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# From paper to product: Engineering a 27,000 kg fully-electric mobile railcar mover in 6 months

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**Short Abstract**

In this paper, the authors present the challenges & opportunities behind the engineering of a fully-electric mobile railcar mover. We present how building the right toolbox of simulation software, proper analysis and understanding of the duty cycle and usage of unconventional vehicles allows us to tap into their electrification potential. The authors showcase a step-by-step approach, from paper to product, simulation to assembly, of the challenges, opportunities, economic and environmental advantages of electrification. Finding the proper candidate for electrification is key – and we'll show how we did it all in just 6 months. The end result is a fully electric railcar mover which outperforms its diesel counterpart in many aspects.

## 1 Introduction

In this paper, the authors present the challenges & opportunities behind the engineering and commissioning of a fully-electric mobile railcar mover. With the current government push for new regulations to reduce fossil fuel consumption and greenhouse gas emissions in many cities and port towns, Nordco, a world-leader in railway maintenance service and technologies, is paving the way with the first zero-emission mobile railcar mover. These vehicles, used in rail yards and maritime ports across North America, are well suited to allow operators to reach their electrification goals. The emphasis of this paper is going to be on the engineering challenges behind designing a 30 tons electric vehicle, it's electrical and mechanical architecture, and how properly analyzing and understanding the duty cycle and usage of unconventional vehicles allows us to tap into their electrification potential, which would usually be overlooked due to the sheer size of these vehicles.

## 2 Finding a candidate for electrification

Not all vehicles are good candidates for electrification – long-haul transportation, energy intensive applications – and finding good, overlooked and out-of-the-box applications requires a sound understanding of the duty cycle and usage of these vehicles. Specific to this application is the duty cycle and usage of the vehicle – very high power and torque, but low energy - as it is used a few hours a day, with pulls of varying intensity and length, over short distances. These vehicles, kept in rail yards and maritime ports, are used to move loaded railcars, are more versatile and less costly to operate than locomotives.

Due to the various on-board auxiliary systems (hydraulics, compressed air) and the requirement for cabin temperature management, these pieces of heavy machinery are often left idling for long periods of time between use – resulting in wasted fuel and unnecessary vehicle emissions. Electrification opens the possibility to control the auxiliaries independently, allowing us to cycle loads on & off when needed and optimize energy use while the vehicle is stationary.

Figure 1- Nordco NVX5025e Electric Shuttlewagon undergoing rigorous testing in Kansas City, MO.

Understanding how and where these vehicles are used is key to identifying compatibility with electrification, mainly due to the energy density of current battery technology. A single kilogram of diesel fuel holds nearly 10 kWh of energy, whereas the densest lithium-ion cells suited for an automotive market will hold around 0.2 kWh / kg – about 50 times less energy when compared to diesel fuel. Even though electric vehicles are more than 3 times as efficient as their diesel counterparts, we are still a long way from fossil fuels. However, this mentality from the automotive market shouldn't carry over to specialized land vehicles – and here's why:

A quick glance at this vehicle could scare away any thoughts of electrification due to its sheer size. However, its size is not irrelevant: these vehicles are purposely developed to be heavy in order to increase the tractive effort at the wheels. In this case, replacing a diesel powertrain with 1800kg of lithium-ion batteries is not an issue – but could be seen as one if the application is not properly understood.

## 2.1 Tapping into the electrification potential of specialized land vehicles

When researching the feasibility of electrifying different vehicles, the most important factor is understanding the duty cycle and use of these vehicles. A baseline comparison with the fossil-fuel equivalent gives us a good idea of the power & energy requirements that we will need to meet. This allows us to quickly determine the economic feasibility and electrification compatibility of all kinds of vehicles.

In the case of the Nordco NVX5025, Nordco and LTS Marine inc., the lead integrator on the project, looked first at the specification of the current diesel powertrain, as well as the fuel consumption based on different scenarios (idle, full-power pull, etc.). By taking into account the efficiency of the diesel powertrain, we were able to quickly estimate the required energy (kWh) and power (kW) for the electric counterpart:

Table 1 – Powertrain requirements of the Nordco NVX5025

| Engine | Cummins QSB6.7 with torque converter | Electrified Powertrain *Estimated Requirements* |
|---|---|---|
| Displacement | 6.7L | |
| Stall torque | 1025 lb-ft (1391 Nm) | 1288 Nm |
| Horsepower | 215 @ 2500 RPM | Approx. 160 kW |
| Wet weight | 475 kg | |
| | | |
| Avg. Fuel Consumption | 1.3 gal/h | Based on data from Nordco NVX5025 use in the field |
| Equivalent kWh | 127 kWh | Assuming 30% diesel PT efficiency, 8hr shift |

This simple estimation allowed the project team to get a quick idea of the compatibility with powertrain electrification – 160kW, 990 Nm at the motor shaft, and a minimum of 127 kWh of batteries would be required to meet more-or-less similar performances.

Knowing therefor that the required powertrain specifications are attainable using an electric powertrain, we could further the analysis by carefully evaluating how the diesel equivalent vehicles were used on a daily basis. Nordco provided all the operational data on its vehicles, including average fuel consumption, average length of a work shift, etc. This allowed us to quickly understand the power and energy requirements, allowing us to target battery and power train components well suited for this application. Had this information not been available at the time, a simple data logging of the vehicle could have sufficed.

Throughout various vehicle electrification projects, we have developed a short list of key indicators to help us identify candidate vehicles for electrification:

- Identifying the key indicators for compatibility with powertrain electrification
    - High-Torque/Low Speed Applications
    - High-Power/Low Energy Applications
    - ICE vs Electric powertrain operating points
    - Applications with high idle times
    - Applications with multiple auxiliary systems
    - Low distance applications

- Identifying potential candidates in niche markets
    - Specialized land vehicles
    - Subsidized markets, with purchase or operating incentives for green tech

- Rough estimate of compatibility
    - What is the power requirement? (kW)
    - What is the energy requirement? (kWh)
    - What is the duty cycle?

- For more complex situations, a simple model and analysis can be elaborated
    - Matlab Simulink Advisor for battery, powertrain and cycle evaluation

This analysis allowed us to confirm the Nordco Shuttlewagon NVX5025 as an ideal candidate for electrification. Without this analysis, we could have easily overshot the power and energy requirements, which may have negated the economic and operational feasibility of this project.

# 3 Vehicle architecture and sizing of components

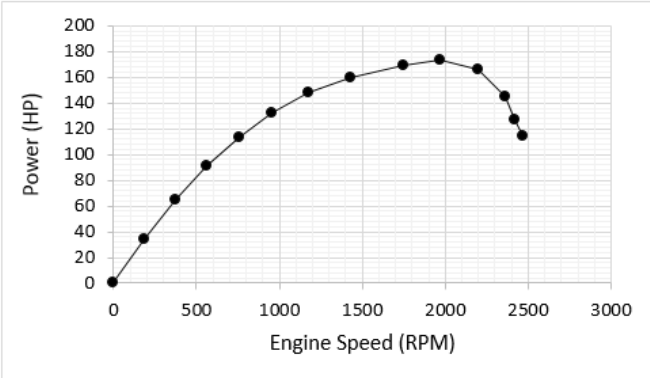
Our previous estimations gave a rough idea of the powertrain requirements. However, the different power curves and performances between diesel and electric motors must be taken into account, and so does the difference between the method in which the auxiliary components are powered.

Specific to this application is the requirement for high torque in order to displace up to 40 loaded railcars at speeds of up to 10 MPH continuously for up to 15 minutes. This demands that the system be designed to maintain and support a very high-load operation for extended periods of time.

Based on previous simulation results, the electric powertrain was selected to meet the continuous power requirements of this application. The table below shows the performances of both the current diesel powertrain and the Canadian-made TM4 Sumo MD LSM200C-2300 permanent magnet motor:

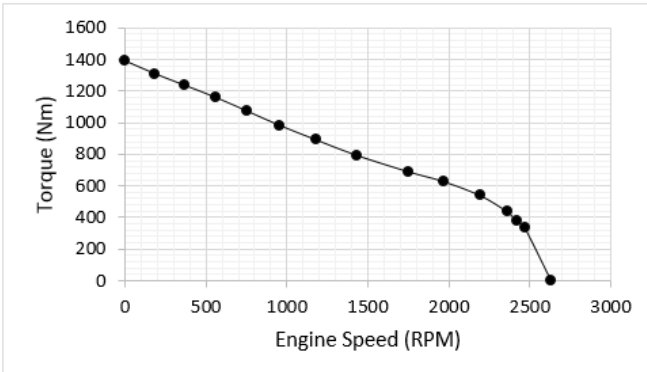
| Powertrain | Cummins QSB6.7 with torque converter | TM4 Sumo MD LSM200C-2300 |
|---|---|---|
| Stall torque | 1025 lb-ft (1391 Nm) | 2300Nm peak; 1230 Nm continuous. |
| Horsepower | 160kW @ 2500 RPM | 200kW peak; 150kW continuous. 2350 RPM max. |
| Wet weight | 475 kg | 220kg + 36kg (motor + inverter, dry) |

In order to select the proper electric motor for this application, the performance curves of the Cummins QSB6.7 coupled with a torque converter were analysed to ensure an electric motor would provide similar or better tractive power. Below, we can see that the peak torque of 1390Nm is developed at the stall torque of the torque converter (nT = 0), and the max power output of 130 kW is developed at 1970 RPM:




**Power Output - QSB6.7 with Torque Converter**

| RPM | hp | kW |
|---|---|---|
| 0 | 0 | 0 |
| 200 | 37 | 28 |
| 400 | 69 | 52 |
| 600 | 98 | 73 |
| 800 | 121 | 90 |
| 1000 | 138 | 103 |
| 1200 | 150 | 112 |
| 1400 | 156 | 116 |
| 1600 | 168 | 125 |
| 1800 | 175 | 130 |
| 2000 | 176 | 131 |
| 2200 | 166 | 124 |
| 2400 | 134 | 100 |
| 2600 | 114 | 85 |




**Torque Output - QSB6.7 with Torque Converter**

| RPM | ft-lb | N-m |
|---|---|---|
| 0 | 1025 | 1390 |
| 200 | 966 | 1310 |
| 400 | 902 | 1223 |
| 600 | 839 | 1138 |
| 800 | 778 | 1055 |
| 1000 | 716 | 971 |
| 1200 | 654 | 887 |
| 1400 | 594 | 806 |
| 1600 | 541 | 733 |
| 1800 | 496 | 673 |
| 2000 | 457 | 619 |
| 2200 | 405 | 549 |
| 2400 | 300 | 406 |
| 2600 | 67 | 91 |

Figure 2 - Cummins QSB6.7 Performance Curves with torque converter

A well-known advantage of electrifying the powertrain is the permanent-magnet motors intrinsic property of supplying maximum torque at 0 RPM, however in this particular application both the ICE and electric powertrain have similar characteristics due to the torque converter. In this particular application, we found that the torque converter could be eliminated from the power train and that coupling the electric motor directly to the transmission would amount to superior tractive effort. Eliminating the torque converter also greatly improved the overall efficiency of the powertrain and extended the electric machine's range significantly.

The curve below shows the performances or the TM4 LSM200 motor, with the motors iso-power curve for peak and continuous power from 800 RPM to 2350 RPM at 450 VDC:

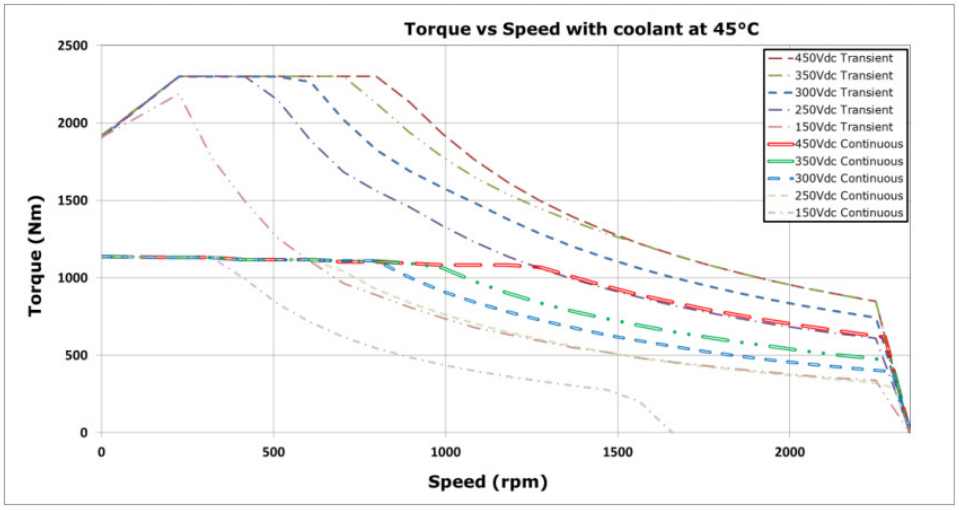



Figure 3 -TM4 LSM200C-2300 Performance Curves[1]

The simplified architecture below outlines the diesel powertrain of the NVX5025. From engine to wheels, there's a combined reduction ratio of over 130:1, in order to generate the tractive effort necessary to displace the railcars. A multi-speed gearbox is used in order to reach the torque requirements using the QSB engine.

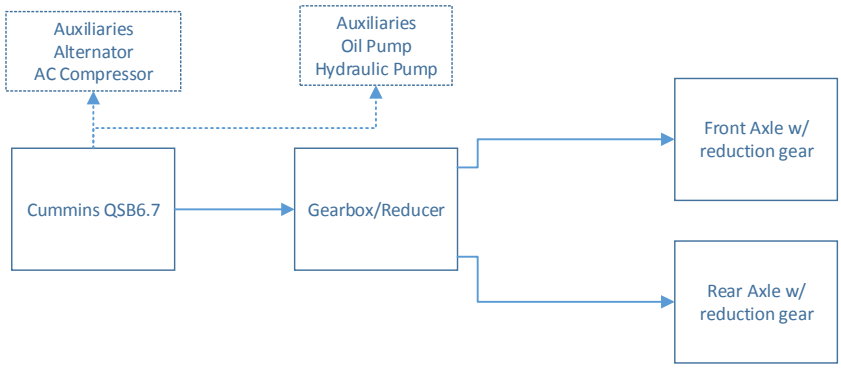



Figure 4 – Nordco NVX5025 simplified architecture

## 3.1 Electric Powertrain

This specific application has a requirement for very high starting torque in order to displace up to 40 loaded railcars at speeds up to 10 MPH. Electrifying the powertrain allows us to develop more torque at a lower RPM, thus possibly eliminating the need for a multiple speed gearbox. For the prototype vehicle, it was decided that the gearbox be left in place, even though the electric motor torque would have to be limited to the maximum gearbox input torque. The TM4 motors torque was electronically limited to 1390 Nm, instead of the 2300 Nm peak that it can attain. This was to ensure that the electrified vehicle could attain the same performances as the diesel powertrain, as we profit from the torque multiplication of the multi-speed gearbox.

The electrified powertrain, as shown below, demonstrates the removal of the QSB engine and the electrification of the auxiliary components.

[1] Not to be used as a reference for new designs. Contact TM4 for updated performance curves.

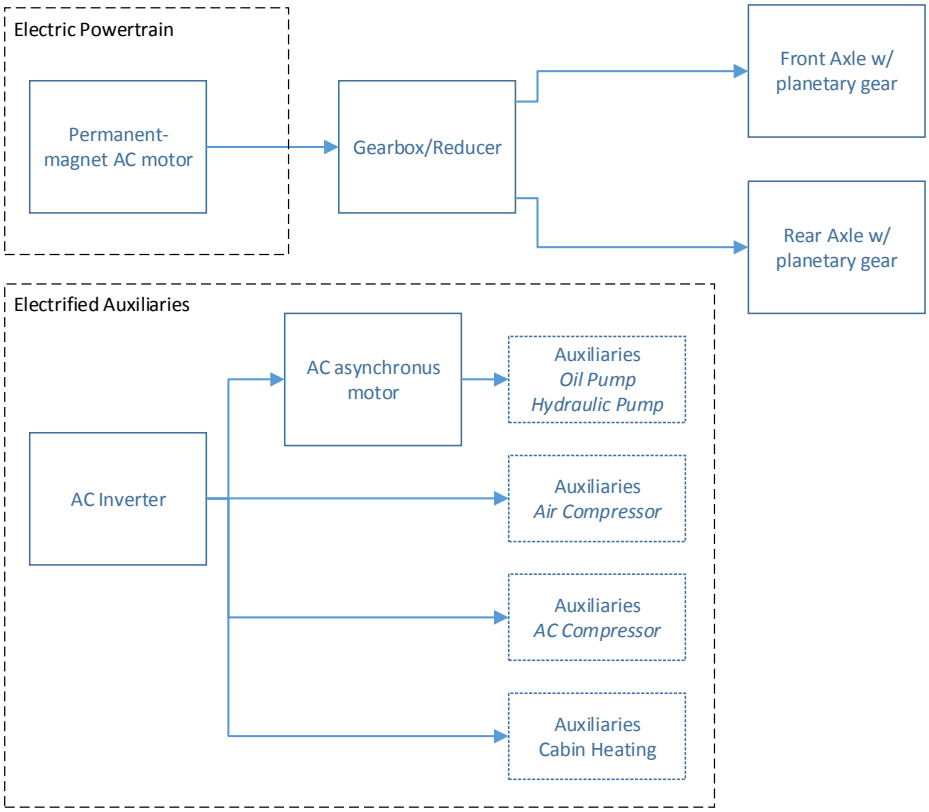



Figure 5 – Nordco NVX5025 simplified architecture after powertrain electrificaton

## 3.2 Electrifying the auxiliaries

Specific to the Shuttlewagon's architecture – which differentiates it from conventional automotive architectures - is the amount of auxiliary components that must be electrified: dual hydraulic steering axels, air and hydraulic couplers & pumps, rail wheels, air activated sanders and more. In the conventional vehicle with an internal combustion engine, all these accessories are coupled to power-take-off outputs. What this meant is that all the devices would operate in parallel, together, and not in an independent manner, and require that the diesel engine powers all the accessories, even if only a single one is needed. While this approach is fine, as the auxiliaries are mainly used while the vehicle is in motion, we identified that these systems could be improved in the electrification of the powertrain. This allowed us to selectively activate the required systems during operation, thus optimizing the power consumption of the vehicle and extending the time between charges. Also, by electrifying auxiliaries we were able transfer 100% of the traction motor power to tractive effort without losses usually attributed to multiple PTO's

In search for a low-cost/high reliability solution, it was decided that auxiliary pumps would be powered by a simple asynchronous AC induction motor, powered by an inverter feeding off the high-voltage DC bus. These low-cost motors are widely used in industrial applications, and although they are not designed to be lightweight or compact, this was not an issue with this type of vehicle. In addition to the auxiliary electric motor, the same inverter powers the cabin AC compressor and heater as well as a standalone high capacity electric air compressor

## 3.3 Battery pack engineering

The battery packs for this project were custom designed by LTS Marine for high continuous load vehicle electrification. Our previous estimations allowed us to determine the battery capacity that would be needed to meet the use case requirements. Knowing that we would be able to reclaim a significant amount of energy from a convoy of fully loaded train cars through regenerative breaking, this added a safety margin to our estimation, total energy consumption would be much less than that of the baselined diesel model.

LTS Marine developed a custom architecture, composed of 6 parallel high-voltage packs operating between 250-400VDC. This parallel architecture allows for redundancy, as the system can still function in the odd event of a failure in a single or multiple packs. The unique liquid cooling interface allows for heating and cooling of the packs, based on cell temperatures. The packs are also engineered to eliminate the possibility of coolant entering the packs in case of a leak in the cooling system. This makes for a redundant, fail-safe architecture which can be used in a wide-range of ambient temperatures.

### 3.4 Mechanical considerations

As discussed previously, in this specific application, the overall system weight was not a limiting factor. However, a proper analysis of the use-case of this vehicle allowed us to identify specific mechanical requirements which arise during the coupling phase between the Shuttlewagon and the railcars.

During the coupling, the vehicle advances towards the railcars and can suffer a deceleration of up to 8Gs upon contact, due to the sheer weight of a train of up to 40 railcards. This excessive force must be taken into account in the design of the battery brackets and motor mounts.

A finite element analysis (FEA) was developed in order to ensure the design of the battery brackets, motor mounting and energy absorbing capacity of the driveshaft were sufficient in a variety of different load cases.

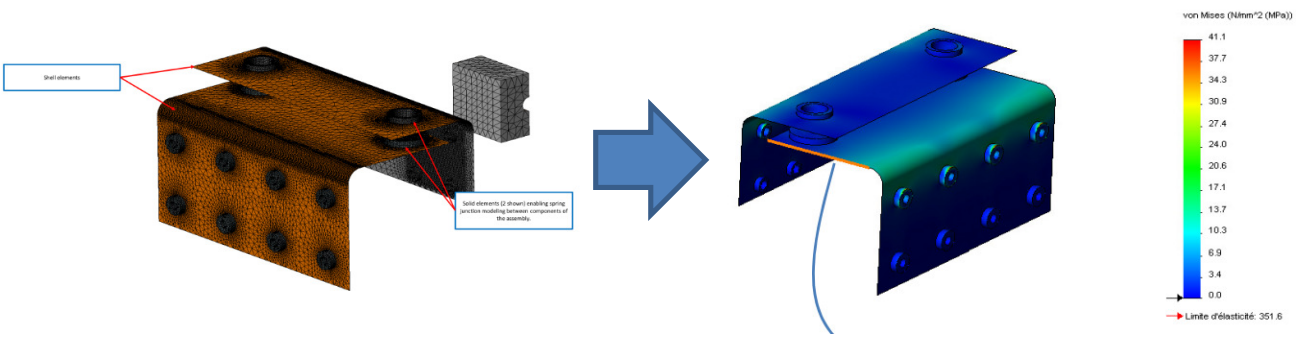



Figure 6 - FEA analysis of the motor mounts during high-stress load cases

One important consideration was that by removing the torque converter, the decoupled mechanical link between the motor and wheels was no longer present in the powertrain. Therefore, when the vehicle would be suddenly halted upon impact with the railcars, the driveshaft would be subjected to the rotational inertia of the TM4 motor. By careful analysis of the energy absorbing capacity of the driveshaft, it was determined that the driveshaft would be able to support all of the worst-case scenarios of a sudden stop.

## 4 Results

Real-world testing of the electric Shuttlewagon is on-going since August 2015. The data collected thus far has been compared to the estimations and analysis completed beforehand, and shows with stunning accuracy how the tools and simulations represent real-world usage. So far, testing has shown that the electric Shuttlewagon can keep up with its Diesel counterpart, and then some – the electric version of the Shuttlewagon can pull more than the similarly equipped Diesel version. This retrospect allows us to understand how rated power alone is not the key indicator for sizing internal-combustion engines and electric motors – we must consider how the operating points of the engines are different and how we can maximise efficiency by going electric.

Figure 7 - Prototype testing in the outskirts of Kansas City, MO.

## Acknowledgments

The authors would like to acknowledge Nordco for its willingness to think outside the box and go where no other manufacturer has gone before.

## References

[1] *Nordco NVX5025e 'Electric'*, http://www.nordco.com/products-catalog/mobile-rail-car-movers/navigator-series/NVX5025e.htm, accessed on 2015-10-28

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Marc graduated in electrical engineering from l'École de technologie supérieure in 2012, where he specialised in microelectronics, digital signal processing and real-time programming. Marc has developed a battery management system, contributed to the development of multiple lithium-ion battery packs for heavy vehicles, designed electric and hybrid vehicle architectures and lead the commissioning of on-road and marine vehicles. He currently holds a position of project manager at the Innovative Vehicle Institute.

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