LOS ANGELES COUNTY
METROPOLITAN TRANSPORTATION
AUTHORITY

Diesel Multiple Unit (DMU)
Technical Feasibility Analysis

Contract No. PS4370-2064

Task 2.3.3

Propulsion Technology Investigation

FINAL

LTK

LTK Engineering Services

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LOS ANGELES COUNTY
METROPOLITAN TRANSPORTATION AUTHORITY
Diesel Multiple Unit (DMU) Technical Feasibility Analysis
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1. PROPULSION TECHNOLOGY COMPARISON APPROACH

This report compares propulsion technologies based on different fuel sources available to propel DMU vehicles, and addresses the viability of electric propulsion to provide an equivalent level of service. The Alternate Fuel section of this report (Section 2) lists all alternative fuels for diesel engines as well as how diesel propulsion can be made cleaner in the near future. Most information was collected by reviewing literature from potential suppliers of rail vehicles and diesel engines as well as public documents and discussions with industry professionals. This report includes links to a few Internet sites which provide additional and more detailed information.

1.1 Diesel Propulsion

There are a number of ways the drive train in a diesel-driven railcar can be configured. Regardless of the type of drive, however one important aspect of the drive mechanism is that it allow decoupling of the engine rotation from the wheel rotation. This is because diesel engines must build up sufficient rpm (revolutions per minute) to develop a minimum power level before engaging the wheels and moving the train. In an automotive drive train this is accomplished via the clutch and a gear: the clutch decouples the engine from the wheels and the gear transforms the engine rpm into a different rpm, as required by the speed the automobile is travelling. At a standstill, the clutch modulates the diesel engine effort normally transmitted to the wheel, in the process dissipating the power difference between the engine operating point and the vehicle speed-effort power state (speed x effort = power), which is zero until the automobile begins to move.

For rail vehicles, there are two different approaches to matching engine power to needed vehicle performance.

1.2 Diesel-Electric Drive

A diesel-electric rail vehicle is basically an electrically driven vehicle which carries its own power plant. This power plant consists of a diesel engine mechanically connected to an electric generator. The generator produces alternating current (ac) which is rectified to provide a direct current (dc) link to the traction inverter, similar to a power substation in an LRT system. This dc link can be compared to the catenary. The traction inverter converts the dc power to 3-phase ac, which drives the traction motors in the DMU truck in exactly the same way as an inverter in an LRV converts OCS power to 3 phase power for the traction motors.

In other words, the ”power plant” is part of the vehicle and generates sufficient electricity to drive the traction motors with the desired effort at any given speed.

Diesel-electric propulsion is a very efficient drive train at all vehicle speeds. It completely de-couples the diesel engine rotation speeds from axle speeds. For every power demand, the rpm of the diesel can be selected so that it always runs at the most efficient point for any given power level, thus reducing fuel consumption and emissions.

Since a diesel-electric drive uses the same propulsion components as an electric vehicle (LRV or EMU), it also has a powerful, wear-free dynamic brake. The brake power is normally dissipated as heat through brake resistor grids. Modern technologies are targeted on harvesting this wasted energy, as explained in Section 2.5, Hybrid Technology.

The typical major components in a diesel electric drive are shown in Figure 1, following:

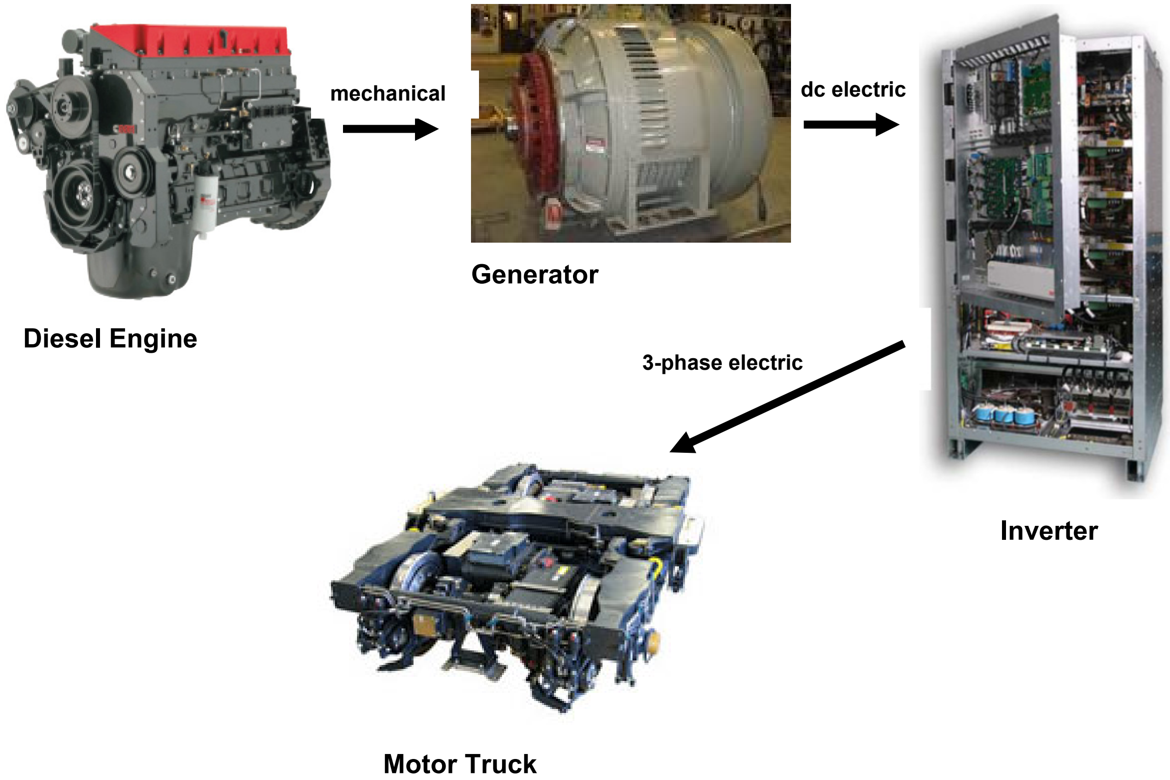


Figure 1: Diesel Electric Drive Components

1.3 Diesel Hydraulic Drive

The diesel hydraulic drive is very similar to the automatic transmission used in automobiles. In rail applications, it typically has 3 different speeds. The first gear uses a hydraulic torque converter, while the second and third gears are normally direct gears, using hydraulic assist only during gear change. These last two gears are very efficient in that there are no hydraulic losses. The first gear however, also called starting gear, has a lower efficiency due to the hydraulic torque converter.

Diesel hydraulic drives also have a wear free dynamic brake, albeit not as efficient as an electric brake. In the dynamic brake mode, the hydraulic torque converter acts as a “pump” forcing the oil through a “retarder” which is part of the transmission. The brake power is dissipated as heat in the hydraulic oil, which is routed through a heat exchanger (typically, an oil-to-water radiator) and is dissipated via the radiator banks on the roof of the vehicle.

1.4 Comparison of Diesel-Electric vs. Diesel-Hydraulic

Although diesel-electric offers advantages not found in diesel-hydraulic systems (such as energy recovery during braking, and efficient “hybrid-like” drive-train operation), diesel-hydraulic remains a popular propulsion drive system, and should be considered for Metro’s purposes. As noted in the *DMU Vehicle Market Survey* (Task 2.3.1.1), there are presently no manufacturers of FRA-compliant DMUs, although a number of carbuilders have expressed interest. In that the FRA-compliant DMU market (should one surface over the next few years) would be restrictive at best resulting in only a modest incentive for carbuilders to invest in this technology, neither propulsion technology should be ruled out.

2. ALTERNATE FUELS

2.1 Emission Requirements

The Environmental Protection Agency (EPA) sets emission limits for several different operating applications of diesel engines. For transit operators, the following three applications are relevant:

☐ Highway engines (Buses)
☐ Off-road engines (DMU)
☐ Locomotives

DMU diesel engines are classified as off-road engines because their power rating is between a highway and a locomotive engine. DMUs are a new vehicle concept in the U.S., and do not have a set of uniquely designed regulations, as the locomotives do. It is for this reason that they fall under the general category of "off-road engines." DMU emission limits, as defined within the off-road category, are more stringent than for locomotives but currently still less stringent than highway engines.

The EPA has implemented emissions standards in a tiered system that changes by year of engine production and engine power rating. DMU engines must comply with EPA off-road Tier 3 if manufactured from 2006 through 2010, and Tier 4 int ("intermediate"), if built in 2011 or later. New locomotive engines must currently comply with Tier 2 for locomotive. From 2011 on, they need to comply with Tier 3.

The emission limits given in Tables 1 and 2 below apply. Emission calculations in this report, comparing DMU operation with locomotive hauled train operation, are based on Tier 3 for DMUs and Tier 2 for locomotives.

Tier 4 limits (most restrictive) will not be imposed on DMUs until 2014. Most SCRRA locomotives were built to Tier 1 (least restrictive) standards. Tier 2 is being met with the rebuilt MP36 locomotives as far as NO_x pollution is concerned, with other pollutants close to Tier 2 limits. For comparative purposes it was decided to use the current (Tier 3 for DMUs and Tier 2 for locomotives) applicable EPA requirements in that new (not rebuilt) locomotives will be built to this standard. The EPA emissions levels should be considered as the upper bounds of expected actual emissions, regardless of the final engine manufacturer.

Five categories of emissions are considered:

☐ Carbon monoxide (CO) is formed by incomplete combustion and contributes to smog formation and cardiovascular disease.

☐ Particulate matter (PM) is the minute solid exhaust content. Current emissions standards regulate all particles less than 10 microns in diameter (PM10), notably visible as smoke and soot. Future emissions standards will regulate all particles less than 2.5 microns in diameter (PM2.5), as they are contributors to respiratory problems.

☐ Oxides of nitrogen (NOx) are caused by high ignition temperatures, contribute to visible yellow/brown smog, and are a precursor to ground-level ozone.

☐ Hydrocarbons (HC) are a precursor to smog and ground-level ozone. Non-methane hydrocarbons (NMHC) have the greatest ability to react with NOx to produce smog and ground-level ozone.

☐ Combined NOx + NMHC define the amount of emissions most likely to create smog and ground-level ozone.

EPA Regulated Contaminant	Substance	grams/kilowatt-hour			
		Tier 2	**Tier 3**	**Tier 4 int***	**Tier 4**
		2001	2006	2011	2014
CO	Carbon Monoxide	3.487	3.487	3.487	3.487
PM10	Particulate Matter (course)	0.201	0.201	0.020	0.020
PM2.5	Particulate Matter (fine)		-	0.013	0.013
NO_x	Nitrogen Oxide		-	2.012	0.402
NMHC	Non-Methane Hydrocarbon		-	0.188	0.188
NO_x + NMHC	Nitrogen Oxide + Non-Methane Hydrocarbon	6.437	4.023	2.199	0.590

* Tier 4 int is an intermediate step to Tier 4, which brings the U.S. Tier 3 limits in line with the European EURO 4 limits

Table 1: DMU (130 to 560 kW; 175 to 750 hp)

EPA Regulated Contaminant	Substance	grams/kilowatt hour	
		Tier 2	**Tier 3**
		2005	2011
CO	Carbon Monoxide	2.012	2.012
PM10	Particulate Matter (course)	0.268	0.101
PM2.5	Particulate Matter (fine)	-	-
NOx	Nitrogen Oxide	7.376	3.487
NMHC	Non-Methane Hydrocarbon	0.402	0.402
NO_x + NMHC	Nitrogen Oxide + Non-Methane Hydrocarbon	7.778	3.889

Table 2: Locomotives (>560kW; >750 hp)

2.2 “Clean Diesel”

The term “clean diesel” refers to the use of Ultra Low Sulfur Diesel (ULSD) fuel, plus the use of whatever exhaust after-treatments are available to reduce the emissions profile in order to meet EPA Tier 4 standards.

ULSD has a maximum sulfur content of 15 ppm (parts per million) compared to the traditional Low Sulfur Diesel (LSD) of 500 ppm. This is a reduction of 97% in sulfur content. The State of California began to require ULSD in 2006 for highway engines. Off-road engines will follow in 2010, and locomotives in 2012. It should be noted, however, that while not yet using “clean diesel,” Metrolink already operates their locomotives with ULSD, well in advance of the EPA requirements. It can be assumed that any DMU ordered today will be designed to run on ULSD.

The use of both ULSD and the new series of increased efficiency exhaust filters such as the particulate filter and SCR (Selective Catalyst Reduction) exhaust after-treatment process will be necessary in order to meet the off-road (DMU) Tier 4 requirements.

The particulate filter collects the very fine particles generated due to the high temperature of diesel fuel combustion. These particles are trapped in a filter which is periodically heated to the ignition point of the particulates, vaporizing them, rather than blowing them out as part of the exhaust.

SCR exhaust after-treatment converts nitrogen oxide (NOx), with the aid of a catalyst, into nitrogen and water. To do this, ammonia is sprayed into the exhaust before it is passed over a catalyst. This requires the vehicle to carry an ammonia tank in addition to the diesel fuel tank. An additional tank will increase maintenance expenses slightly, but, in our opinion, it is a reasonable trade-off considering the potential for reducing smog.

The SCR process is a proven technology and has been in use for years in *stationary* applications such as power plants.

2.2.1 Current Situation

ULSD is available and being used in a number of highway (truck and bus) applications. It should be noted that although ULSD has a number of positive attributes from an emissions perspective, it also has a lower energy density, due to its lower sulfur content, than low sulfur diesel. The exhaust after treatment approach is presently undergoing engineering trials for transit applications, as this technology has not yet been applied to rail vehicles.

Metrolink is testing one of its F59PH locomotives as a clean diesel engine by adding a particulate filter and an SCR treatment unit. It is expected that nitrogen emissions (NOx) will be reduced by up to 97%, and that the particulate (PM) content will be reduced by 50%. This is substantially lower than the Tier 2 values indicated above, but since this application is in an experimental stage and not fleetwide, it is not considered for the emission calculations in this report.

For more information regarding this experimental project, please refer to the following link:

http://www.westcoastdiesel.org/files/grants/Metrolink%20SCR%20Factsheet.pdf

2.2.2 Future Applications

DMU Tier 4 levels, which will be mandatory after 2014, necessitate that carbuilders utilize the SCR technology to meet the imposed emission limits. At this time, there is no information available regarding any ongoing tests of this new exhaust after-treatment on DMUs, including in Europe and Asia. Some highway trucks and fueling stations in Europe are equipped with the necessary hardware, so that adapting the equipment for rail applications should not cause significant technical challenges. It will, however, have an (as yet undetermined) impact on the cost of DMUs and their servicing.

2.3 Biofuels

Popular, but disputed today, is the use of biofuels. Diesel engines are to some extent forgiving in regard to the source of the fuel that they burn. Diesel fuel can be synthesized from many types of organic matter (biodiesel). The most popular biodiesel sources include soy beans and rapeseed (brassica napus). Currently, some transit agencies are testing a mixture of biodiesel and ultra low sulfur diesel, typically 5 to 20 percent biodiesel (B5 to B20) for their bus fleets. While there are technical challenges associated with higher grade biodiesel, such as cold temperature operation, fuel quality, fuel storage, and some material incompatibilities (gaskets; hoses), these problems can be overcome. There are no technical challenges with biodiesel formulations of less than 5%. Up to 5% biodiesel can be mixed with ULSD or low sulfur diesel (generically “petrodiesel”) without having to make special accommodations for the handling and use of biofuel in the engines.

The use of biodiesel reduces most emissions with the exception of nitrous oxide (NOx), as shown in Table 3 below (*Note:* Table 3 reflects the change in emissions from petrodiesel to 100% biodiesel). In fact, the use of biodiesel increases the production of NOx. An increase in NOx produces a corresponding increase in the Ozone pollution (smog) at near ground levels. The reduction of ground level Ozone is so important, and EPA Tier 3 NOx limits so stringent, that most engine manufacturers no longer approve of the use of biodiesel. In other words, the use of biodiesel would make their on- or off-road engines EPA Tier 3 non-compliant without exhaust after-treatment.

Substance	Amount
Hydrocarbon (HC):	- 67%
Carbon Dioxide (CO):	- 47%
Nitrogen Oxide (NOx):	+10%
Particulates:	- 48%
Sulfur Dioxide (SO2)	No emission

Table 3: Emissions Comparison (Petrodiesel vs. 100% Biodiesel)

The use of biodiesel has a secondary impact on the environment. It diverts crop production away from the food chain, thus increasing food prices. It also increases the pressure to use virgin land, particularly forests (which absorb CO_2), for additional fuel crop plantations. Some recent studies indicate that this and the energy needed to grow, harvest and process fuel plants can result in more CO_2 emissions per gallon of biodiesel than the use of ULSD alone.

2.3.1 Current Situation

Biofuels are being promoted by the U.S. government. Some diesel road vehicles, such as automobiles, trucks and buses are running on B5 to B20 blends. A few automobiles have been converted to run on B100 (100% biodiesel). Since the perceived environmental benefits of biodiesel are questionable, biodiesel has been downgraded by most countries to be used only as a replacement fuel for petrodiesel in the event that petrodiesel is either unavailable or too expensive.

Ethanol, derived mainly from sugar cane, has been used as a gasoline substitute for decades, with Brazil leading the deployment of this technology. Ethanol, however, is not used in rail vehicles due to its lower energy content (approximately 70%) as compared to diesel.

2.3.2 Future Applications

Until technologies are available to produce biofuels directly from grass or algae, reducing the impact to forests and food production, their viability remains uncertain. Regardless, it will be decades before biofuels will have an impact on low sulfur diesel usage.

An alternative source for future biofuels is algae. Its very fast growth rate would allow producing up to 20 times more biomass than current biofuel crops, in the process reducing the amount of CO_2 in the atmosphere. Algae production would not compete with the food chain since it can be grown in restricted ocean areas or on non-agricultural land in ponds. It has a projected development time of 5 to 10 years.

2.4 Natural Gas

There are two different proven technologies employing natural gas in motive applications. In both technologies, the difficulty in storing the gas, and its lower energy content (25% to 50% of diesel) as compared to diesel have prevented widespread application of these fuels in rail transit.

Natural gas has the reputation of being a “clean” energy. This can be misleading. Although natural gas is the cleanest of all fossil fuels, by way of producing fewer emissions than any other fossil fuel, and although natural gas has a lower carbon content than diesel or gasoline, it also has a lower efficiency than petrodiesel, thus necessitating the use of larger amounts of natural gas than diesel for the same application. Natural gas is also a limited resource, and adds to global warming by producing carbon dioxide as a combustion by-product. As such, it can only be considered an interim solution, similar to diesel technology.

2.4.1 CNG (Compressed Natural Gas)

CNG is a mature technology, used globally in automotive applications. Even though high pressure is required to store the gas (up to 2900 lbs/in^2), experience from automotive and bus applications show that

CNG is a simple and viable technology, allowing a refueling process similar to that for diesel fuel, although some safety measures are needed due to the very high pressures at refueling. CNG reaches only 25% of the energy density of diesel.

2.4.2 LNG (Liquefied Natural Gas)

LNG offers higher energy density than CNG and would be a better choice in terms of range. LNG reaches 50% of the energy density of diesel. A major disadvantage is the requirement to store the fuel at -160°C (-260°F) and the difficulty in transporting it to fueling stations. The availability of LNG is not an issue.

2.4.3 Current Situation

There are no CNG or LNG powered Multiple Units (MUs) on the market, although some modified older vehicles are running in Germany at the Usedomer Baederbahn (UBB). Some switching (yard-only) locomotives in the U.S. and Europe are being operated with CNG on a trial bases.

Diesel MU engines can be converted to burn natural gas (CNG or LNG); however the tank design required to safely contain compressed or liquefied gases would have a relatively small capacity, and would be quite heavy. This limited capacity would necessitate refueling of the vehicles during revenue hours, while diesel operated vehicles normally are refueled only once per day.

Peru has been operating a converted GE locomotive with natural gas since 2005. This locomotive including fuel tender is shown in Figure 2.

With the development of clean diesel, interest in natural gas-powered MUs has diminished to a large extent, as emission levels similar to those produced by natural gas are achievable with clean diesel without the need for major design changes.

Figure 2: GE Natural Gas Locomotive

In the U.S. and Canada tests were run with an LNG tender pulled by the locomotive, which yielded a range of up to 1600 miles without refueling. (This has no relevance to DMU technology, since DMUs do not have tenders. It is included herein for information only).

For more information, please reference: http://www.rrdc.com/article_07_2006_fcca_dual_fuel_pwr_RGI.pdf

2.4.4 Future Applications

Since the price of diesel has fluctuated tremendously recently, and alternatives to oil are becoming more important, natural gas powered MUs and locomotives could be candidates for development at some time in the future. However, industry expectations are such that natural gas applications would not become commercially viable until 10 years out. Of course, this depends heavily on the increasing cost and reduced availability of diesel fuel.

2.5 Hybrid Technology

Hybrid technologies permit the storage of energy normally dissipated during braking. In a typical arrangement, the instant braking is commanded and the drive motors are electrically reconfigured as generators. The current produced by these generators is used to charge a battery, which stores the energy in preparation for the next acceleration command. This technology is becoming more and more popular in the automotive industry. Toyota introduced it in the U.S. with the Prius car in 2001.

Hybrid technology combines a smaller internal combustion engine with batteries (or another energy storage device), to provide an overall performance level that is acceptable, yet uses substantially less fuel than a typical vehicle with a larger, standard engine. Hybrid buses and plug-in hybrids, such as the future GM sedan “Volt,” are based on a “series” hybrid configuration which uses an engine generator to provide electricity. The generator, driven by the combustion engine, charges a battery and can also provide power directly to an electric motor that propels the vehicle. The batteries provide bursts of power when needed, so the acceleration is acceptable, even though the combustion engine may be small.

This technology is very well suited to transit applications, in that frequent starts and stops are a good application for the energy recovery feature.

This technology can be adapted for DMUs, but requires a diesel-electric drive. Currently no such diesel-electric DMUs are available which also comply with FRA requirements. The Colorado Rail Car Manufacturing DMUs are all diesel-hydraulic drives, which do not allow energy to be regenerated while braking. A diesel-electric DMU, also called DEMU, utilizes electric traction motors and a diesel generator unit to provide the power to the propulsion equipment. Examples of agencies which use this technology are the SNJT and CapMet DMUs (reference Task 2.3.1.1, *DMU Vehicle Market Survey* portion of this analysis). On a DEMU, an energy storage system, such as a battery, super capacitors, or flywheel can be added to store the brake energy.

All U.S. diesel locomotives have diesel-electric drives.

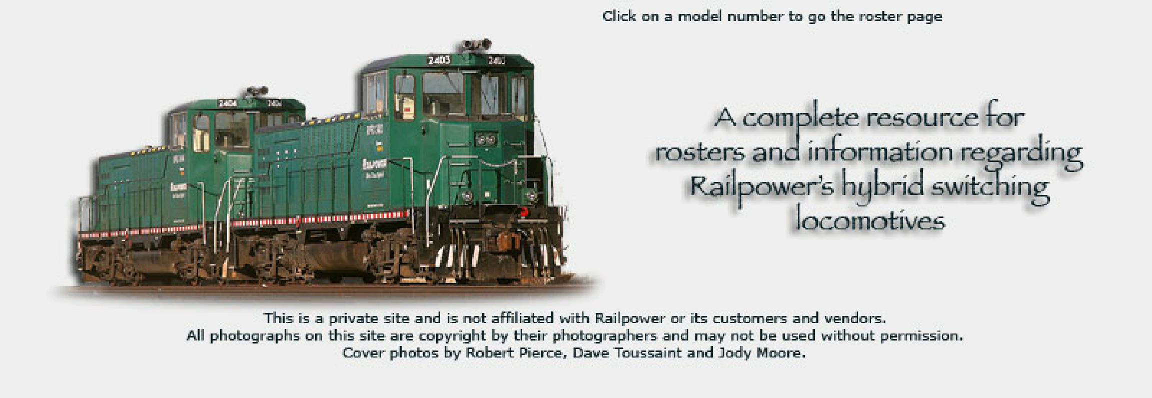
2.5.1 Current Situation

Hybrid drive-train applications in the rail industry face some challenges. Because the vehicle is much heavier than an automobile and travels at faster speeds, the battery needed to store the energy must be substantially larger, to the point where feasibility becomes technically and commercially questionable with current battery technologies. Some carbuilders, such as Alstom (see Figure 3), Bombardier and Siemens, are investigating the use of super capacitors or flywheels instead of batteries to store the energy.

In early 2000, an experimental DEMU LIREX from Alstom was used to investigate the efficiency of flywheel energy storage in Germany. Although technically successful, the DEMU was a commercial failure. The cost of the vehicle was too high to attract any buyers.

Figure 3: Alstom LIREX Experimental DEMU with Flywheel Storage

In the U.S., an FRA-compliant hybrid switching locomotive was developed by RailPower Technologies and sold to several yard operators (See Figure 4, below).



Click on a model number to go the roster page

A complete resource for rosters and information regarding Railpower's hybrid switching locomotives

This is a private site and is not affiliated with Railpower or its customers and vendors.
All photographs on this site are copyright by their photographers and may not be used without permission.
Cover photos by Robert Pierce, Dave Toussaint and Jody Moore.

Figure 4: GreenGoat

For further information, please visit: http://www.railpower.com/products_gg.html

GE presented a mainline hybrid locomotive (Figure 5), rated at 4000 hp, this summer at Union Station in Los Angeles. GE uses this locomotive as a research locomotive and will continue to improve its regeneration capability. Currently GE uses Sodium Nickel Chloride (Na-NiCl2) batteries and estimates an average fuel consumption savings of 10%.

RailPictures.Net - Image Copyright © Craig Walker

Figure 5: GE Prototype Locomotive at Union Station in Los Angeles

2.5.2 Future Applications

No large scale production of hybrid DEMUs is expected anytime soon. The additional equipment needed, especially the energy storage devices, are still too expensive for commercial viability.

2.6 Fuel Cells

While fuel cells have been considered an emerging technology since the late 1970's, they were actually invented in the early 1800's but were never developed as a practical energy source for transportation technologies. There are two major reasons for this:

(1) Fuel cell technology is intrinsically expensive

(2) Investing in a hydrogen infrastructure for refueling of vehicles is costly and would require significant engineering

The most common fuel cell design is shown in Figure 6. Essentially a fuel cell forms water from hydrogen and oxygen gases. When the water is formed, electricity is generated. This process is described chemically as $2H_2 + O_2 \Rightarrow 2H_2O$ and requires both pressurized hydrogen and oxygen to occur.

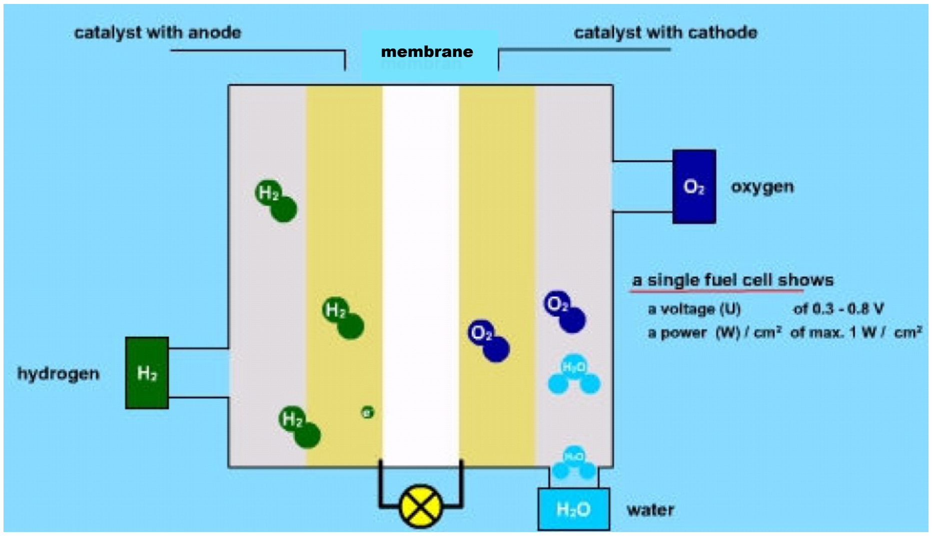


Figure 6: Fuel Cell Design

Hydrogen gas is not readily available. In the earth's atmosphere, hydrogen has a tendency to mix with the oxygen in the air and creates water, or other stable molecules such as ammonia and hydrocarbons. Hydrogen must be made by adding electricity to water to split the molecule (electrolysis) or removing it from natural gas (reforming); however, generating hydrogen from natural gas defeats the purpose behind the use of hydrogen in that this process both consumes energy and generates CO_2, a contributor to global warming. Additionally, the overall energy efficiency is no better than burning the natural gas directly. The efficiency of reforming hydrogen from natural gas is about 70%. The efficiency of the fuel cell is a function of the electrical load it is driving and will be, at best, 45%. The losses in the electric drive train (inverter and motor) are roughly 87% so that the overall efficiency of the fuel cell system calculates to about 30% or less, slightly worse than a regular combustion engine. Such results do not justify the additional cost of hydrogen fuel cell vehicles and the necessary attendant hydrogen infrastructure (fueling stations).

In order to avoid the environmental impacts generated by reforming hydrogen from natural gas, hydrogen would have to be generated by electrolysis of water during those times of the day when electric energy is less expensive and available in excess, such as from wind generators, solar or nuclear power stations at a time when demand is low. In other words, hydrogen would be used the way a battery is used: Hydrogen would store energy and subsequently convert it back to electricity and water, as needed.

2.6.1 Current Situation

The automotive industry developed some fuel cell automobiles and buses which are presently undergoing road testing. Since there have been some remarkable improvements in battery technologies, however, the automobile industry is now focusing on all electric drives, which store the energy directly in batteries, rather than in hydrogen. In Europe, the bus industry has initiated a fuel cell test program by the name of CUTE (Clean Urban Transport for Europe). The results thus far are mixed, and an imminent breakthrough of this technology seems unlikely.

In the rail industry, the application of fuel cells is also being considered as an alternative to diesel operation. Denmark, with an abundance of wind power with which to produce hydrogen, is supporting the development of a fuel cell MU train by a consortium of Vossloh and several other interested parties. Their goal is to provide a prototype vehicle by 2010. For more information, please refer to the following link: http://www.hydrogentrain.eu/

In the U.S., BNSF recently announced the development of a fuel cell locomotive in Topeka, Kansas. *Fuel Cell Propulsion*, a company based in Golden, Colorado, is working on a fuel cell shunting locomotive among other fuel cell applications. For more information about this program, please refer to the following link: http://www.fuelcellpropulsion.org/Rail/Websites/RailProg.htm

2.6.2 Future Applications

Fuel cell technology will not play a major role in the near future. If the costs can be decreased, and the durability of the fuel cells increased, and if a completely new fuel distribution network can be established, fuel cell driven vehicles might become viable in, perhaps, 20 years or more. It is definitely not a technology to be considered for the near term.

2.7 Summary

As indicated in Section 1.4, the choice of a propulsion technology will be limited to either diesel-electric or diesel-hydraulic; other technologies, such as hydrogen fuel cell systems, are nowhere near mature enough to command carbuilder interest. Since the technology will be diesel, Metro will be further constrained by the diesel manufacturer's choice of a fuel drive. Since the imposition of the EPA's Tier 4 requirement will fall within Metro's DMU procurement window, the only fuel solution will be "clean-diesel" (ultra-low sulfur diesel plus after-exhaust treatments) since this is the only option available consistent with the Tier 4 requirements.

3. ELECTRIC PROPULSION

A quick overview of an electrified rail system is given below. There is no question that electric propulsion is beneficial in reducing dependence on foreign oil, and reducing atmospheric pollution. As such, this mode of transportation will probably become more common in the future. Electric propulsion for rail vehicles plays a larger role in countries other than the U.S.

3.1 Infrastructure

Electric propulsion is the cleanest solution of all possible propulsion technologies, resulting in minimal emissions. If emissions are generated, they occur at the power source. The emissions at the power source depend on the primary fuel being used to produce electricity. Renewable energy such as hydro, wind or solar has virtually no emissions. Gas is the cleanest form of primary fossil fuels. Oil is worse and coal is the least clean source of fossil energy; however, burning fossil fuels in a modern stationary power plant will still result in less pollution than using these fuels to power a locomotive or DMU. Moreover, modern fossil power plants have exhaust-after treatments.

Another inherent advantage in obtaining propulsion power from the electrical grid is that every improvement in power generation can be taken advantage of without modifying the transit operation. The operator can take advantage of these advancements without changing equipment or infrastructure, or risking the reliability of the operations. Service reliability should never be compromised in order to accommodate technological development.

Electric Multiple Units (EMUs) utilize electric power, supplied via an overhead contact system (OCS) or third rail system. For the lines under investigation in this report, an OCS system would be operated at 25 kVac. This system is common throughout the world, including the East Coast of the United States, for heavy suburban or interurban rail systems. By comparison, the local light rail vehicles operated by Metro utilize lower voltage dc-power. 750 Vdc (Metro) or 1500 Vdc (Seattle) are common for such applications.

25 kVac is also the overhead power system planned for the new California High Speed Rail Project. As such, it is to be expected that future commuter rail improvements in Southern California will be based on this voltage now that the High Speed Rail bond has passed.

25 kVac electrification has the advantage that more power can be transmitted at lower current, reducing the losses along the catenary (OCS), as well as reducing the size of overhead wire needed. 25 kVac also allows for increased distances between substations, up from one mile for 750 Vdc systems to 20 miles for 25kVac systems.

Electric power also permits the utilization of higher powered locomotives and EMUs, decreasing travel times between stations.

A typical 25 kVac system layout is shown in Figure 7:

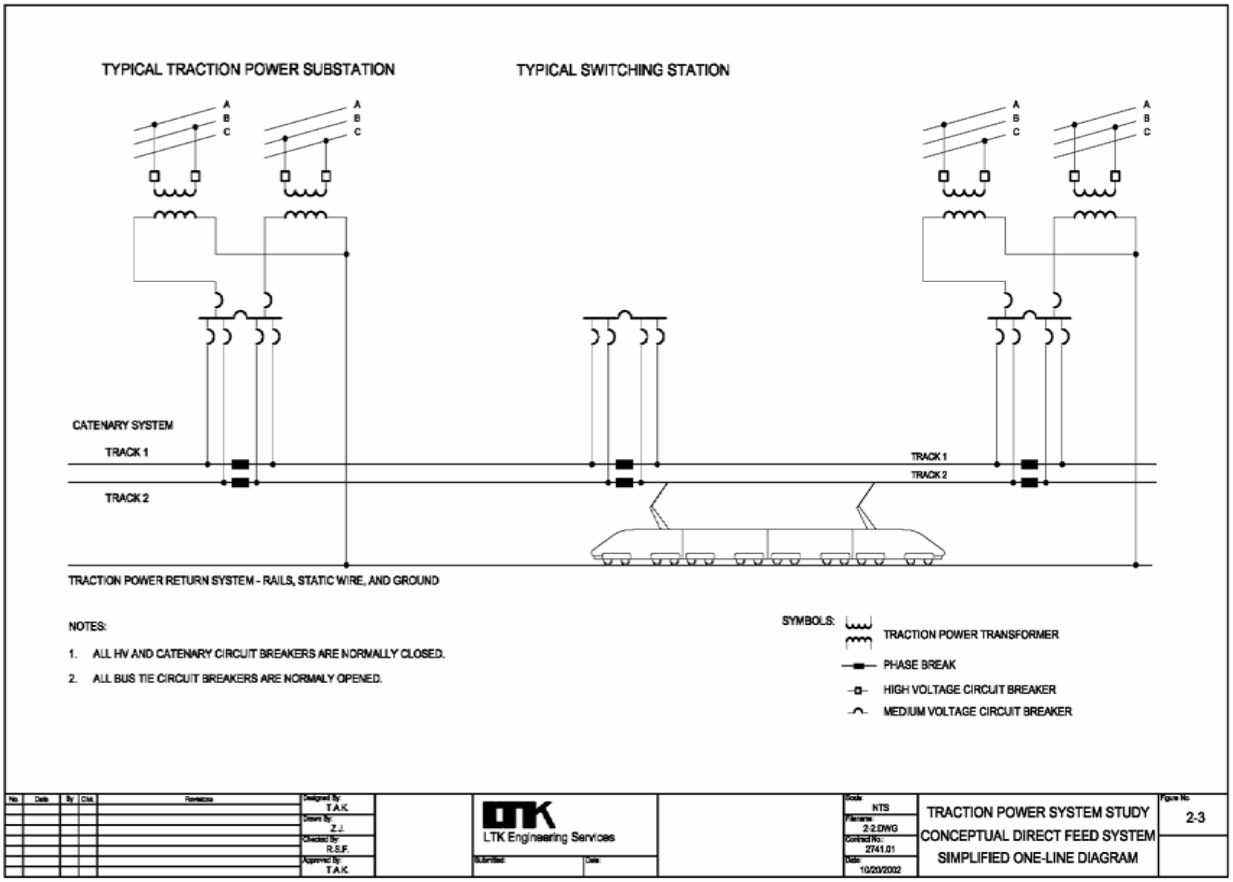


Figure 7: Typical 25kVac System Layout

Typically, electrification becomes more commercially attractive as rail traffic on the alignment increases. For the alignments under investigation in this report, this is not yet the case, since the freight trains on the candidate alignments will still be operated with diesel power for years to come. Additionally, the lack of a modern, efficient signaling system reduces the train throughput on the alignments under investigation to levels where the cost of electrifying the lines is not justified.

3.2 Costs

Infrastructure costs are independent of the propulsion technologies used with the exception of all electric propulsion. Electric propulsion requires an extensive infrastructure to power a moving vehicle. This infrastructure consists of high voltage switching stations to connect the high voltage grid to the traction power substations, where the power will be transformed to feed into the OCS from which the vehicle will draw power. Additional medium-voltage switch gear allows “sectionizing” (electrical partitioning) the OCS to isolate certain sections in case of maintenance or failures (see Figure 7 above).

The costs of the OCS system can be divided amongst three different categories:

☐ Construction costs
☐ Maintenance costs
☐ Power costs

3.2.1 Construction Costs

Typical 25 kVac overhead catenary construction costs for the electrification equipment mentioned above would vary between U.S. $150 million to $180 million typically for all three lines. These costs do not include the additional real estate needed to install the wayside equipment. It also does not include the cost of enlarging the 1.2 mile tunnel between Sylmar and Newhall to provide additional clearance for the catenary system.

Electrification was only considered to Via Princessa on the Antelope Valley line. This is to avoid electrifying the section through the Soledad Canyon, which has with no stations for 24 miles. (We assume a cost-benefit analysis would indicate that the cost of electrification for this section would be too steep for the resulting benefit).

3.2.2 Maintenance Costs

Based on a report comparing electric operation with diesel operation for several RTD lines in Denver, the ROM costs to maintain OCS and wayside equipment can be estimated at $40,000 to $60,000 mile/year.

3.2.3 Power Costs

The electric power costs vary depending on location and individual power company rates. A reasonable cost assumption of 12 cents per kWh (2008 dollars) is taken into consideration for the vehicle operating cost comparison.

3.3 Summary

Although the use of electric vehicle technology offers many advantages (market availability of electrical multiple unit --- EMU --- cars, controllable vehicle emissions, high-performance, etc.), there are near-term disadvantages which would rule out this technology as an overlay service. The principle issue is one of electrification. In order to operate EMUs, the alignment must be electrified. In addition to the estimated cost ($170,000,000), an environmental analysis would have to be conducted and approved. This would be no trivial exercise; excess ROW would have to be acquired in order to locate catenary structure. Acquiring even small amounts of additional ROW, and the attendant environmental approval, has proven very problematic for SCRRA. Also, maintaining EMUs and DMUs in the same facility, would be very difficult. All issues considered, for the purposes of this study, EMU technology was ruled out as a viable, near-term option.

4. RUN SIMULATION: ENERGY CONSUMPTION AND EMISSIONS PROFILE COMPARISONS

Two train runs were simulated for this report. One train consisted of a three coach Metrolink train pulled by an MP36 diesel locomotive. The other train was a three car Colorado Railcar DMU train. Three cars are needed to fulfill the freight railroads' requirement that no train with less than 12 axles shall be permitted on the Metrolink system. The goal of the simulation was to estimate the fuel consumption and the upper limits (as defined by the EPA Tier level under which they operate) of the tailpipe emissions for each of these two trains. The results are summarized in this section.

4.1 Simulation Definition and Characteristics

4.1.1 Route

The route chosen for this simulation was the Ventura County Line from Chatsworth to Union Station. This line runs through the most populated area of the three corridors in this study, and it was also rated the highest (most likely corridor to realize positive impacts from the implementation of DMU overlay service) in our *Community Impact Report* (Task 3.1.3). The line is 28.5 miles long and has a slightly descending grade from Chatsworth to Union Station. (Refer to the simulation plots, Figure 13 to Figure 17, which show the elevation of the line.)

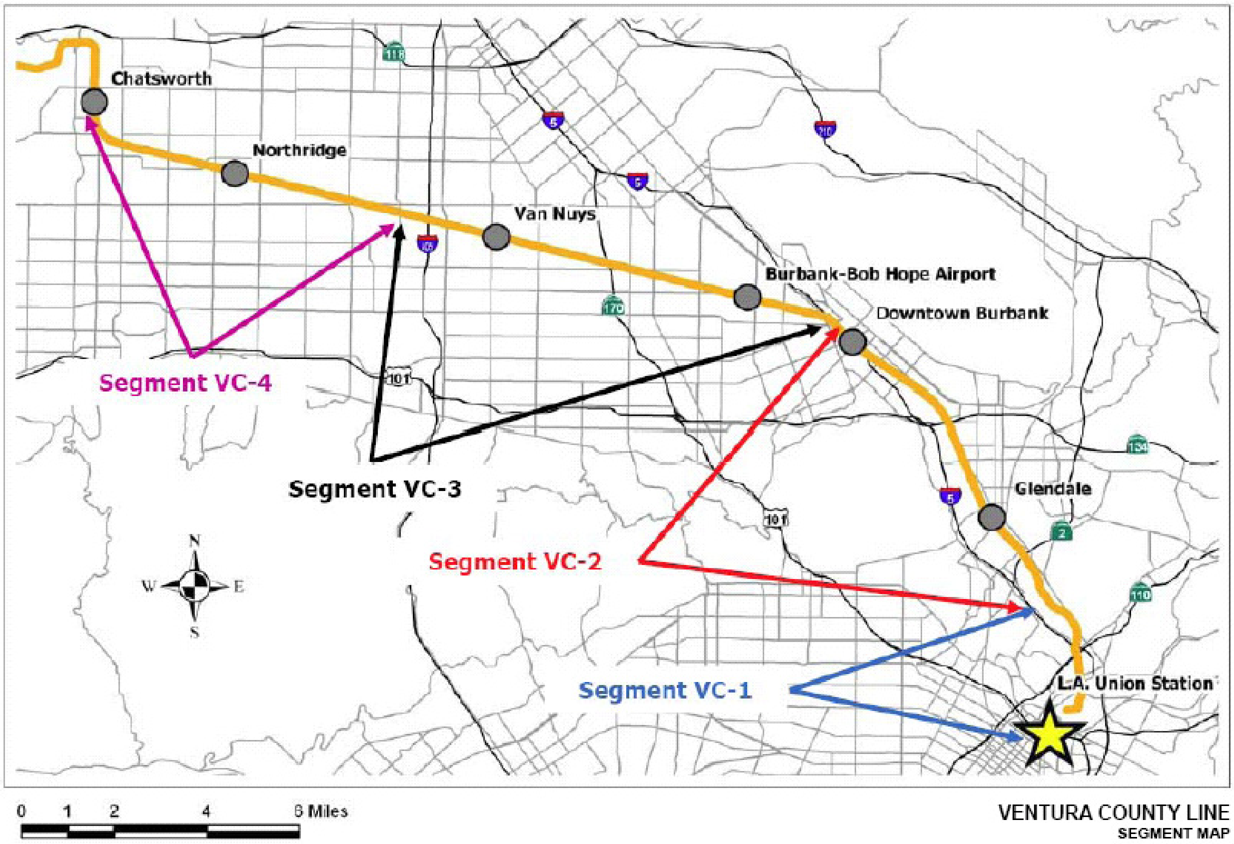


Figure 8: Ventura County Corridor Alignment, Union Station to Chatsworth

The following alignment characteristics were entered into the software model database based on information compiled from Metrolink track charts. The following alignment sections were used (see Figure 8):

☐ Ventura Subdivision, Segments VC-4 and VC-3

☐ Antelope Valley & River Subdivisions, Segments VC-2 and VC-1

The following characteristics were digitized for our model:

☐ Track distance

☐ Track elevation

☐ Track speeds

☐ Station locations

☐ Turn out locations with reduced speeds[1]

We also modeled 30 second station dwell times in our simulation.

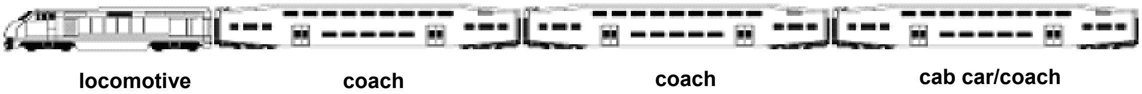
4.1.2 Trains

The unique characteristics of each of the two trains were modeled. This included the locomotive and DMU performance characteristics, the characteristics of the unpowered coaches in the train, and the passenger loads. Train resistance was calculated using the well-established Modified Davis Formula, which takes the vehicle shape, weight and number of axles into consideration. The maximum available tractive effort was restricted at fixed locations along the track. At these locations, the acceleration of the train is limited or the train is put into coast for up to one mile, depending on the geographical location, before initiating a brake application.

4.1.2.1 Metrolink Train

The simulated Metrolink train consists of a Bombardier cab car, 2 Bombardier double deck coaches and a MP36 locomotive. One locomotive and three coaches is the minimum train length that Metrolink operates regularly in revenue service. For the revenue operation simulation it was assumed that all seats are occupied.

The simulated Metrolink train, providing 420 seats, is as shown below:



The following train parameters were used to model this train:

Parameter	Locomotive	Coach
Consist	1 MP36	3 Bombardier Cars
Weights (AW1)	289,000 lbs	3 x133,520 lbs
Total seated passengers	-	420
Number of axles	4	12
Maximum Traction Power	2400 kW at wheel	-
Maximum Head End Power (HEP)	41 kW	3 x 72kW
Max Electrical Auxiliary Power (prime mover)	Aux Gen: 185 kW	
Max Mechanical Auxiliary Power (prime mover)	115 kW	
Maximum Acceleration	1.25 mphps	-
Maximum Deceleration	1.5 mphps	-
Maximum Operating Speed	79 mph	-

Table 4: Parametric Values Used in the Simulation of the Metrolink Train

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[1] Speeds over turnouts are not always the same. Normally, the speed restriction applies only if the switch is lined for a siding, and does not apply if it is lined for the main line. For the simulations, the worst case conditions were taken; all simulated trains were commanded to reduce speed over turnout locations, independent of which track they are actually running on.

The MP36 locomotives have a diesel-electric drive, wherein the traction diesel engine drives a generator which provides electricity for the traction motors, as explained in Section 1.2 of this report. The traction diesel engine also drives an auxiliary generator which provides electric power to the locomotive's auxiliary equipment, such as the blowers for engine cooling. Additional locomotive "parasitic" loads such as water and oil pumps, traction motor blowers and air compressor for the brakes are directly driven mechanically from the diesel engine. These loads vary with engine power and are simulated to be 50 kW at the lowest throttle notch and 300kW at the highest throttle notch. This power demand is added to the traction power demand.

In addition to the traction diesel engine, each MP36 has a head end power (HEP) diesel engine which provides auxiliary power for the Bombardier coaches to power loads such as air-conditioning, lighting and control and communication equipment. The HEP engine runs at a fixed speed of 1800 rpm to provide 480Vac, 60Hz auxiliary power. A constant 257 kW to power all three Bombardier coaches is included in the simulation.

This HEP engine complies with the Tier 2 limits for locomotives as shown in Table 2.

Propulsion Characteristics of the MP36:

The tractive effort vs. speed curve for the Metrolink locomotive is given in Figure 9, below:

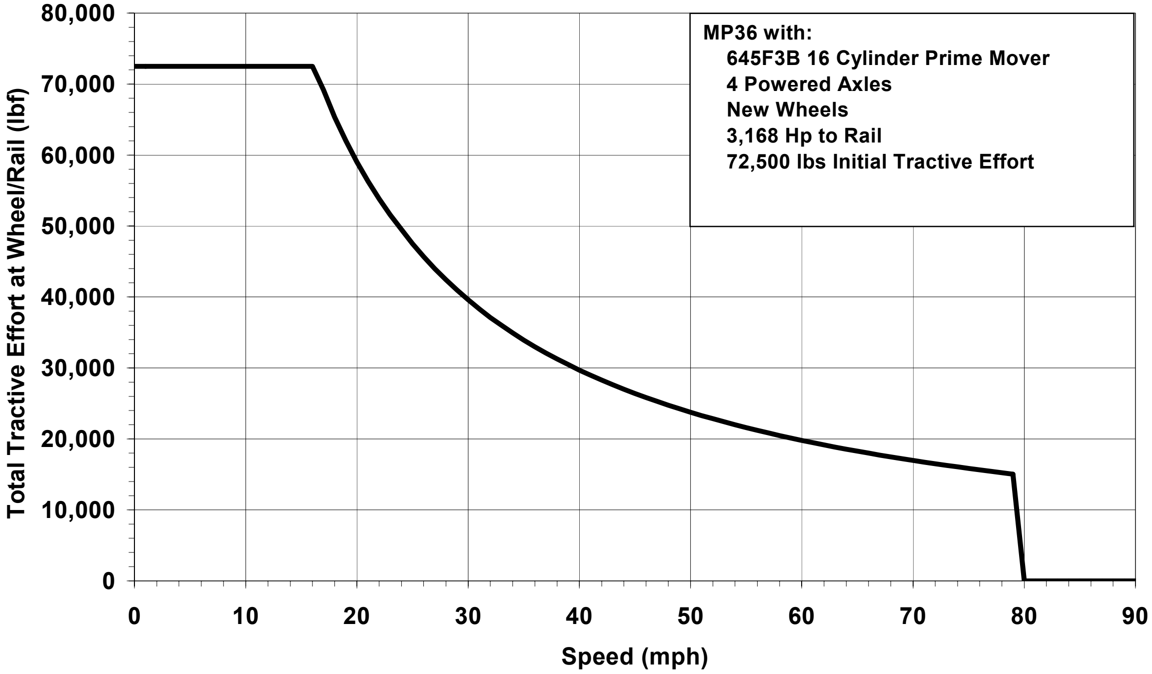

Figure 9: Propulsion Characteristics of the MP 36 Diesel Locomotive

The engine was assumed to operate on ultra low sulfur diesel (ULSD) fuel, as presently used by Metrolink. Table 5 shows the engine characteristics used for the simulation:

Control Notch	Speed	Engine Torque	Max Engine Power		Fuel Consumption Rate	
	(RPM)	(ft. lbf)	(bhp)	(kW)	(lbm/bhp.hr)	(g/kWh)
0	200	315	12	9	1.428	869
1	270	8909	458	342	0.523	318
2	346	13721	905	675	0.384	234
3	500	14198	1353	1009	0.373	227
4	582	16263	1802	1344	0.369	224
5	669	17676	2251	1679	0.363	221
6	757	18738	2700	2013	0.352	214
7	848	19512	3150	2349	0.353	215
8	940	20114	3600	2685	0.360	219

Table 5: Parametric Values Used in the Simulation of Metrolink's MP36 Diesel Locomotive

Locomotive control notches 0 through 8 are the positions of the locomotive throttle controls, with 0 indicating idle and 8 the maximum power position.

4.1.2.2 DMU Train

The DMU train was simulated as a train consisting of two DMUs with a single level coach in-between. The simulated train weight is AW2, which means that in addition to having all seats occupied, some passengers are assumed to be standing in open areas. As such, the DMU and the Metrolink train carry about the same number of passengers, which makes a comparison of fuel consumption and exhaust emissions as fair as possible.

The simulated DMU train providing 230 seats and 150 standee spaces is as shown below.

Figure 10: Simulated DMU

The following train parameters were used to model this train:

Parameter	DMU	Coach
Consist	TriMet Colorado Rail Car DMU	TriMet CRM Cab Car
Weights (AW1)	2 x 193,200 lbs	160,500 lbs
Total seated passengers	2 x 75	80
Total standees	2 x 47	55
Number of axles	2 x 4	4
Maximum traction power	2 x 360 kW at wheel	-
Maximum engine auxiliary power	2 x 40 kW	-
Maximum auxiliary power	2 x 88 kW	88 kW
Maximum acceleration	2 mphps	-
Maximum deceleration	1.5 mphps	-
Maximum operating speed	79 mph	-

Table 6: Parametric Values Used in the Simulation of the DMU Train

The Colorado Railcar Manufacturing (CRM) DMU has two diesel hydraulic drives as explained in Section 1.3. Each diesel engine powers one axle of the DMU. Therefore, out of the 4 axles of this DMU, 2 axles are powered and 2 are trailing. The maximum acceleration rate is slightly higher than for a locomotive-haul train because the smaller engines of the DMU can increase the rpms much faster than the large diesel engine of the MP36. This means that the power can be applied faster in the DMU.

The “parasitic“ loads per DMU are assumed to vary between 40 and 80 kW, as a function of engine output power.

Each DMU also has an auxiliary generator set. Two auxiliary generators (manufactured by Stadco-Railgen, 175 kW each) provide the hotel power to all three vehicles in the train. 260kW of auxiliary power for all three cars was used for these simulations. These generators also comply with Tier 3 emission limits, as shown in Table 1.

Propulsion Characteristics of a Single DMU

The tractive effort vs. speed curve for the CRM DMU is given in Figure 11:

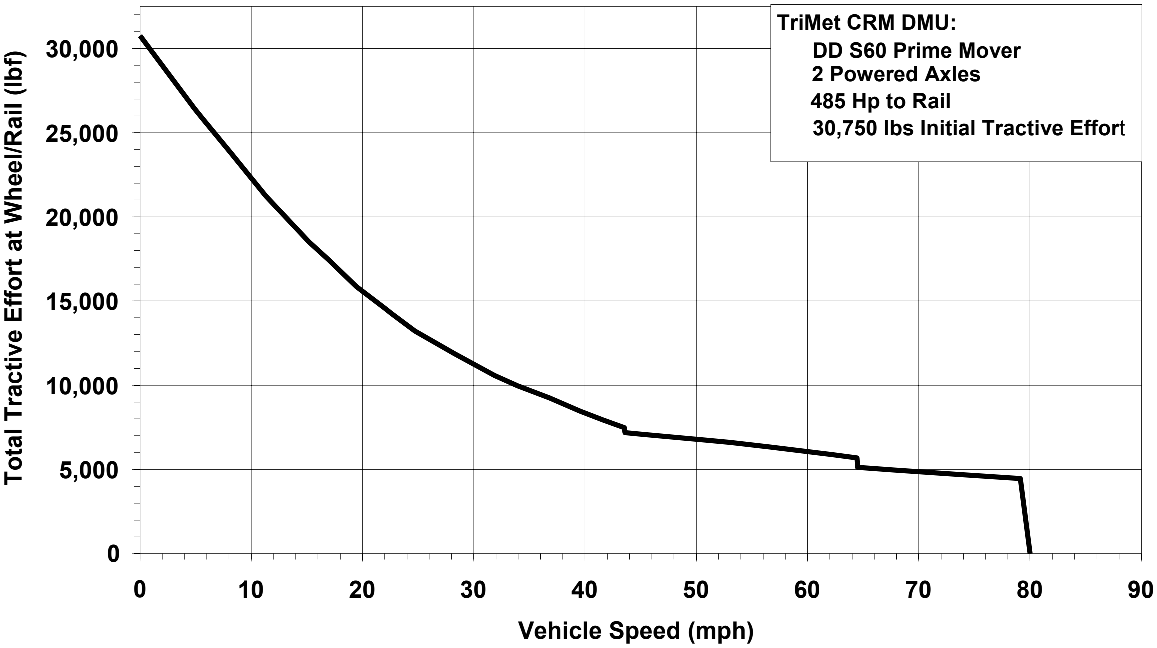

Figure 11: Propulsion Characteristics of One CRM DMU

Note that this tractive effort diagram shows the gear changes which take place at 44 and 65 mph during full acceleration.

This engine was also assumed to operate on ultra low sulfur diesel (ULSD) fuel. The following table shows the engine characteristic used for the simulation:

Speed	Engine Torque	Max Engine Power		Fuel Consumption Rate	
(RPM)	(ft.lbf)	(bhp)	(kW)	(lbm/bhp.hr)	(g/kWh)
600	400	45	33.5565	0.335	203.7729
800	1100	167	124.5319	0.33	200.7315
1050	1711	342	255.0294	0.325	197.6902
1200	1851	423	315.4311	0.323	196.4736
1350	1900	488	363.9016	0.326	198.2984
1500	1849	528	393.7295	0.328	199.515
1650	1802	566	422.0661	0.334	203.1647
1800	1751	600	447.4199	0.339	206.206
1950	1616	600	447.4199	0.342	208.0309
2100	1501	600	447.4199	0.348	211.6805

Table 7: Parametric Values Used in the Simulation of the DMU (Power Car)

4.2 Simulation Results

Run time simulations for the two trains described above were performed for each direction on the Ventura County Line between LAUS and Chatsworth.

The run time was adjusted to be approximately 40 minutes (typical run time) in each direction for the locomotive-haul and the DMU trains to allow a meaningful comparison of the simulations.

The simulated trip times include dwell times of 30 seconds at intermediate stations. No dwell time was programmed for the starting location and the terminal location.

The scheduled Metrolink trip times are approximately 45 minutes in each direction. This allows for a 5 minute buffer to compensate for unexpended delays and is consistent with current Metrolink scheduling practices.

4.2.1 Fuel Economy

For each trip, energy usage and fuel consumption were calculated. At each point in time, the vehicle tractive effort at the wheel was matched to engine power and fuel consumption rate. Energy usage was calculated by incrementally “summing” the product of power output and time over the whole of the run (power x time = energy). Fuel consumption was calculated by integrating the fuel consumption rate over time, which is a function of the DMU output at any given moment. Fuel and energy consumptions of the DMU mainly are a function of the number of accelerations and throttle controls.

Fuel consumption values include the operation of the auxiliary engines to provide the auxiliary power during all travel and intermediate station dwell times.

4.2.2 Emissions

The EPA limits used to calculate the total emissions for one round trip on the Ventura County Line are based on the regulatory emission limits applicable today and not on actual engine data, which is very difficult to obtain from the manufacturer. The SCRRA refurbished traction diesel engines in the MP36 locomotives generally comply with EPA Tier 2 exhaust requirements; however, measurements taken during the commissioning of the locomotives at SCRRA indicate that the Tier 2 emission levels are exceeded at very low rpm, or in dynamic (electric) braking. Nevertheless, the emissions are calculated as if they were consistent with Tier 2, with which new locomotives must be compliant. This allows for an “apples-to-apples” comparison between the Tier 2 requirements for all new locomotive engines and the Tier 3 requirements for new DMU engines.

Emission values were calculated from the run simulations, which include intermediate station dwell times of 30 seconds.

Emissions values given in this report include the operation of the auxiliary engines to power all auxiliaries during travel and intermediate station dwells.

The Detroit Diesel S60 engines used in the CRM DMU comply with Tier 3, off-road exhaust requirements. No measured data was available from the manufacturer. Using the official Tier 3 limits for the calculations reflects a worst case condition, since most engine manufacturers fine-tune their engines to meet the most restrictive requirements, with the result that all other emissions are typically lower than the EPA limits.

4.2.3 MP36 and 3 Bombardier Coaches

Following are the results of the simulation for the MP36 locomotive, both Eastbound (Chatsworth to Union Station) and Westbound (Union Station to Chatsworth). Differences between the two runs can primarily be attributed to the change in elevation: Chatsworth is higher than Union Station; hence, the Eastbound run is “downhill”, and consumes significantly less energy. Parameters in **bold** are summary level.

Results: MP36, Eastbound, Chatsworth – LAUS		
Trip time	39:53	min
Propulsion energy consumed	372.81	kWh
Propulsion fuel consumed	37.03	gallons
Propulsion gallons per mile	1.30	gpm
Propulsion mpg	0.77	mpg
Propulsion emissions	Tier 2 locomotive	
CO	750	grams
PM10	100	grams
NOx + NMHC	2,900	grams
CO_2 (not part of Tier 2)	370,927	grams
HEP power	Tier 2 locomotive	
Auxiliary power	257.4	kW
Auxiliary energy consumption	167.52	kWh
Auxiliary power fuel consumed	33,220	grams
Auxiliary power fuel consumed	10.56	gallons
Auxiliary gallons per mile	0.37	gpm
HEP emissions	Tier 2 locomotive	
CO	584	grams
PM10	34	grams
NOx + NMHC	1,078	grams
CO_2 (not part of Tier 2)	106	grams
Fuel consumption per train		
Total fuel consumed	**47.59**	**gallons**
Total gallons per mile	**1.67**	**gpm**
Total mpg	**0.60**	**mpg**
Total emissions per train		
CO	**1,334**	**grams**
PM10	**133**	**grams**
NOx + NMHC	**3,978**	**grams**
CO_2 *	**371,033**	**grams**

Results: MP36, Westbound, LAUS – Chatsworth		
Trip time	40:21	min
Propulsion energy consumed	656.41	kWh
Propulsion fuel consumed	54.70	gallons
Propulsion gallons per mile	1.93	gpm
Propulsion mpg	0.52	mpg
Propulsion emissions	Tier 2 locomotive	
CO	1,321	grams
PM10	176	grams
NOx + NMHC	5,106	grams
CO_2 (not part of Tier 2)	547,906	grams
HEP power	Tier 2 locomotive	
Auxiliary power	257	kW
Auxiliary energy consumption	169.26	kWh
Auxiliary power fuel consumed	33,565	grams
Auxiliary power fuel consumed	10.67	gallons
Auxiliary gallons per mile	0.38	gpm
HEP emissions	Tier 2 locomotive	
CO	590	grams
PM10	34	grams
NOx + NMHC	1090	grams
CO_2 (not part of Tier 2)	107	grams
Fuel consumption per train		
Total fuel consumed	**65.36**	**gallons**
Total gallons per mile	**2.30**	**gpm**
Total mpg	**0.43**	**mpg**
Total emissions per train		
CO	**1,911**	**grams**
PM10	**210**	**grams**
NOx + NMHC	**6,195**	**grams**
CO_2 *	**548,013**	**grams**

* EPA tiers do not address CO_2 emissions. CO_2 emissions are a direct result of fuel consumption only and not how clean an engine is operated. CO_2 values in this chart were calculated not by permissible tier limits, but by fuel consumption only.

4.2.4 DMU Train Consist

Following are the results of the simulation for the CRM DMU train. Both Eastbound and Westbound runs were made over the same alignment as for the locomotive-haul trains.

Results: DMU, Eastbound, Chatsworth – LAUS		
Trip time	39:08	min
Propulsion energy consumed	319.16	kWh
Propulsion fuel consumed	21.45	gallons
Propulsion gallons per mile	0.75	gpm
Propulsion mpg	1.32	mpg
Propulsion emissions	Tier 3 off road	
CO	1113	grams
PM10	64	grams
NOx + NMHC	1284	grams
CO_2 (not part of Tier 3)	214,865	grams
Auxiliary power	262.5	kW
Auxiliary energy consumption	171.14	kWh
Auxiliary power fuel consumed	10.83	gallons
Auxiliary gallons per mile	0.38	gpm
Auxiliary emissions	Tier 3 off road	
CO	597	grams
PM10	34	grams
NOx + NMHC	688	grams
CO_2 (not part of Tier 2)	108,455	grams
Fuel consumption per train		
Total fuel consumed	**32.28**	**gallons**
Total gallons per mile	**1.14**	**gpm**
Total mpg	**0.88**	**mpg**
Total emissions per train		
CO	**1,710**	**grams**
PM10	**99**	**grams**
NOx + NMHC	**1,972**	**grams**
CO_2 *	**323,320**	**grams**

Results: DMU, Westbound, LAUS – Chatsworth		
Trip time	40:22	min
Propulsion energy consumed	586.55	kWh
Propulsion fuel consumed	37.75	gallons
Propulsion gallons per mile	1.33	gpm
Propulsion mpg	0.75	mpg
Propulsion emissions	Tier 3 off road	
CO	2045	grams
PM10	118	grams
NOx + NMHC	2360	grams
CO_2 (not part of Tier 3)	378,097	grams
Auxiliary power	262.5	kW
Auxiliary energy consumption	172.96	kWh
Auxiliary power fuel consumed	10.97	gallons
Auxiliary gallons per mile	0.39	gpm
Auxiliary emissions	Tier 3 off road	
CO	603	grams
PM10	35	grams
NOx + NMHC	696	grams
CO_2 (not part of Tier 2)	109,891	grams
Fuel consumption per train		
Total fuel consumed	**48.72**	**gallons**
Total gallons per mile	**1.71**	**gpm**
Total mpg	**0.58**	**mpg**
Total emissions per train		
CO	**2,648**	**grams**
PM10	**153**	**grams**
NOx + NMHC	**3,055**	**grams**
CO_2 *	**487,989**	**grams**

* EPA tiers do not address CO_2 emissions. CO_2 emissions are a direct result of fuel consumption only and not how clean an engine is operated. CO_2 values in this chart were calculated not by permissible tier limits, but by fuel consumption only

4.3 Summary: Estimated Total Emission Outputs and Energy Consumption for One VC-line Round Trip

4.3.1 EPA Tier and Other Emissions

Following is a bar chart graphically illustrating the locomotive and DMU emissions profile for carbon monoxide (CO), particulate matter (PM10) and nitrous oxide (NO_x + NMHC). The emissions are roughly equivalent for PM10, with the DMU putting out 1,000 more grams of CO than the MP-36 locomotive-haul train. The locomotive-haul train, however, puts out more than twice as much nitrous oxide as the DMU train. Also provided is a summary of CO_2 emissions (this information could not be "scaled" enough to place on the bar chart) indicating that the DMU train produces less carbon dioxide than an equivalent locomotive-haul train over the same alignment.

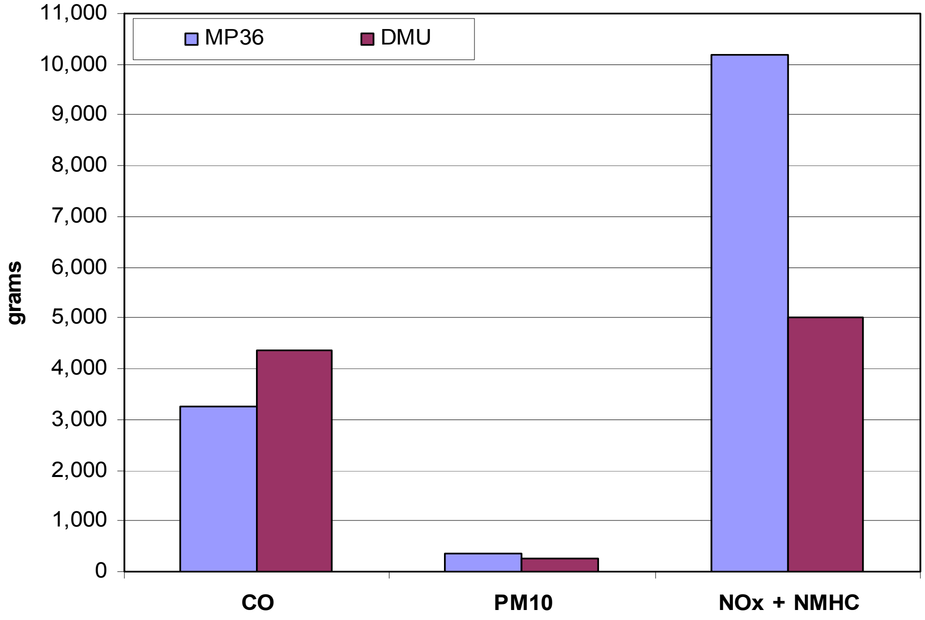

Figure 12: EPA Tier Emissions Comparison

CO_2 Emissions

- ☐ MP36 & 3 Bombardier Coaches: 919,000 grams
- ☐ DMU-Trailer-DMU: 811,000 grams

Comments Regarding Emissions

These emission calculations are based on the current regulatory requirements for new locomotives and DMUs. It is known that the refurbished MP36 engines do not comply with the Tier 2 requirements at low power loads. Since the lower power mode prevails at station stops and in braking, it is to be expected that the actual MP36 emissions are slightly higher than what the above summary shows.

Locomotive idling emissions control is also under review by the EPA. Automatic engine shutdown devices may be considered to minimize idling for emissions, fuel, noise, and maintenance concerns.

It is difficult to compare locomotive, DMU, and on-board HEP generator emissions based solely on EPA regulations in that, in most cases, actual engine levels will be less than or equal to the EPA levels. Engines tend to be tuned to match one specific emission level per EPA requirements. The resulting other levels may produce emissions less than the EPA guidelines for one or more contaminants. In general terms, DMUs will produce fewer emissions than locomotives due to stricter off-road regulations (except for CO emissions, which tend to be lower on larger diesel engines), better engine component refinements for high-volume, lower horsepower market, and lower fuel consumption. Based on this simulation, it is reasonable to conclude the following:

- The fuel consumption for the DMU train was about 29% less than for the locomotive-haul train
- Carbon monoxide emissions for the DMU train were about 38% higher than for the locomotive-haul train
- Particulate matter emissions for the DMU train were about 26% less than for the locomotive-haul train
- Nitrous oxide emissions were for the DMU train about 51% less than for the locomotive-haul train
- Carbon dioxide emissions for the DMU train were about 12% less than for the locomotive-haul train

4.3.2 Energy Consumption

The DMU consists considered in this report consume less energy to travel the same route, in the same amount of time, and carrying the same number of passengers, than a comparable locomotive-haul consist. Over a Union Station-Chatsworth round trip, the DMU consumed the following amounts of energy:

Union Station to Chatsworth (propulsion):	586.55 kWh
Union Station to Chatsworth (auxiliaries):	172.96 kWh
Chatsworth to Union Station (propulsion):	319.16 kWh
Chatsworth to Union Station (auxiliaries):	171.14 kWh
Round Trip Total:	1249.81 kWh

There was less propulsion energy consumed on the Chatsworth to Union Station run in that this run is downhill. There was less auxiliary energy consumed because this run took 74 less seconds than the Union Station to Chatsworth run.

Similarly, the energy consumption data for the locomotive-haul train was:

Union Station to Chatsworth (propulsion):	656.41 kWh
Union Station to Chatsworth (auxiliaries):	169.26 kWh
Chatsworth to Union Station (propulsion):	372.81 kWh
Chatsworth to Union Station (auxiliaries):	167.52 kWh
Round Trip Total:	1366.00 kWh

Consequently, it is apparent that the locomotive haul train uses (1366.00-1249.81)/(1366.00) = 8.51% more energy than the DMU train for essentially the same level of service. This is also reflected in the fuel consumption data. The DMU train consumed 81.00 gallons for the entire round trip, while the locomotive-haul train consumed a total of 112.95 gallons; hence the DMU train is (112.95-81.00)/(112.95) = 28.29% more fuel efficient. The DMU train is more energy efficient for the following reasons:

- Reduced train weight
- Reduced traction power need
- Higher drive-train efficiencies

The higher drive-train efficiency, plus more efficient diesel engines account for the even higher fuel efficiency of the DMU train, over and above its energy consumption advantage. It is also noted that the energy and fuel consumption advantages translate directly to a reduced emissions profile for the DMU train.

4.4 Trip Charts

Figures 13 through 17 show the train speed as a green line (typically more rounded), at any given location along the corridor. The red line (square) shows the maximum allowable track speed at every route location. The blue line, running diagonally across the chart, indicates the accumulated trip time at every route location. The y-axis on the left indicates the speed in miles per hour, and the second y-axis on the right shows the trip time, starting at 12:00 AM.

Below each main chart is another smaller chart which shows the altitude of every route location. It shows that Chatsworth is located slightly more than 600 feet higher than Los Angeles Union Station. This explains the difference in fuel consumption and emissions for east or west bound trains.

The names at the very bottom of the chart indicate station locations and other landmarks such as Control Points (CP), which require the train to slow down.

The first two charts show the simulated round trip of the MP36 train. The following pair of charts show the same round trip simulation for the DMU train.

For comparison purposes only (Figure 17), the same MP 36 simulation as in the first chart was performed absent any throttle limitations. It can be seen that the speed trace increases at maximum acceleration until a brake cycle starts. The resulting trip time difference is only about 2 minutes.

From these charts, it can be concluded that:

☐ In the westbound direction, the locomotive-haul train takes 40.21 minutes to complete the run, whereas the DMU train takes 40.22 minutes, a negligible difference.

☐ In the eastbound direction, the locomotive-haul train takes 39.53 minutes to reach Union Station from Chatsworth, and the DMU train takes 39.08 minutes, 1.14% less time.

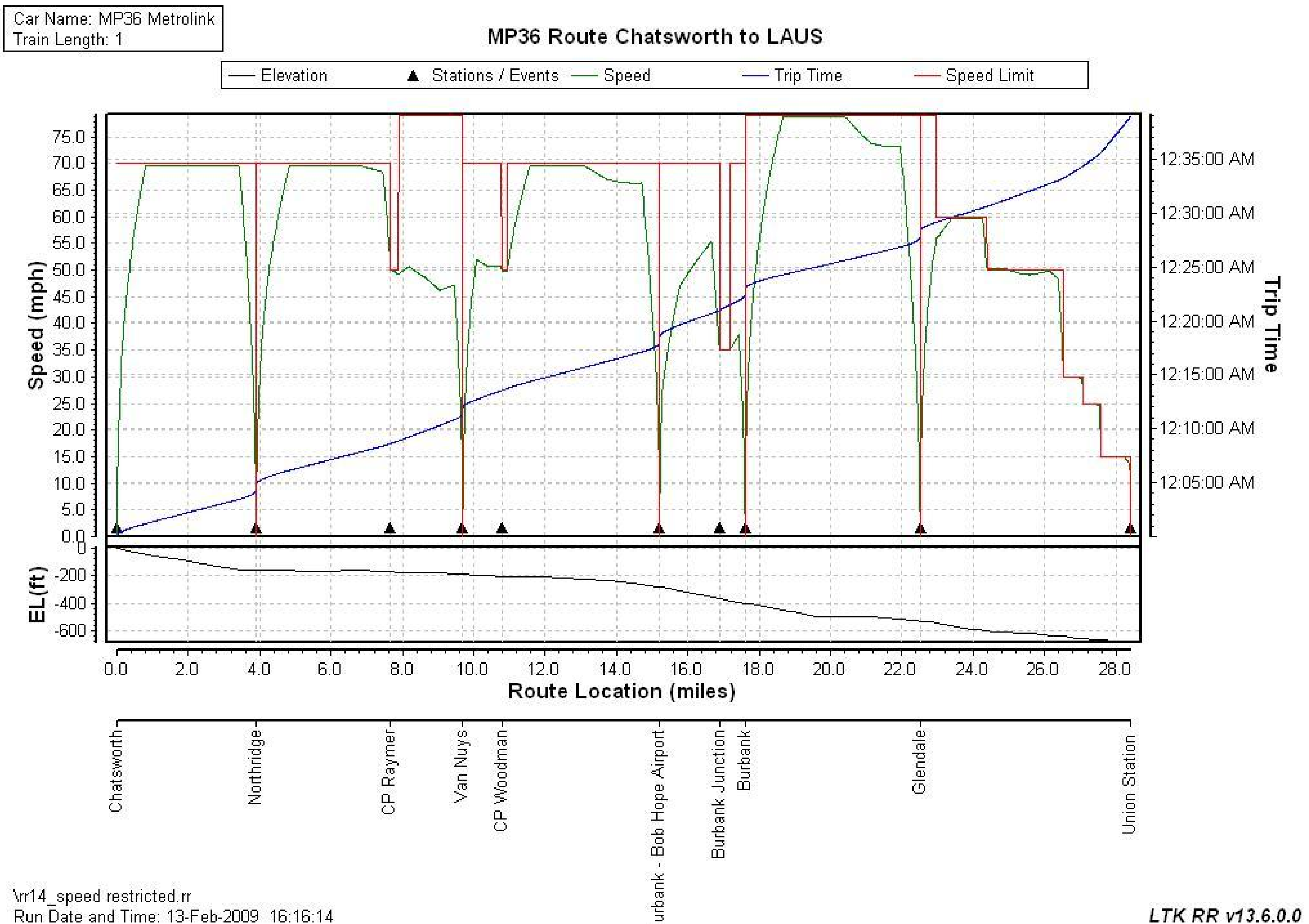

Figure 13: Trip Chart – MP36 from Chatsworth to LAUS

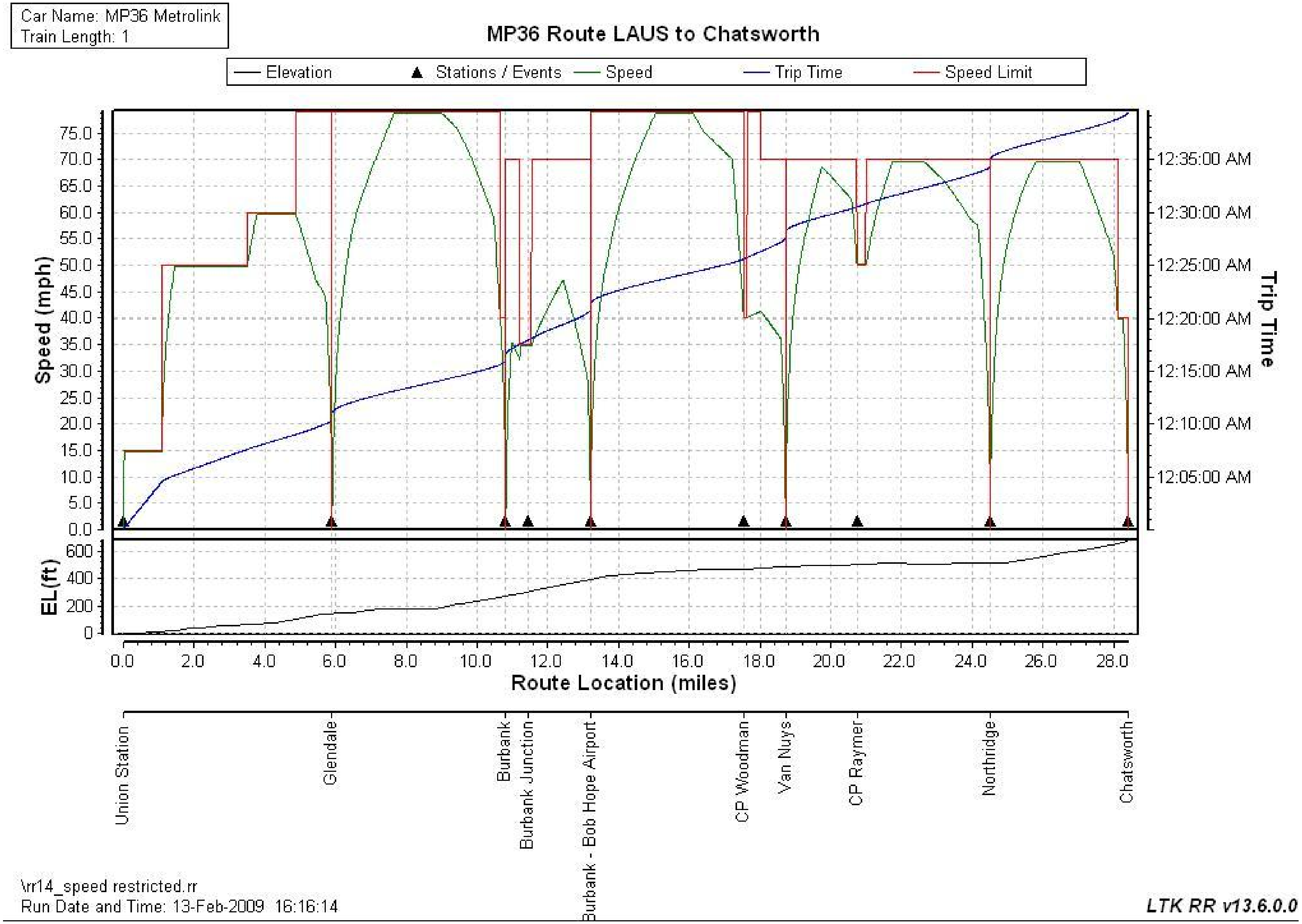

Figure 14: Trip Chart – MP36 from LAUS to Chatsworth

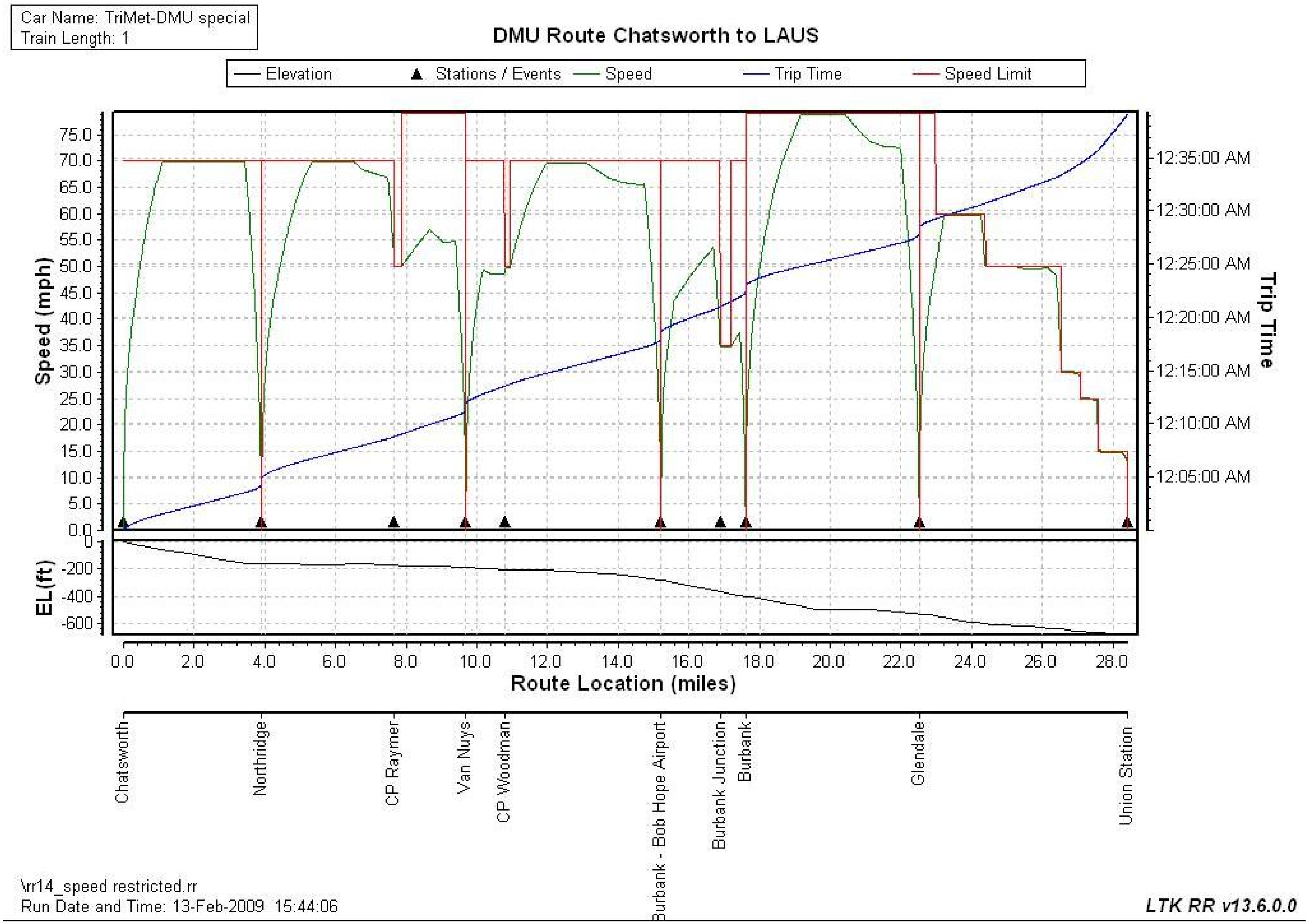

Figure 15: Trip Chart – DMU from Chatsworth to LAUS

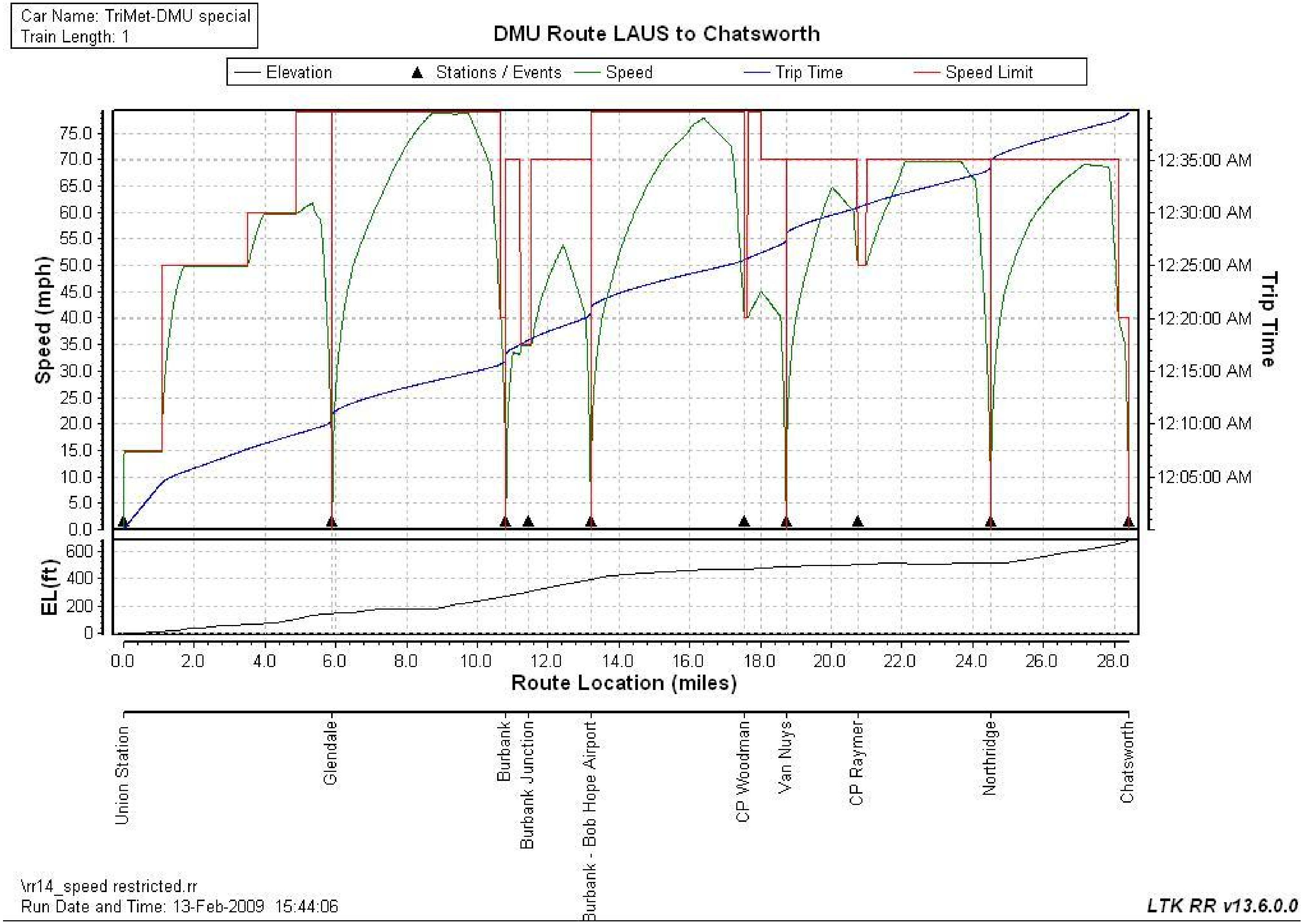

Figure 16: Trip Chart – DMU from LAUS to Chatsworth

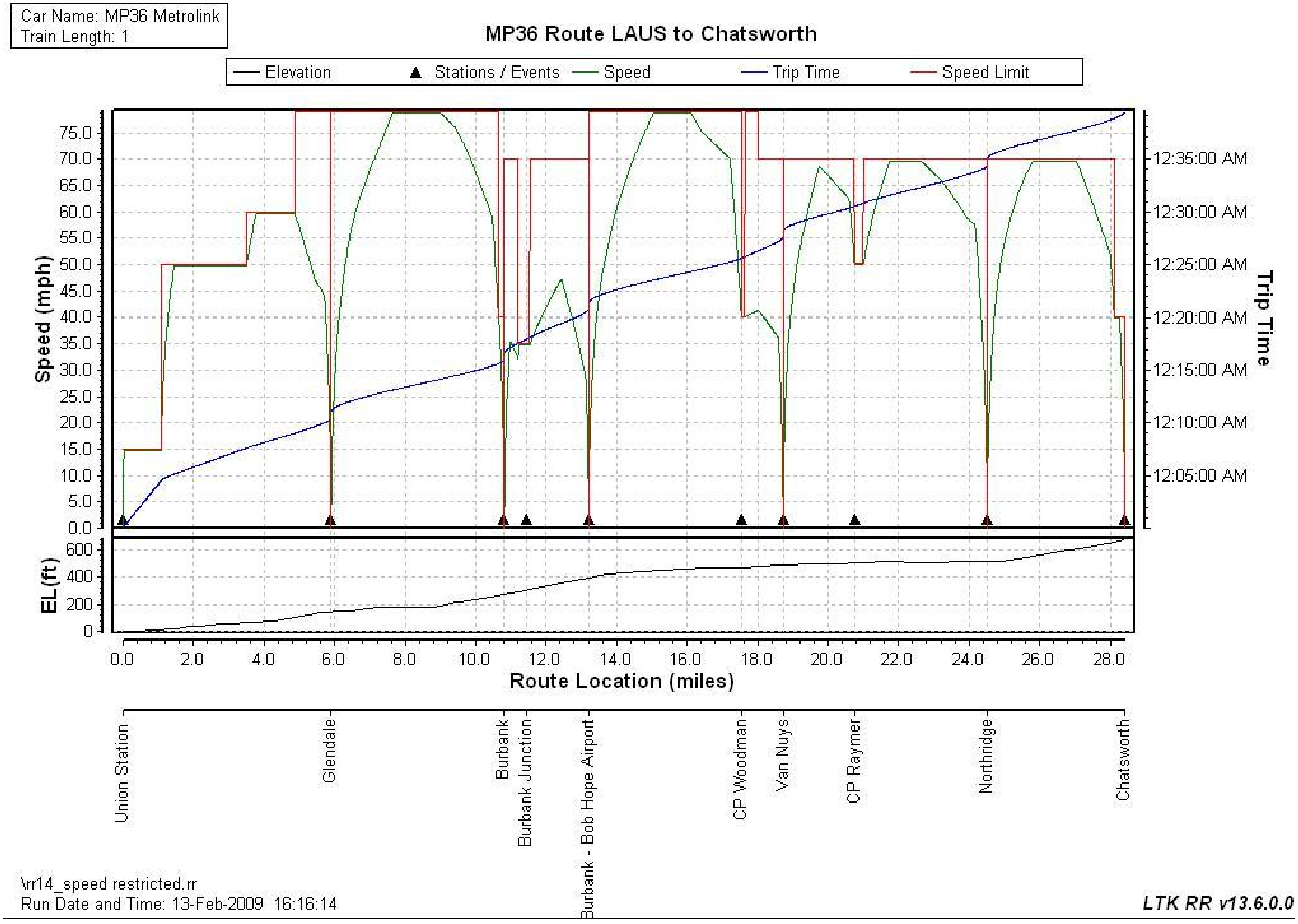

Figure 17: Trip Chart – MP36 from LAUS to Chatsworth (without throttle restriction)