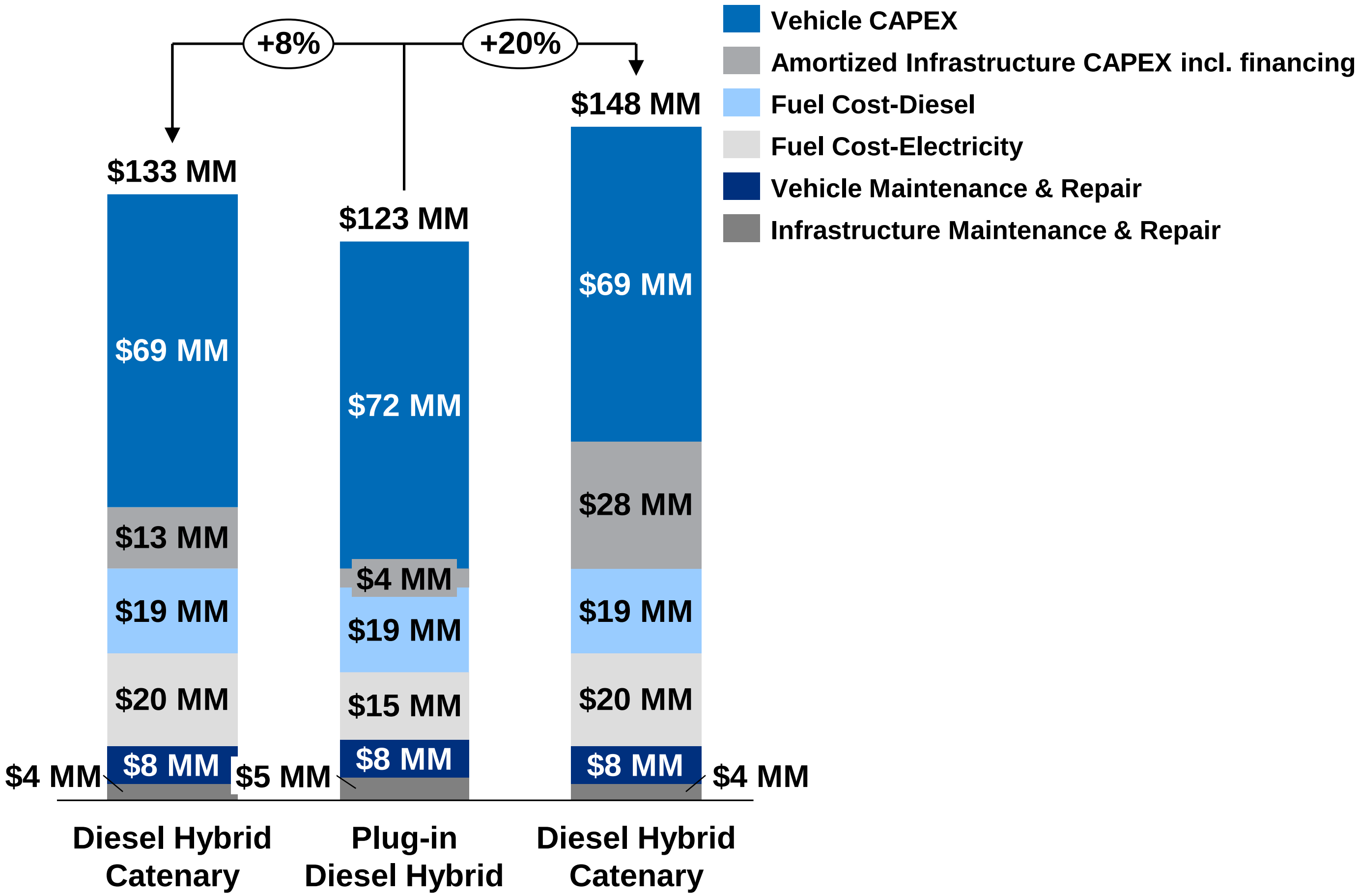
Contents

The business case of catenary diesel hybrid trucks has been analyzed relative to fast charging capable plug-in hybrid trucks

- This study is a TCO analysis for catenary truck fleet and a PHEV truck fleets operating with similar zero emissions capabilities at POLA/POLB. Diesel powertrain provides additional range in both trucks
- The study captures costs estimates today and considers how these may change in future. This study is a technology business case and does not include identifying specific locations PHEV fast chargers nor any associated real estate purchase costs
- The total cost of ownership has been analyzed for 500 drayage trucks on Alameda Street and 15,000 drayage trucks on I-710
- TCO calculation is based on capital and operational costs for the entire volume of trucks on each of the two routes as well as supporting catenary and charging infrastructure
- Plug-in hybrid trucks are assumed to require mix of overnight and fast chargers
- Trucks on I-710 routes are estimated to require 2 charging events:
  - One 24 minute fast charging during the day
  - One 4.5 hours slow charging overnight
- Trucks on Alameda St. route have enough battery capacity to get through the day with only overnight charging at fleet locations
- According to Ricardo estimation, 500 fast chargers are needed to support PHEV operation and assumed to be located in the vicinity of I-710. Overnight chargers or depot chargers can be located at fleet sites

Catenary truck TCO is 8-20% higher than PHEV on Alameda St; Catenary infrastructure is underutilized and more expensive

TCO for system of 500 trucks on Alameda Street over 10 years of vehicle ownership



Base scenario: Catenary cost - $5.7 M per mile

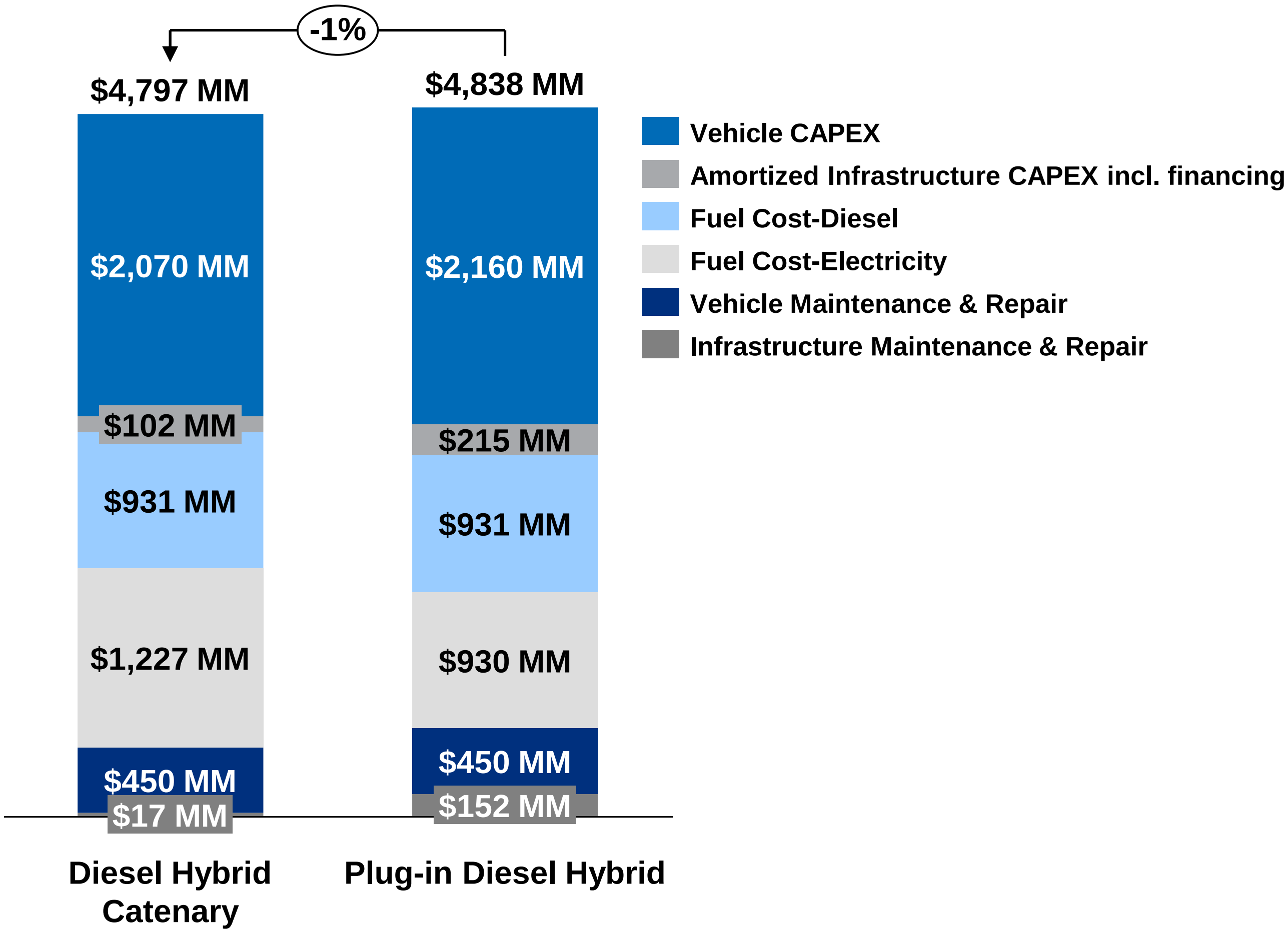
High scenario: Catenary cost - $12 M per mile

A high scenario for catenary infrastructure cost is assumed to capture potentially high cost of construction on Alameda St.

- Plug-in diesel hybrid are more expensive than catenary trucks due to cost of battery pack
- Catenary infrastructure is underutilized for a volume of 500 trucks and is more expensive than charging infrastructure which are sized to meet demands of truck volume
- Miles driven on diesel are same for catenary and plug-in hybrid trucks
- Zero emission miles driven on catenary are 10% more efficient than PHEV as there are no losses in battery. However cost of electricity is higher in catenary due to increased usage during day time peak hours. Plug-in trucks on Alameda St. are assumed to require only overnight charging which keeps electricity rates low
- Maintenance and repair cost for 250 overnight chargers is higher than cost for maintaining catenary infrastructure

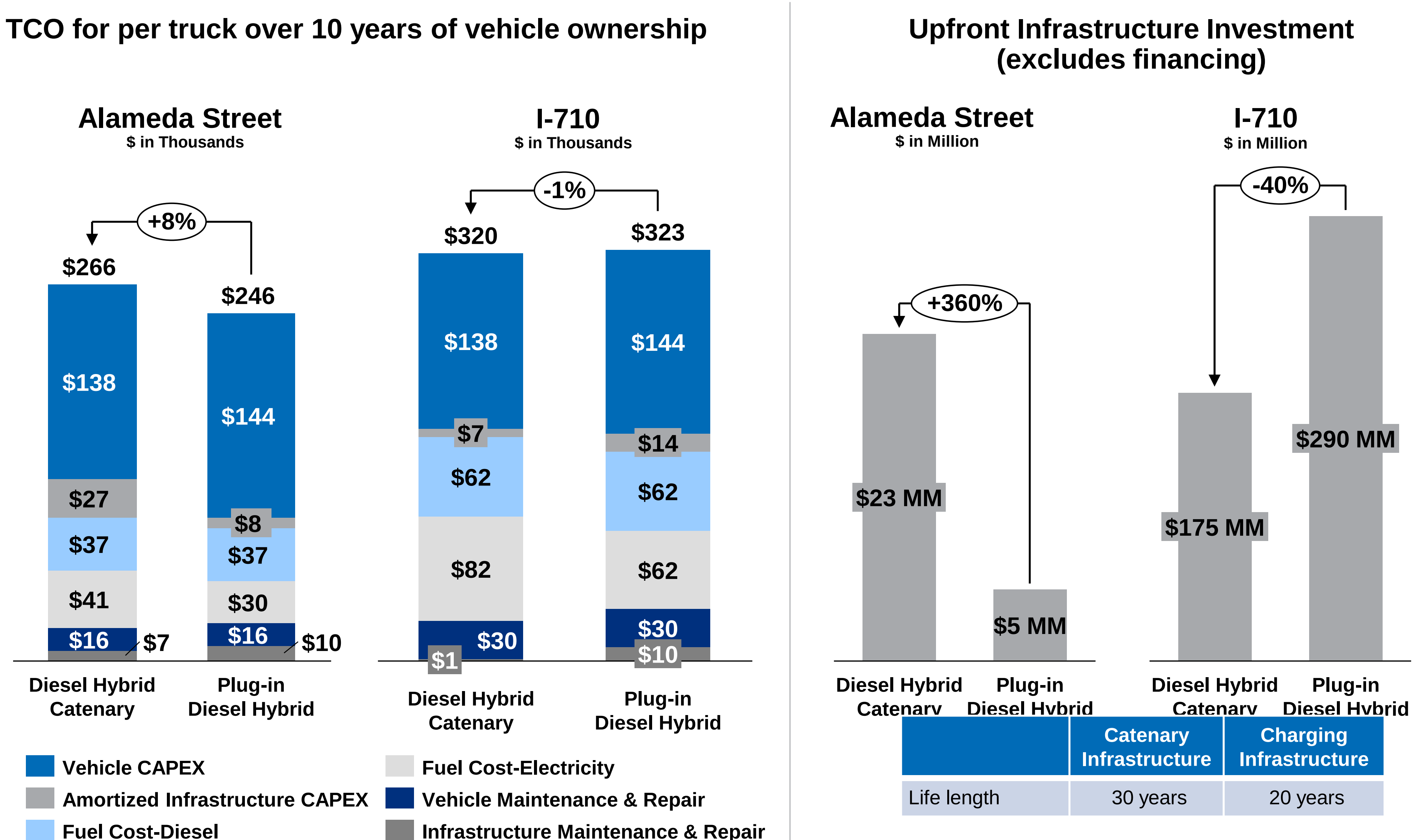
Catenary truck TCO is comparable to PHEV on I-710; Vehicle and catenary CAPEX is more attractive but OPEX is higher than PHEVs

TCO for system of 15,000 trucks on I-710 over 10 years of vehicle ownership



- Plug-in diesel hybrid are more expensive than catenary trucks due to cost of battery pack
- Catenary infrastructure is less expensive than estimated network of 500 fast chargers and 7,500 overnight chargers required for 15,000 trucks
- Miles driven on diesel are same for catenary and plug-in hybrid trucks
- Zero emission miles driven on catenary are 10% more efficient than PHEV as there are no losses in battery. However cost of electricity is higher in catenary due to usage during day time peak hours. Plug-in trucks on I-710 are assumed to require one fast charging event during day followed by overnight charging which mitigates overall electricity rates
- Maintenance and repair cost for 500 fast chargers and 7,500 overnight chargers is significantly higher than cost for maintaining catenary infrastructure

TCO of catenary and PHEV trucks are quite comparable; Overall investment in catenary infrastructure is lower than cost of chargers

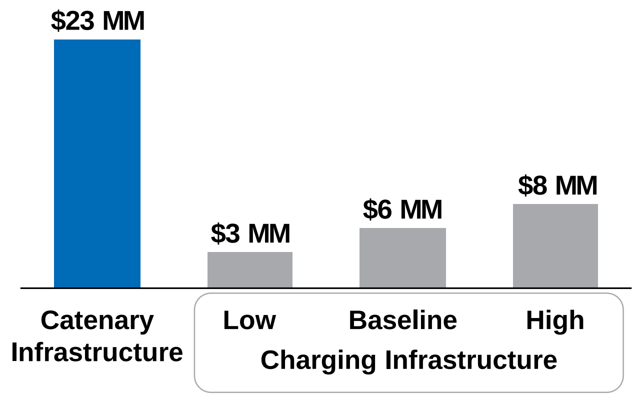


	Catenary Infrastructure	Charging Infrastructure
Life length	30 years	20 years

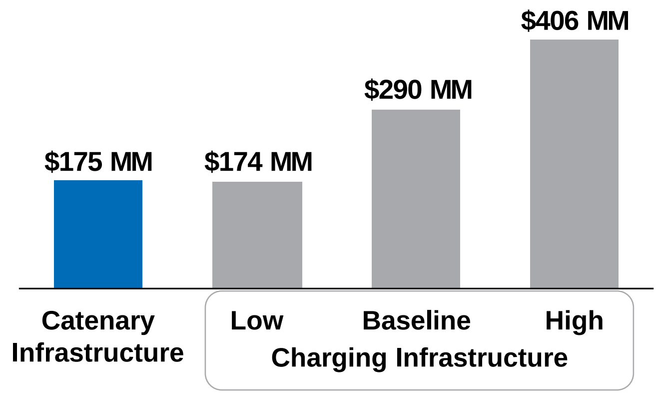
CAPEX for chargers can be competitive with catenary for trucks using I-710, if charger costs can come down to $600/kW by 2025

Sensitivity analysis of charger cost

Infrastructure cost for Alameda Street



Infrastructure cost for I-710

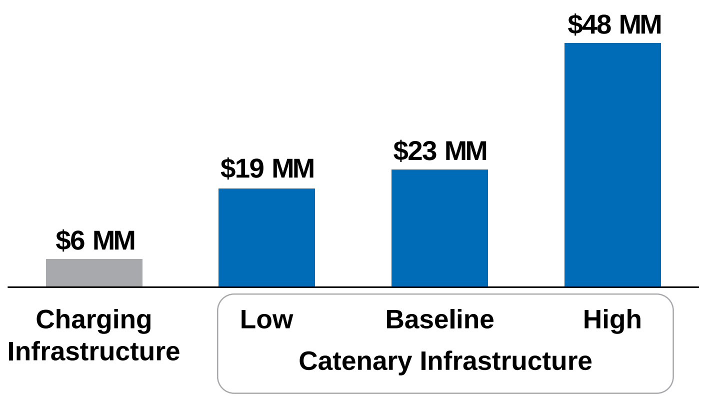


Charger cost $/kW scenario

Low	Baseline	High
$600	$1,000	$1,400

Sensitivity analysis of catenary indirect cost

Infrastructure on Alameda Street



Catenary indirect cost for Alameda Street

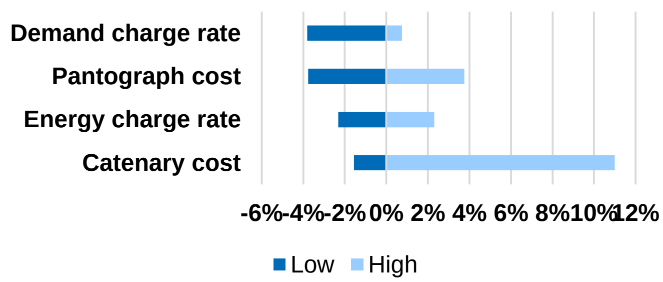
Low	Baseline	High
10% of direct cost	30% of direct cost	172% of direct cost

- Charging Infrastructure cost is already lower than the catenary infrastructure for Alameda St. route
- Based on baseline assumption of $1,000/kW for chargers, the CAPEX is higher than catenary for I-710 route which may be disadvantage from funding perspective
- However, at $600/kW per charger which is in the realm of possibility, CAPEX can be competitive with catenary
- Variations can be expected in indirect costs for catenary infrastructure on Alameda St. but overall catenary infrastructure CAPEX still remains significantly higher than charging infrastructure

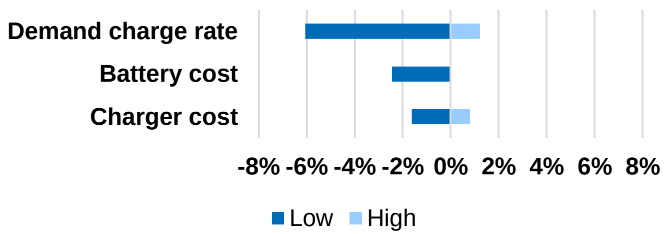
TCO results, in general, show less than 4% variation to large swings in key parameters and hence not very sensitive to assumed values

% change in TCO as a result of variation in key parameters

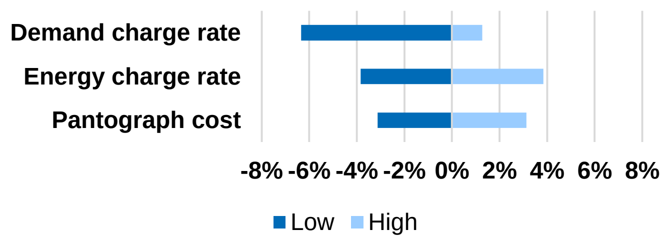
Catenary on Alameda Street



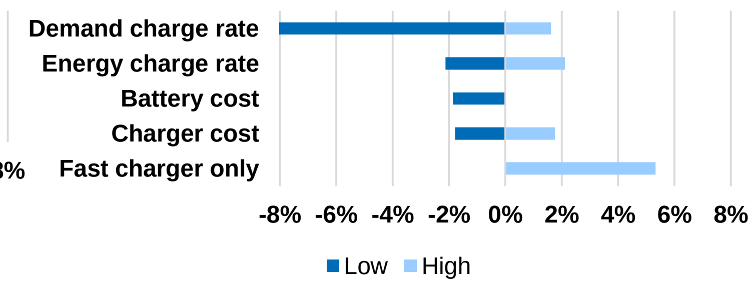
PHEV on Alameda Street



Catenary on I-710



PHEV on I-710



Sensitivity analysis list

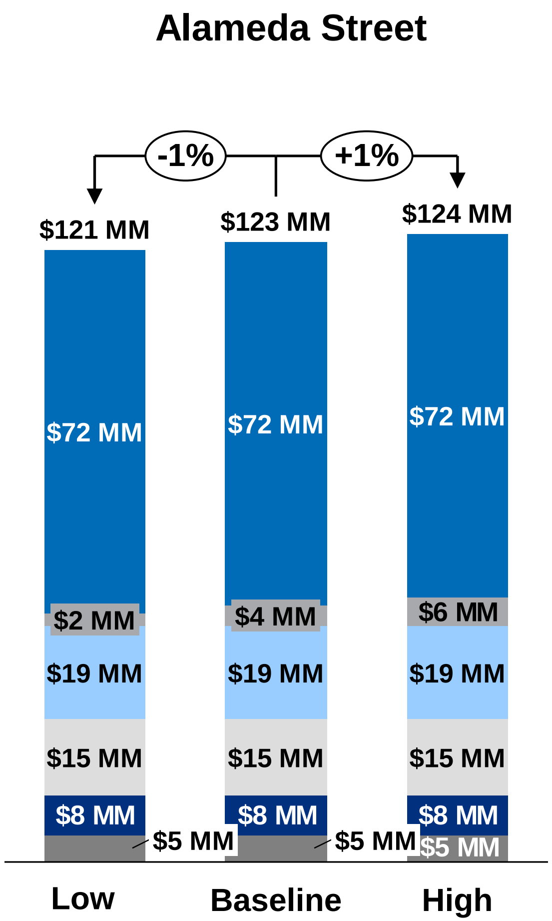
Sensitivity Analysis	Low	Baseline	High
Charger cost $/kW	600	1000	1400
Pantograph cost $ per truck	10000	20000	30000
Battery cost $/kWh	150	200	NA
Catenary indirect cost	10% of direct cost	30% of direct cost	172% of direct cost
Fast charger	NA	Fast charger + Overnight charger	Fast charger only
Average energy charge rate $/kWh	0.11	0.14	0.16
Demand charge rate $/kW	0	11	14

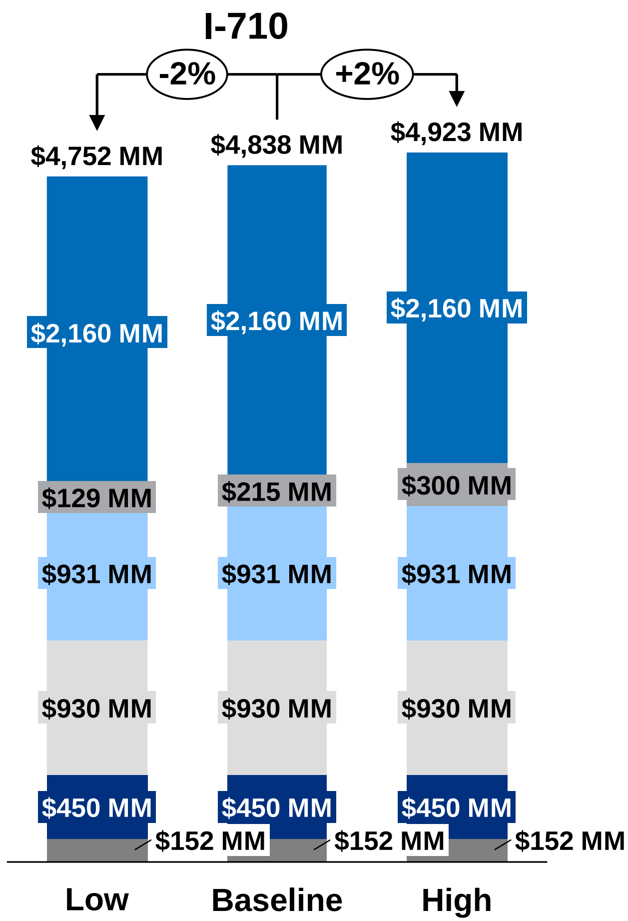
- Elimination of demand charge rate has appreciable impact on TCO of both Catenary and PHEV truck but does not change the business case. Overall TCO still remains comparable
- Catenary infrastructure cost high scenario increases TCO on Alameda Street of Catenary truck by 11%, but in the base scenario, Catenary infrastructure cost is already significantly higher than charging infrastructure

Contents

40% swing in charger cost results in 1% to 2 % change in TCO suggesting that impact on TCO is not significant

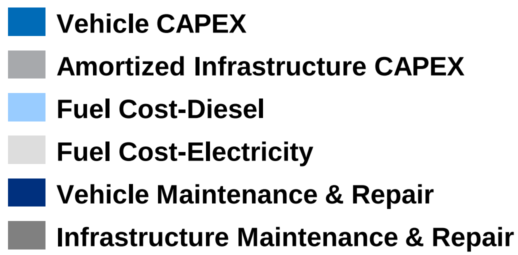
TCO sensitivity analysis on charger cost for PHEV





Charger cost $/kW

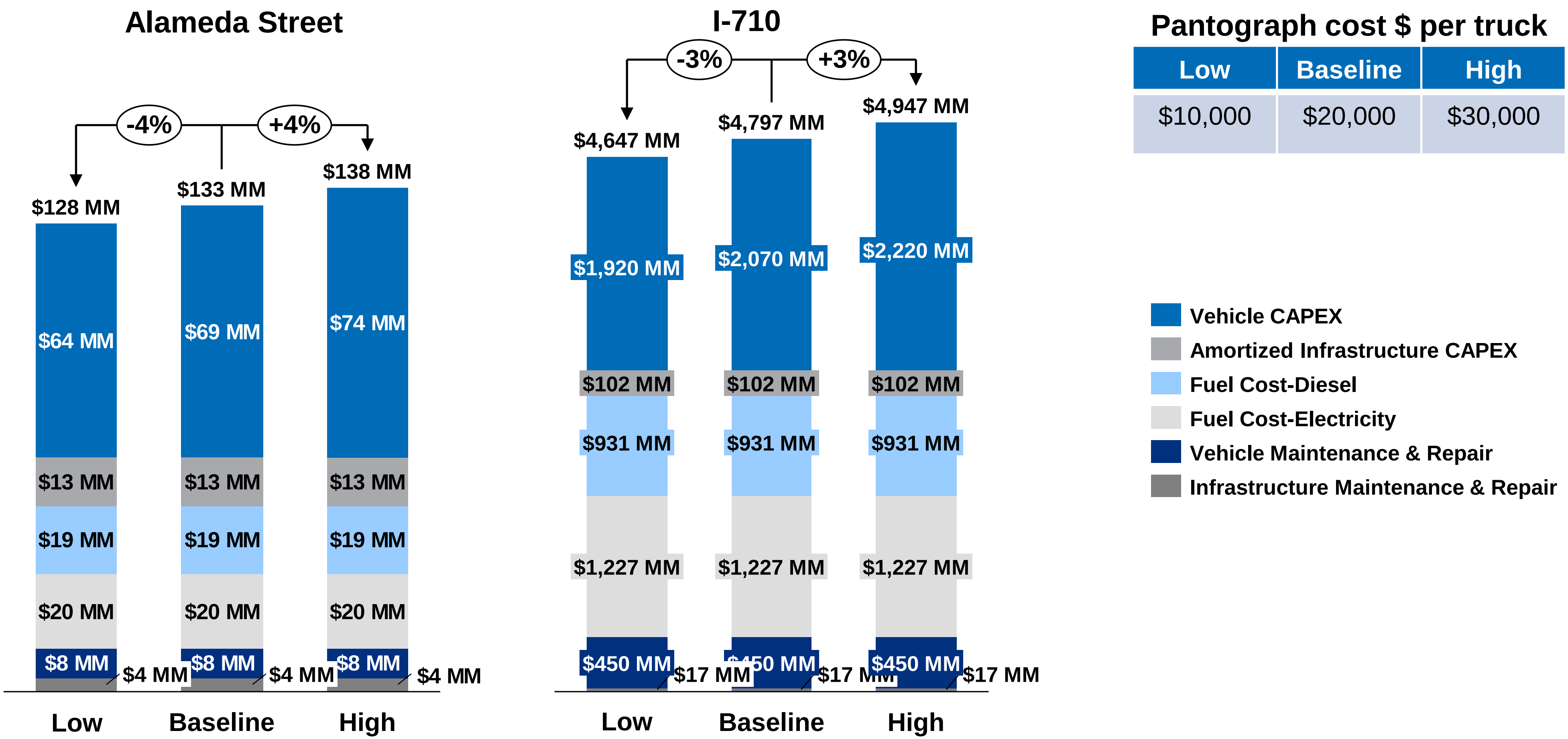
Low	Baseline	High
$600	$1,000	$1,400



- Level II AC charger costs have been declining due to increase in demand from light-duty segment. There is potential for DC fast charger costs to decline too as volume goes up and $600/KW installed cost may be feasible
- Study on charger cost roadmap can provide further insights on future infrastructure investment needs and comparison with catenary

Pantograph accounts for small proportion of catenary truck cost; Hence 50% change in pantograph cost varies TCO by 3% to 4% only

TCO sensitivity analysis on pantograph cost for catenary truck



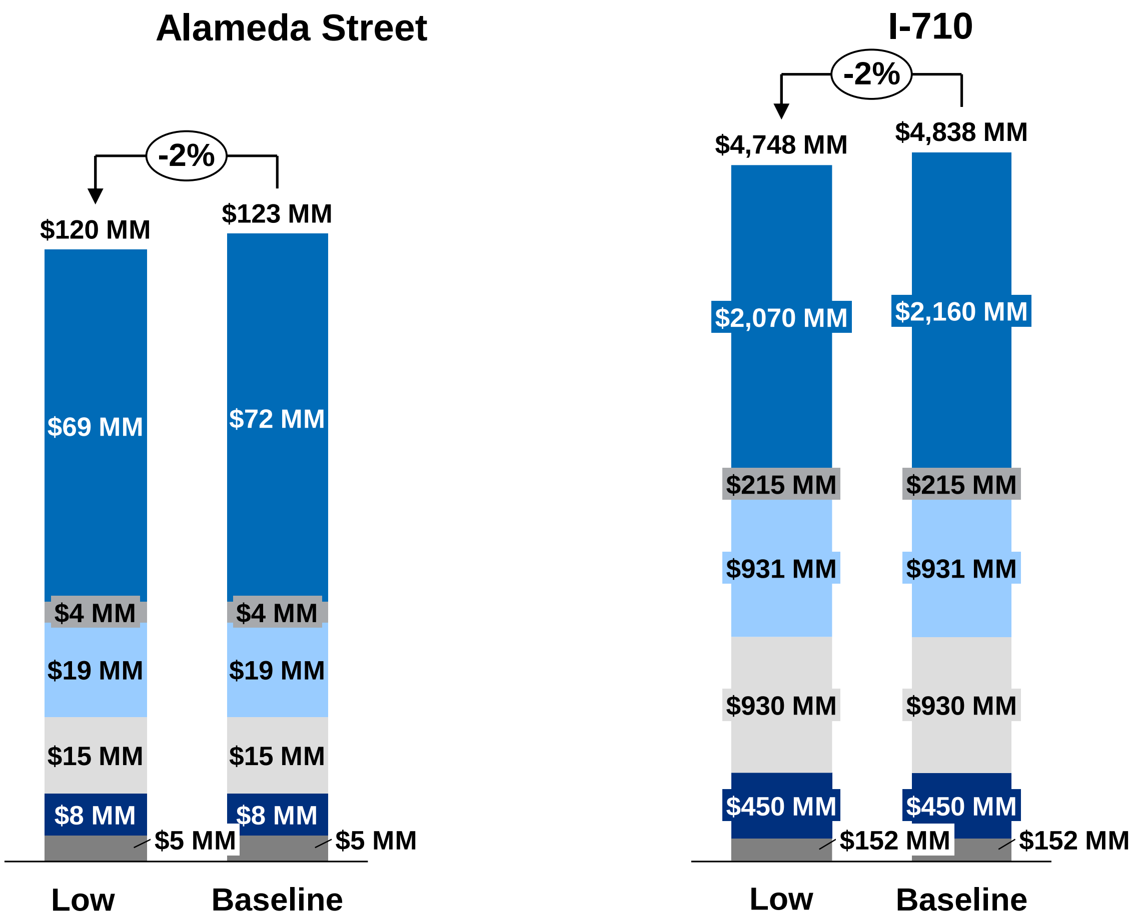
Pantograph cost $ per truck

Low	Baseline	High
$10,000	$20,000	$30,000

- Although vehicle CAPEX constitutes a high percentage of TCO, pantograph only accounts ~8% of total vehicle cost
- Even though impact on TCO is not appreciable, $10,000 different vehicle cost can impact purchase decision of fleet operators

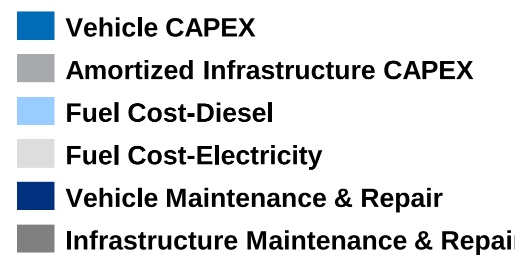
Reduction in battery cost from $200 /kWh to $150 /kWh brings the PHEV cost at par with catenary truck; TCO changes by 2%

TCO sensitivity analysis on battery cost



Battery cost $/kWh

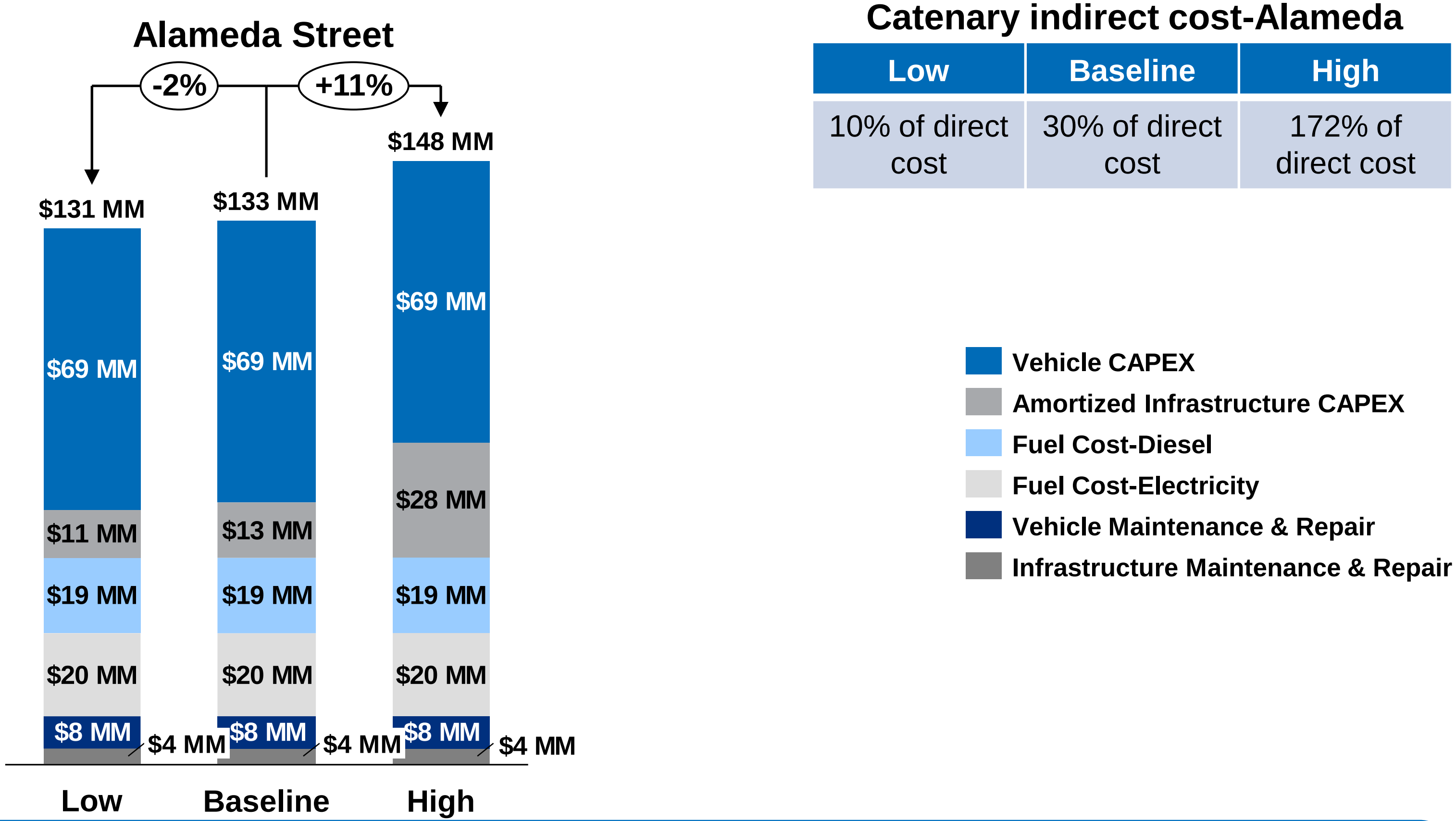
Low	Baseline	High
$150	$200	NA



- Automotive battery price projections for 2025 are aggressive but Ricardo has assumed that prices will continue to be relatively higher for heavy-duty industry due to lower demand. Baseline battery cost of $200/kWh is based on Ricardo’s adoption model
- However, OEMs in both light duty and heavy duty markets can achieve lower battery prices. Hence, a scenario with $150/kWh is considered

Construction of catenary infrastructure on Alameda St. presents higher degree of uncertainty in costs; TCO varies by 2% to 11%

TCO sensitivity analysis on catenary indirect cost



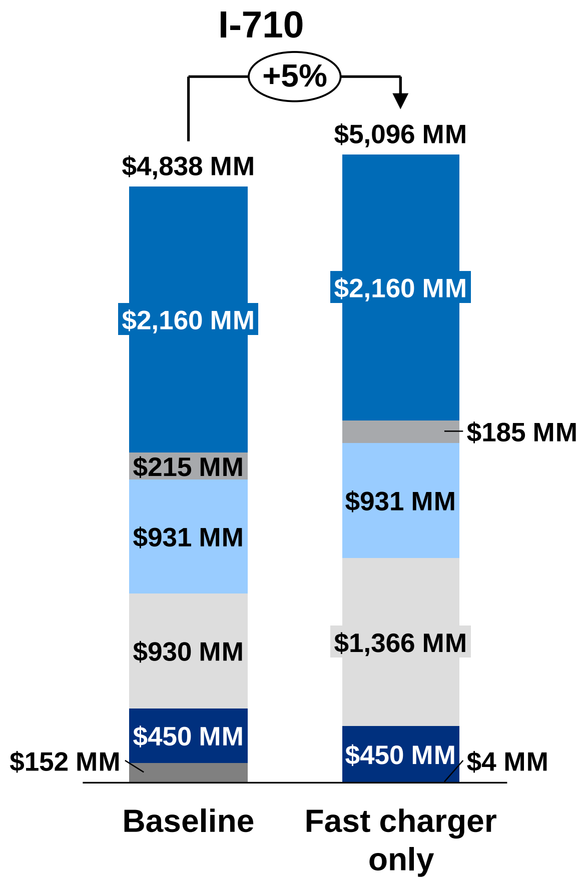
Catenary indirect cost-Alameda

Low	Baseline	High
10% of direct cost	30% of direct cost	172% of direct cost

- Indirect costs for the baseline scenario assumes 10% of direct cost for project management cost and 20% for contingency.
- However, catenary construction at Alameda street may also have potential costs such as viaduct elevation, safety adjustment, compensation for Electromagnetic Compatibility issue, etc. The high cost scenario includes these potential costs in the form of a higher contingency
- Low indirect cost scenario assume no contingency cost.

Charging infrastructure comprising of only fast chargers increases TCO; Use of overnight chargers has economic benefits

TCO sensitivity analysis on fast charger numbers



Fast charger or Overnight charger

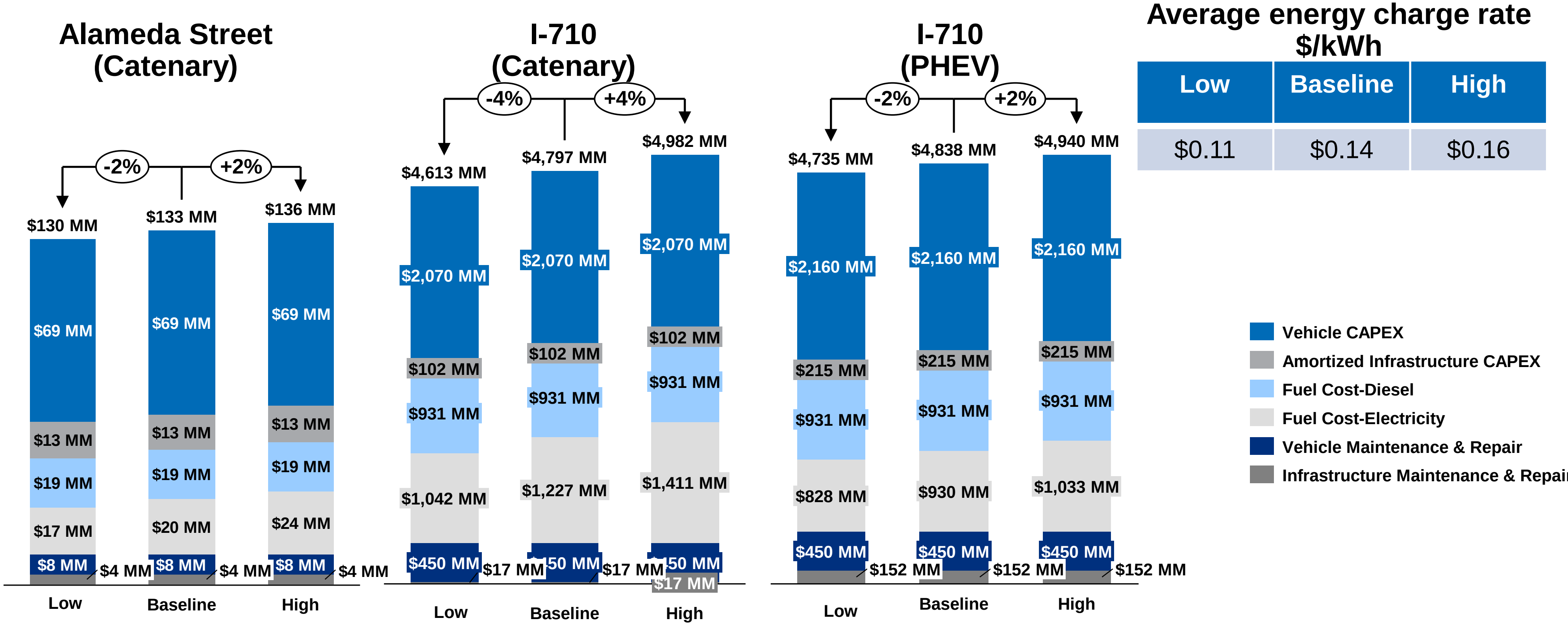
Baseline	Fast charger only
Fast charger + Overnight charger	Fast charger only

- Vehicle CAPEX
- Amortized Infrastructure CAPEX
- Fuel Cost-Diesel
- Fuel Cost-Electricity
- Vehicle Maintenance & Repair
- Infrastructure Maintenance & Repair

- Fast chargers incur higher electricity rates due to day time use (peak periods) and demand charges and hence have higher cost of operation compared to overnight chargers

20% variation on energy charge rate affects TCO by 2% to 4%; Impact is slightly greater on Catenary due to higher day time use

TCO sensitivity analysis on energy charge component of electricity rate



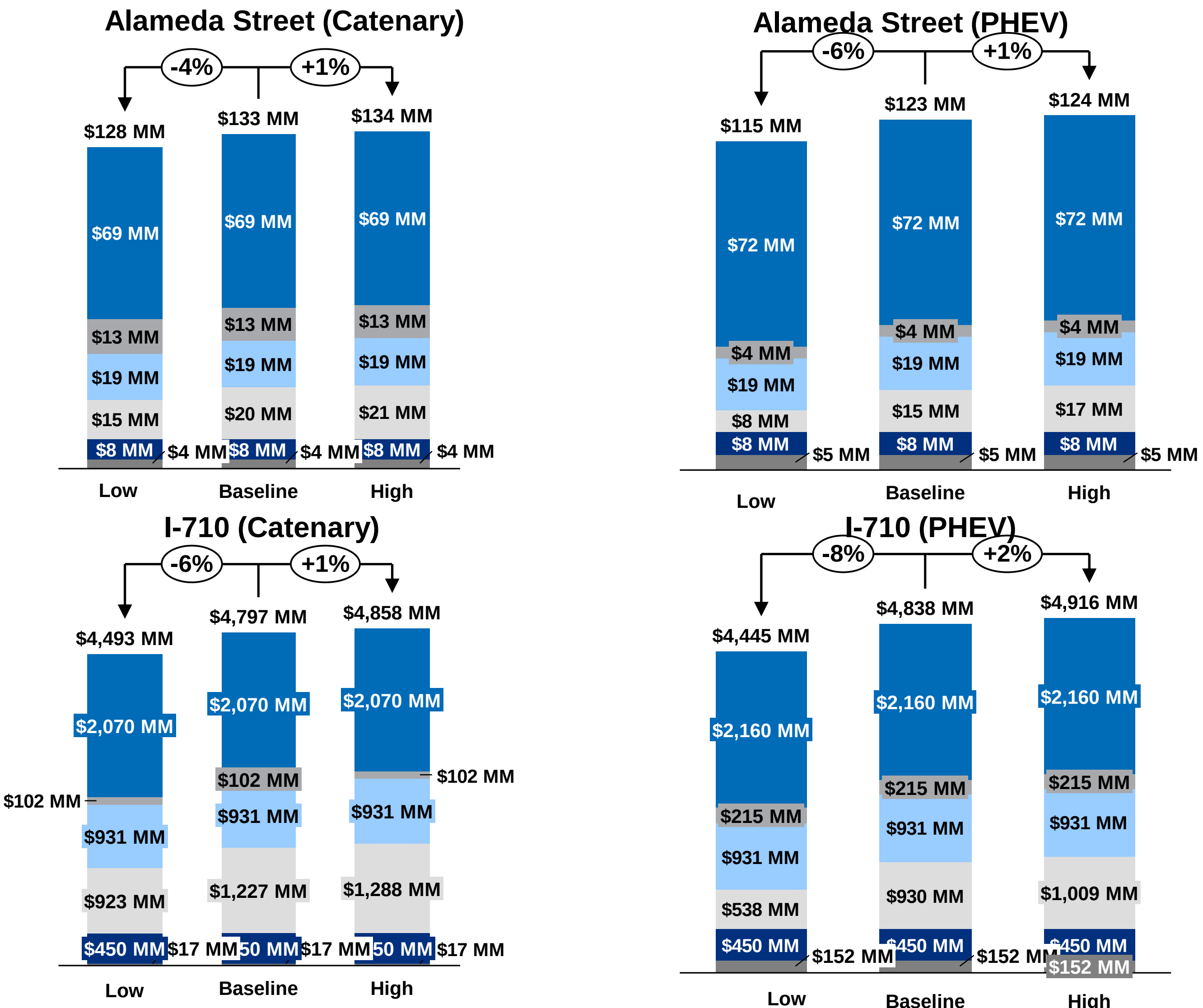
Average energy charge rate $/kWh

Low	Baseline	High
$0.11	$0.14	$0.16

- Average energy charge rate is a weighted-average rate based on traffic distribution during peak-hours and off-peak hours. In this study, the average energy charge rate only applies to power draw from catenary and fast chargers
- Average energy rates do not apply to overnight chargers as they operate during off-peak hours only
- Baseline energy charge rate is calculated on SCE's proposed electricity cost schedule: TOU-EV-9 (From 2 kV to 50 kV). According to SCE' s varied schedules, energy charge rates increase when power requirements (kW and kV) decrease. To reflect the impact from different schedules, Ricardo used a 20% higher rate in high case and a 20% lower rate in low case

Elimination of demand charge reduces TCO by 4% to 8%; Impact is slightly greater on PHEV trucks but TCO remains comparable

TCO sensitivity analysis on pantograph cost for catenary truck



Demand charge rate $/kW

Low	Baseline	High
$0	$11	$14

- Vehicle CAPEX
- Amortized Infrastructure CAPEX
- Fuel Cost-Diesel
- Fuel Cost-Electricity
- Vehicle Maintenance & Repair
- Infrastructure Maintenance & Repair

- Both catenary and plug-in hybrid trucks in the study present a requirement for continuous high power
- Hence there is a possibility that continuous demand from large scale electrification of drayage trucks will not incur demand charges which is reflected in the "low" scenario
- Demand charge costs is a smaller percentage of total electricity cost compared to energy charge for both catenary and PHEV trucks

Contents

The business case has been studied based on electrification of 15,000 trucks on I-710 and 500 trucks on Alameda Street in 2025

Drayage Truck Volume utilizing Alameda St. and I-710

Number of Trucks in system

Sources	Alameda Street	I-710
Siemens	500 (projected in 2021 by Siemens)	14,000 (projected in 2031 by Siemens)
LA Metro	NA	15,000-24,000 (SR-91 to port, projected in 2035)
Gladstein, Neandross & Associates (GNA)	300 (Drayage Truck volume at ICTF in 2012)	9,500 (Actual volume in 2012) 22,000 (projected during 2020-2030)
Ricardo Assumption (in 2025)	**500**	**15,000**

The study assumes catenary length of 4 miles on Alameda Street and 19 miles on I-710

Duty Cycle

Ricardo Assumptions

	Alameda St.	I-710
Catenary length	**4 miles**	**19 miles**
One-way distance	8 miles	30 miles
# of round-trips per day	4	2
Distance per day	64 miles	120 miles

I-710 Project Zero-Emission Truck Commercialization Study

Key Performance Parameter	Baseline Values
Daily Range	Up to 200 miles.
Distance per trip	40 miles, for example from the ports to the Inland Empire.
Number of turns per day	3 is typical, 4-5 on a good day
Refueling interval	Baseline 2-4 days for diesel, daily for LNG. Varies greatly on number of turns daily and the container destinations.
Fuel economy	4.5-5.5 MPG is typical; some new trucks up to 8 MPG.
Range per tank of diesel	400 miles typical for diesel trucks
Availability of refueling infrastructure	On-site refueling is best, either through depot fueling infrastructure or a contractor traveling to the yard to fill up the trucks. Otherwise centralized infrastructure is important.

Source CALSTART.

Previous Ricardo studies show that one-way distances vary between 5 to 60 miles depending on route

Duty Cycle	One-way Distance
Near-Dock (between Port and nearby intermodal facility)	5-6 miles
Local (between downtown LA rail yards and distribution centers)	8-10 miles
Regional (to Inland Empire distribution warehouses)	45-60 miles

Source: Siemens Assumptions, CALSTART, Ricardo Analysis

Diesel mild hybrid catenary truck is selected for analysis due to low vehicle price compared to full electric or series hybrids

Overheard catenary powered port truck configurations in US

Selected configuration for analysis

Base Vehicle:	Mack Pinnacle Daycab
Vehicle Modification by:	Volvo Group
In Operation since:	2017
Vehicle Length:	8,5 m
Vehicle Weight:	9,1 t
Gross Vehicle Weight:	40 t
Drive System:	Parallel Hybrid
Power Electric Machine:	120 kW
Type of Energy Storage:	Battery
Capacity of Energy Storage:	1,2 kWh
Range from On-board Energy Storage:	1-4 km
Type of Pantograph:	Active Pantograph (2nd Gen.)

Diesel Hybrid Catenary Truck

Base Vehicle:	Navistar International Prostar
Vehicle Modification by:	Transportation Power Inc.
In Operation since:	2017
Vehicle Length:	8,4 m (20,50 m incl. trailer)
Vehicle Weight:	10,7 t
Gross Vehicle Weight:	40 t
Drive System:	Serial Hybrid
Power Electric Machine:	300 kW
Type of Energy Storage:	Battery + CNG
Capacity of Energy Storage:	115kWh
Range from On-board Energy Storage:	160-305km
Type of Pantograph:	Active Pantograph (2nd Gen.)

CNG Series Hybrid Catenary Truck

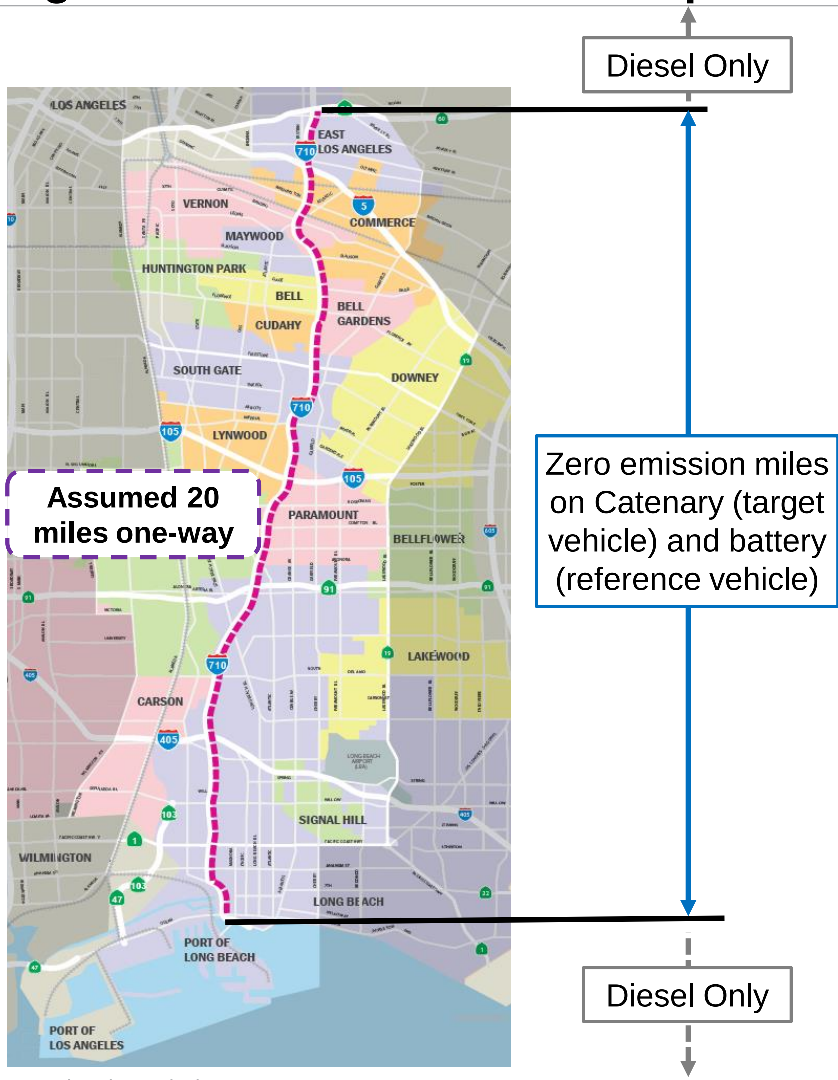
Base Vehicle:	Navistar International Prostar
Vehicle Modification by:	Transportation Power Inc.
In Operation since:	2017
Vehicle Length:	8,4 m (20,50 m incl. trailer)
Vehicle Weight:	9,8 t
Gross Vehicle Weight:	40 t
Drive System:	Full Electric
Power Electric Machine:	300 kW
Type of Energy Storage:	Battery
Capacity of Energy Storage:	115 kWh
Range from On-board Energy Storage:	65-130 km
Type of Pantograph:	Active Pantograph (2nd Gen.)

Full Electric Catenary Truck

Source: Siemens

The study compares Diesel-Catenary drayage truck with a Diesel plug-in hybrid with similar zero emission operation capability

Target and Reference Vehicle Specs



All trucks must be “Full Service” trucks and should be able to serve both I-710 and Alameda St.
Vehicle specs are based on I-710 duty cycle as it is the more demanding duty cycle

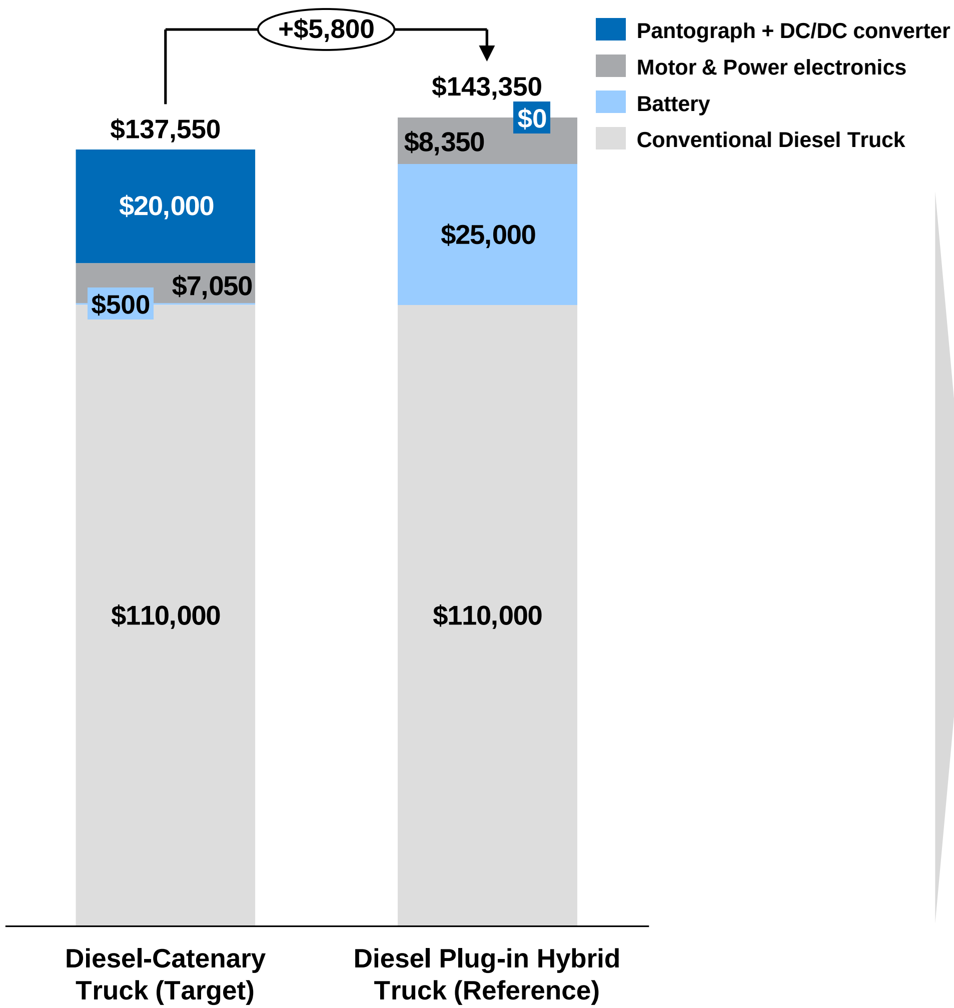
Key Specifications of Target & Reference Trucks for I-710

Parameters	Target Vehicle (Diesel Hybrid Catenary)	Reference Vehicle (Plug-in Diesel Hybrid)
Battery Energy	2.5 kWh	125 kWh (spec’d for power & range)
Electric Range	20 miles each way on Catenary	One round trip with zero emission operation on I-710 on single charge
Motor Peak Power	300 kW	
Engine	11L 405 HP Diesel	
Fuel Tank	75 Gallons	
Diesel Range	400+ miles	

Source: Ricardo Analysis

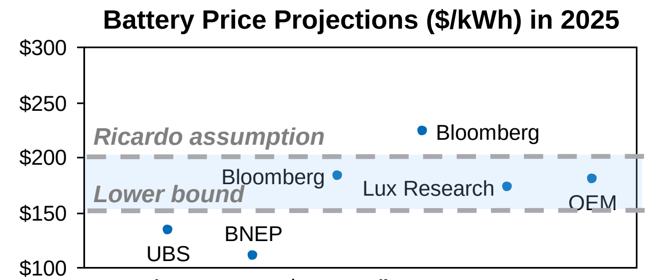
Battery and pantograph are the highest cost differentiators between Catenary and PHEV trucks; Catenary estimated to be $5,800 cheaper

Target and Reference Vehicle Cost



- Vehicle costs are build up of baseline diesel truck and hybrid or catenary components
- Hybrid components and pantograph costs based on high production volume in 2025
  - Battery Pack: $200/kWh

(Based on Ricardo advanced technology commercial vehicle adoption rate model). Automotive battery prices projections by 2025 are very aggressive but it is assumed that prices for HD truck industry will remain somewhat higher due to lower demand than automotive



  - Motor/Inverter: $ 23.5/kW
  - Pantograph: $20,000

Pantograph + DC/DC converter cost	
High volume (15,000+ vehicles)	**$ 20,000**
Low volume (500 vehicles)	$ 50,000

Ricardo assumes both Alameda and I-710 start operation in 2025. Vehicle volume is 15,500 in total. Thus, pantograph cost is based on high production volume at $20,000 for both locations

Source: Ricardo Analysis

Ricardo has estimated $5.7 MM per mile overhead catenary infrastructure cost for Alameda St. and $9.1 MM per mile for I-710

RICARDO

Catenary Infrastructure Cost

Catenary infrastructure cost per mile

Cost types	Scientific Advisory BMVI Report	Ricardo estimations		Confidential quote to SCAQMD
		Alameda St	I-710	
Direct cost	**$4 million**	**$4.4 million**	**$7.6 million**	**$4.7 million**
Indirect Cost	**$0.4 million (10% of investment costs)**	**$1.3 million (30% of investment costs)**	**$1.5 million (20% of investment costs)**	**$8.1 million (172% of investment costs)**
Total	**$4.4 million**	**$5.7 million**	**$9.1 million**	**$12.8 million**

Confidential quote

Direct Cost Assumptions

Direct cost components	Scientific Advisory BMVI Report		Ricardo estimations	
	Assumptions	Cost	Assumptions	Cost
Grid connection point	**3 km distance** between connection points	$9,817	**3 km distance** between connection points	$16,360
Feed line	Trench in underground, built up area; one 20-60 KV cable;	$490,849	Two 10 kV cables	$736,273
Substation	**6 MW** power rating; **3 km distance** between substations	$1,178,037	I-710 – 10 substations (22.5 MW each) Alameda St. - 2 substations (3 MW each)	$4,326,789 (I-710) $1,178,037 (Alameda)
Poles	**50 m distance** between poles; **64** poles per mile	$785,358	**50 m** distance between poles	$785,357
Catenary	Both directions	$1,178,037	Both directions	$1,295,840
Guard rails	Required by regulation	$392,679		$392,678
Direct cost		**$4 million**		**$4.4 million (Alameda)** **$7.6 million (I-710)**

Catenary Power Requirement during peak traffic

I-710	2 x (2.25 kWh/mile x 80 miles / day x 15,000 trucks) / 24 hours = **225 MW**
Alameda Street	2 x (2.25 kWh/mile x 40 miles / day x 500 trucks) / 24 hours = **3.75 MW**

Assumption: Peak traffic and hence peak power requirement is 2 times the 24 hour average (Source: https://ops.fhwa.dot.gov/publications/fhwahop09014/sect2.htm)

Source: Study within the framework of the Scientific Advisory BMVI for mobility and fuel strategy, Siemens Assumption, Ricardo Analysis

500 fast chargers and 7,500 overnight chargers estimated for trucks using I-710; only 250 overnight chargers for trucks on Alameda St.

PHEV Truck Charging Requirement on Alameda St. and I-710

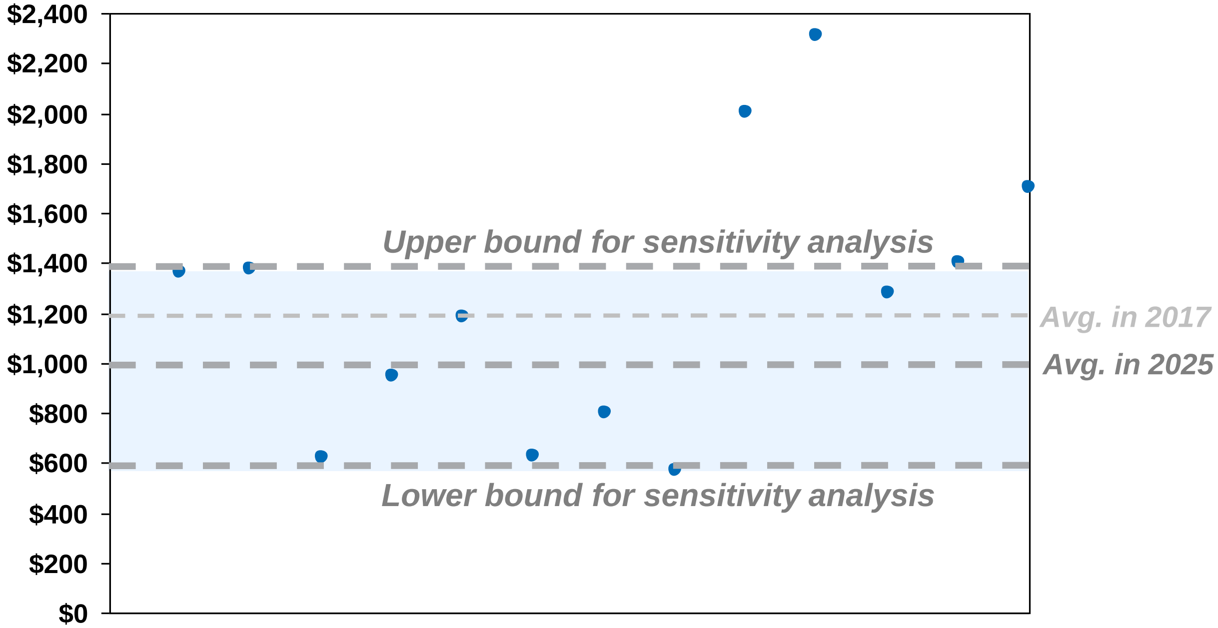
		Alameda St.	I-710
Number of Trucks in system		500	15,000
Number of round-trips		4	2
Fast charging	Number of fast charging events per day	Fast Charger not needed	15,000
	Fast Charger kW (24 min charging @ 2 C rate)		250 kW
	Number of fast chargers		**500** (Assuming traffic in peak hours is twice as average traffic in a 24 hour window)
	Max. System Power Draw		125 MW
Overnight charging	Number of overnight charging events per day	500	15,000
	Charger kW (5 hrs charging)	22 kW	22 kW
	Number of overnight chargers	**250** (One overnight charger per 2 trucks)	**7,500** (One overnight charger per 2 trucks)
	Max. System Power Draw	5.5 MW	165 MW

Source: Ricardo Analysis

Installed cost of charging infrastructure varies significantly; Avg. cost of $1,000/kW assumed by 2025 based on several data points

Charger Cost

Current cost of chargers ranging from 20 kW to 300 kW normalized to $/kW
(includes charging unit and installation)



Assumed installed costs in 2025

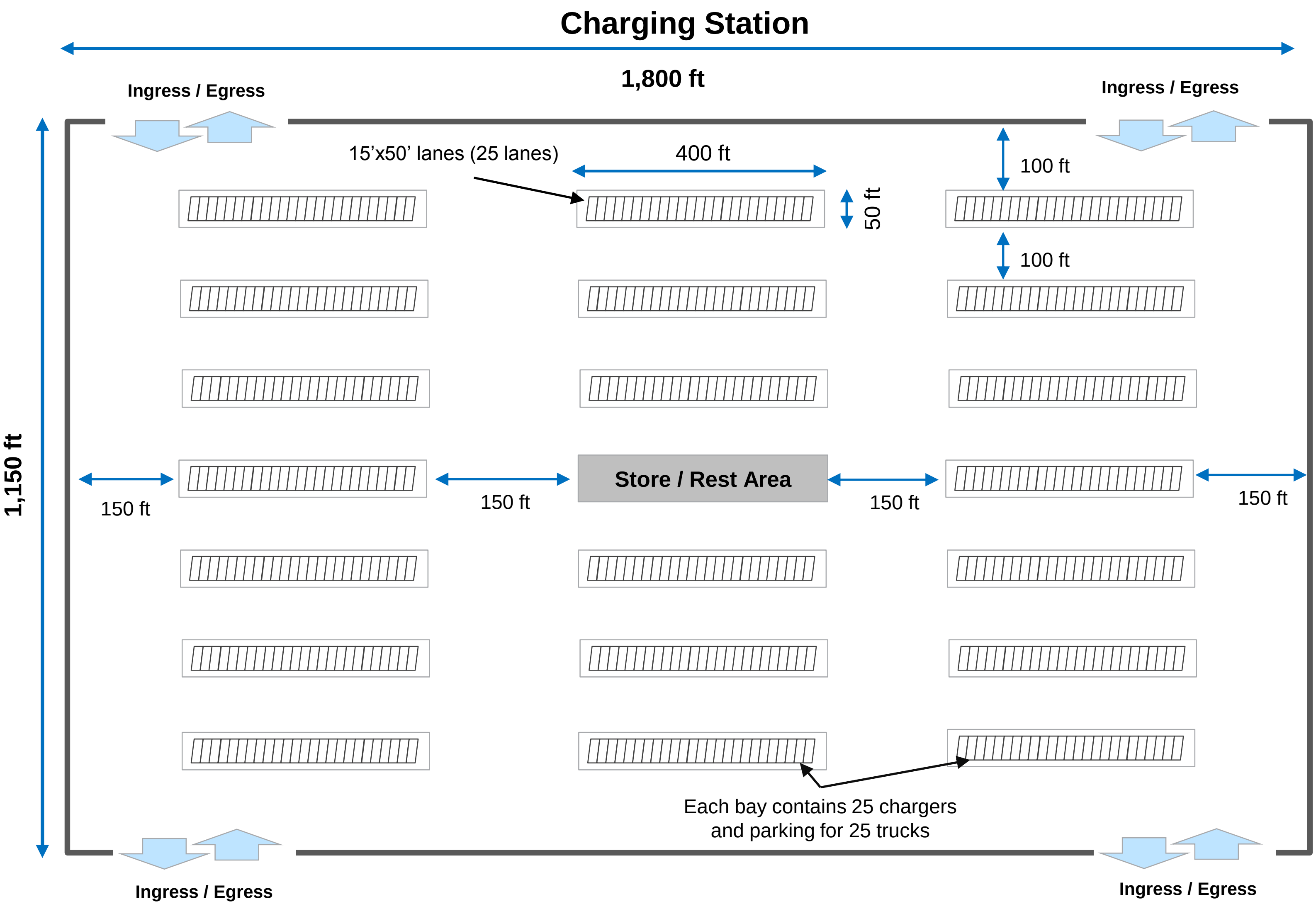
250 kW DC Fast Charger	22 kW Overnight Slow Charger
$250,000	$22,000

- Level II charger costs have been declining due to increase in demand from light-duty segment
- There is potential for depot and fast charger costs to decline too as volume goes up in future. Although cost of charger units are typically less than cost of installation, large scale deployment can also help reduce cost of installation.
- Hence, it is assumed that average cost can come down by $200/kW by 2025

Source: Ricardo Analysis

Installation of all 500 fast charger units within a single facility is estimated to require a footprint of 1,800 ft. x 1,150 ft.

Truck flow patterns and best locations for fast charge around I-710 as well as real estate costs are not in scope of this study



Source: Ricardo Analysis

Dimensions not to scale

- Fast chargers can be distributed across different locations or can be within one facility in the vicinity of I-710
- The footprint has been estimated for just one of the possible layouts
- The actual footprint of chargers is less than 6 x 6 feet and of less consequence
- Footprint requirements is based on number of parking spaces and space to manage ingress, egress and navigation of several trucks
- Possible siting and layout of DC fast charging infrastructure needs to be studied further

Contents

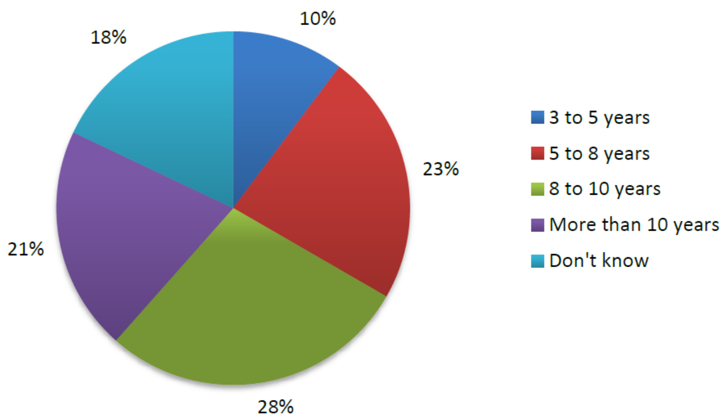
TCO estimated over 10 years of ownership with no residual value; 30 years life for catenary infrastructure and 20 years for chargers

Ownership life and operation time

I-710 Project Zero-Emission Truck Commercialization Study

Vehicle life	10 yrs.
Days in operation per year	250 days/year
Total daily range	100 miles
Electric vehicle energy consumption	2.50 kWh/mile

Drayage Truck Vehicle Life



Source: CALSTART, 2013

Ricardo Assumptions

OPEX Parameters	Assumptions
Vehicle Ownership length	10 years
Catenary infrastructure life length	30 years
Charger life length	20 years
Operation days per year	250 days

Annual maintenance cost for catenary infrastructure is $90,250/mile
Annual cost for fast and overnight chargers are $2,000 and $420

RICARDO

Infrastructure Maintenance cost

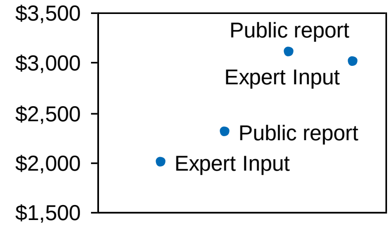
Catenary infrastructure maintenance cost

Siemens assumptions		Ricardo estimations
Alameda St	I-710	
2% of investment	2% of investment	**$90,250** per mile
$114,518 per mile	$171,679 per mile	

Ricardo assumption on maintenance schedule

Maintenance Components	# of action per year	Cost
Inspection catenary system	1	$ 5,000
Re-tensioning catenary system	1	$ 10,000
Replacement overhead wires	1	$ 30,000
Replacement of load carry wire	1	$ 4,000
Replacement isolators catenary system	0.05	$ 833
Replacement load baring arms of the catenary system	0.03	$ 3,333
Revision of substation	0.0001	$ 5,000
Incidental cost	1	$ 2,000
Indirect cost of maintenance activities	50% of direct cost	
Total cost per mile	**$ 90,250**	

250 kW DC fast charger maintenance costs



Key Maintenance Events
Replacement of liquid cooled charging cables (Can cost $3,000 - $4,000 a piece today)
Filtration cleaning every 3 to 6 months depending on operating environment
Regular inspection every 2 years and torque down all high power connections
Manual resets for software malfunction

Assumed Maintenance Cost (2025 and beyond)

$2,000 per year

22 kW overnight charger maintenance costs

Key Maintenance Events
Regular inspection and replacement of cables
No cooling fans and hence no need for filtration replacement or cleaning
Few power electronics compared to DC fast charger

Assumed Maintenance Cost (2025 and beyond)

$420 per year

Source: Expert Interviews, Take Charge: A Roadmap to Electric New York City Taxis, Siemens analysis, Ricardo analysis, Costs Associated With Non-Residential Electric Vehicle Supply Equipment

Ricardo's assumption of 6 mpg for Alameda St. and I-710 in diesel mode aligns with other studies

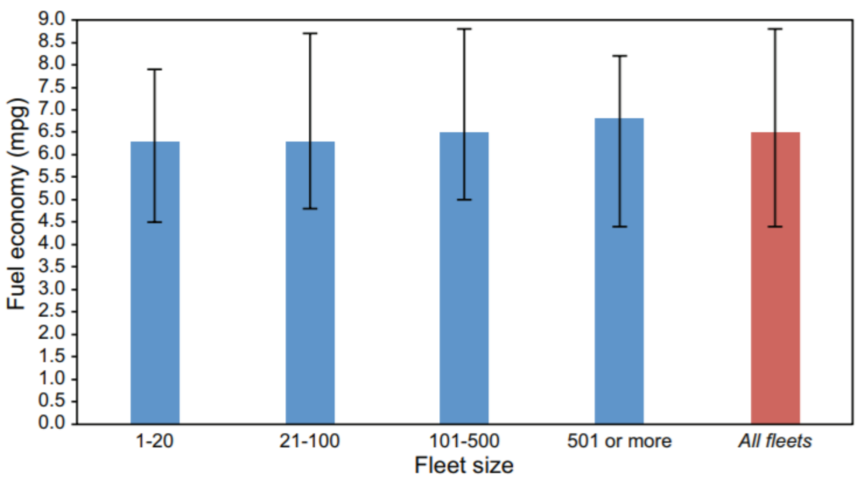
Fuel consumption

Fuel economy for trucks

Key Performance Parameter	Baseline Values
Daily Range	Up to 200 miles.
Distance per-trip	40 mi, for example from the ports to the Inland Empire.
Number of turns per day	3 is typical, 4-5 on a good day
Refueling interval	Baseline 2-4 days for diesel, daily for LNG. Varies greatly on number of turns daily and the container destinations.
Fuel economy	4.5-5.5 MPG is typical; some new trucks up to 8 MPG.

Source: CALSTART, 2013

Heavy-duty truck fleet fuel economy



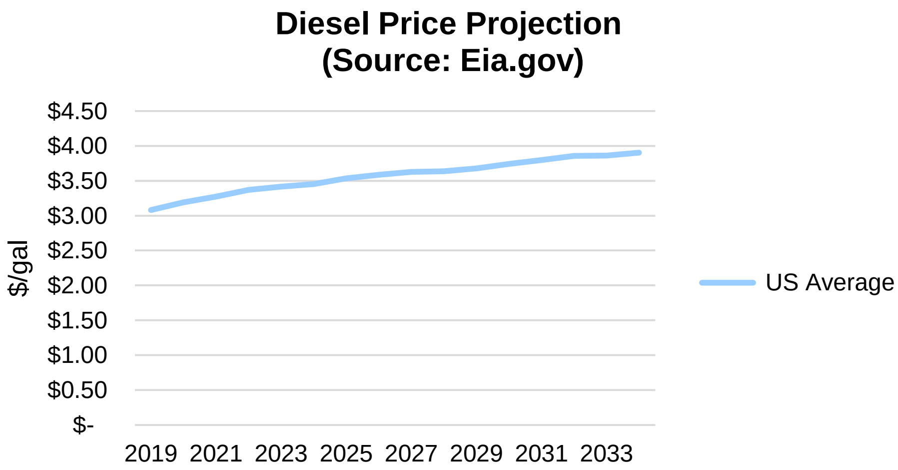
Source: American Transportation Research Institute, The University of Michigan, 2016

Ricardo Assumptions

	Alameda St. Phase 2	I-710
Fuel Economy in Diesel Mode	6 mpg	6 mpg

Diesel cost is estimated based on EIA projection; diesel price is projected to grow steadily

Fuel price projection



Diesel:
Ricardo used EIA projections on diesel cost during the vehicle ownership length

Source: EIA, 2018

Electricity cost is build up of energy charges, demand charges and customer charges; Rates assumed to be flat during ownership

Electricity demand charges

Ricardo Assumptions

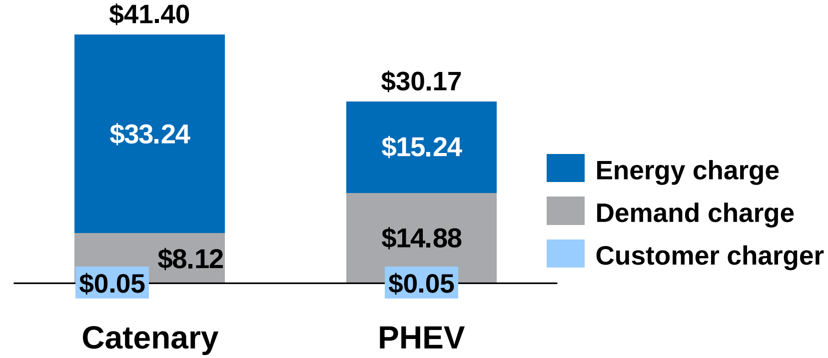
	Assumptions			
	Catenary Truck		Plug-in Hybrid Truck	
	Alameda St.	I-710	Alameda St.	I-710
Energy charges	On-Peak and Mid-Peak rates	On-Peak and Mid-Peak rates	Off-Peak rates	Off-Peak rates (Overnight charger) On-Peak and Mid-Peak rates (Fast charger)
Demand charges	Peak demand: 3.7 MW	Peak demand: 225 MW	Peak demand: 5.5 MW	165 MW (overnight charger) 125 MW (fast charger)
Customer charges	1 account	1 account	1 account	100 accounts (Overnight charger) 1 account (Fast charger)

Electricity rates (TOU-EV-9)

Charge Types		Total Rate
Energy Charge - $/kWh		
	Summer Season (average)	0.18
	Winter Season (average)	0.12
Facilities Related-Demand Charge - $/kW of Billing Demand/Meter/Month		
		11.27
Customer Charge - $/Meter/Month		
		212.25

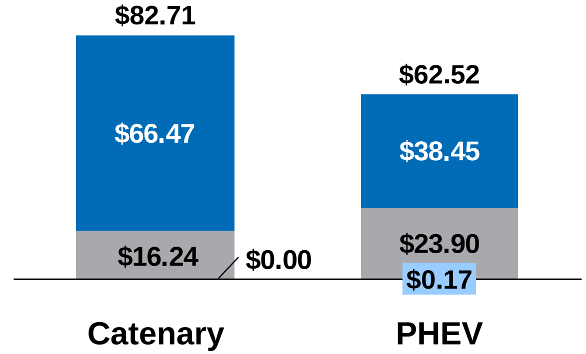
Alameda Street electricity cost for each truck

($ in Thousands)



I-710 electricity cost for each truck

($ in Thousands)



Discussions with Southern California Edison indicated that required power for catenary or fast charge could be provided with appropriate planning

Source: Southern California Edison, 2018

Pantograph maintenance at 50,000 annual production volumes does not seem to be an appreciable cost

Vehicle Maintenance Cost

Ricardo Assumptions for truck maintenance by 2025

	Catenary Truck	PHEV Truck
Vehicle Maintenance	$ 0.10 per mile	$ 0.10 per mile

- Pantograph maintenance involved checkups every 6 months and replacement of overhead stripes
- Resulting cost is $100-$200 per 6 months or 1 cent per mile
- Additional maintenance cost for a pantograph in a catenary truck is assumed comparable to maintenance associated with a larger battery pack and cooling system in PHEV trucks
- Hence, Catenary and plug-in hybrid truck maintenance assumed to be the same in this study

Note: Maintenance costs for pantograph could be higher today as the technology is at demonstration stage in heavy duty commercial truck segment and may be experiencing higher repair costs

Source: Siemens Interview; Ricardo Adoption Rate Model

Overhead Catenary System Final Reports

Agenda

- Summary of five key reports:
  - Siemens Final Report
  - Owner Operator Survey
  - SCE Grid Impact Report
  - Siemens eHighway Business Case
  - Total Cost of Ownership Study
- Open discussion on reports
- Open discussion on the future of OCS technology

Siemens Final Report

- The goal: to promote zero emission goods movement technologies and demonstrate a viable wayside power solution
- Constructed and demonstrated eHighway infrastructure
  - Significant construction challenges given limited discussion
- Demonstrated 3 trucks – Battery electric, CNG Hybrid, Diesel Hybrid
  - Vehicle challenges were discussed in detail
- Conclusion: Alameda Street is a successful proof of concept in a representative application environment
- Recommendation: Technology improvements and lower costs are needed to impact economic feasibility

Owner Operator Survey

- Survey of three entities to assess interest in management of a potential OCS system: SCE, LA Metro, and Cofiroute USA
- The three organizations were open to serving a role in the development and/or operation of an OCS
- Issues: adoption of the OCS by private operators, competition with other technologies, truck costs too high for fleets
- SCE could potentially construct the system but would require approval from the CPUC
- LA Metro discussed the possibility of linking incentive funds for catenary-enabled trucks to commitments to use the system
- Cofiroute’s services are currently limited to operation and maintenance of tolling system

SCE Grid Impact Report

- In parallel with the OCS demonstration SCE performed a grid system impact study to understand potential electrification and expansion of the OCS technology
- The system was evaluated to ensure that the power supply system could operate safely under typical characteristics of power system without having an adverse impact on the grid
- The eHighway system was compliant with IEEE 519 standards based on the data, and operated safely. There were no indications of adverse impact to grid voltage.

Siemens eHighway Business Case

- Optimistic economic feasibility and technical implementation
  - Economic benefits are more optimistic for I-710 than independent study
  - Technical implementation for truck and infrastructure was demonstrated
- Risks are identified:
  - Uncertainty for installation of catenary infrastructure
  - Uncertainty that vehicle operators will adopt (Fleets not included in demonstration)
  - Impacts and mitigation not discussed
- Siemens U.S. division's choice to decommission Alameda St. and that the business case calls for continuation of system shows disconnect between Siemens German and U.S. counterparts

Total Cost of Ownership Study

- A total cost of ownership (TCO) study (by Ricardo) analyzed OCS systems for 500 drayage trucks on Alameda Street and 15,000 drayage trucks on I-710
- **Catenary truck TCO is 8-20% higher than PHEV on Alameda St:**
  - Diesel PHEV cost more than catenary trucks due to battery cost
  - OCS underutilized for 500 trucks and is more expensive than EVSE
  - Siemens said Alameda St. would have insufficient miles under the wire for it to be profitable
- **Catenary truck TCO is comparable to PHEV on I-710:**
  - Diesel PHEV are more expensive than catenary trucks
  - OCS less expensive than 500 fast chargers and 7,500 overnight chargers
  - Siemens claims economic feasibility in their business case

Discussions - Questions