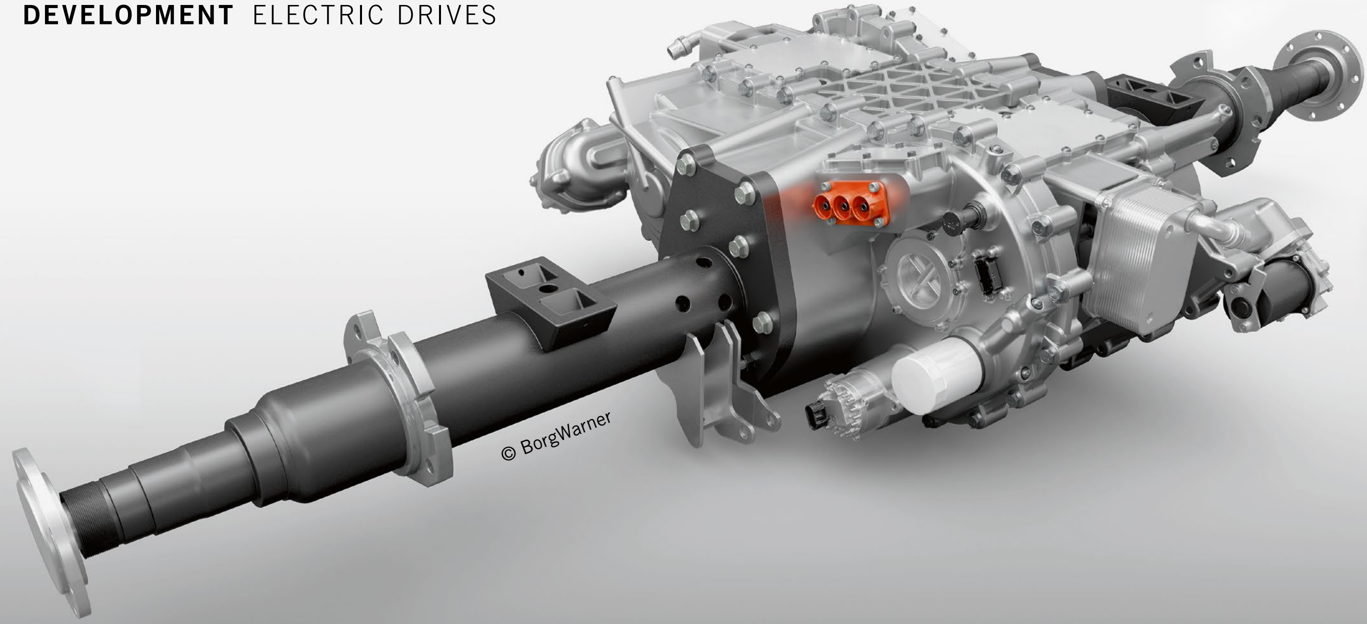

Electric Axles for Medium-duty Commercial Vehicles

WRITTEN BY

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BorgWarner has designed, built, and tested several electrified axles for medium duty commercial applications. The company's experience with the key components that make up the axles – including the motors, inverters, and transmissions – as well as its system level simulation capabilities regarding batteries, on- and off-board charging systems and thermal management components allowed for an optimization from a total vehicle perspective.

The electrification of Medium-duty (MD) commercial vehicles presents a complex set of design challenges. Due to the missions these types of vehicles must complete, a unique set of performance, efficiency, and durability targets must be achieved while ensuring that stringent weight, size, and cost requirements are met. All vehicle manufacturers define their own set of propulsion system requirements for the vehicle they want to build. These requirements can vary depending on Original Equipment Manufacturer (OEM), vehicle segment, model, and variant. These requirements set the foundation for propulsion system design and define the basic features of the vehicle like performance, efficiency, durability, safety, manufacturing, and serviceability. All specifications must be achieved while ensuring that weight, size, and cost targets are met.

REQUIREMENTS FOR COMBUSTION ENGINES VERSUS ELECTRIC DRIVES

Propulsion systems are designed in such a way that the power and torque outputs fulfill all defined performance requirements. For a vehicle powered by an Internal Combustion Engine (ICE), there is only one torque and power curve which is its peak torque and power respectively. Whereas for electric drives, there are usually two curves – for the peak torque and power, which can usually only be maintained for a few seconds, and for the continuous torque and power, which can ideally be maintained indefinitely.

So, when designing an electrified MD truck with equivalent characteristics of its ICE powered counterpart, the performance requirements should be divided into peak and continuous power or torque. Drive situations that occur for a limited, and often short, duration are categorized as a peak performance requirement. Situations that are sustained for longer periods, typically longer than 30 s, are categorized as a continuous performance requirement. Because of the different characteristics of the torque curves, it is difficult to directly compare the performance of a Battery Electric Vehicle (BEV) to an ICE-powered one.

Another large difference between ICE vehicles and BEVs is the performance at near zero speed. As ICEs cannot deliver sufficient torque at low engine speeds, a friction clutch or torque converter is used. BEVs on the other hand use motors that can deliver very high torque at zero speed.

KEY REQUIREMENTS FOR DESIGN DECISIONS

Peak motor torque in a BEV is based primarily on the launch torque requirement with a fully loaded trailer on a maximum grade or when climbing a curb. The continuous torque and power is typically based on cruise speed requirements at various loading and grade situations. The gear ratio also plays an important role ensuring the vehicle can both cruise at its maximum velocity and achieve all its peak torque requirements at low speed. Multi-speed transmissions can help satisfy all the requirements and can avoid unnecessary oversizing of the motor. **TABLE 1** summarizes how the different parameters affect the final vehicle performance.

System parameter	Affected vehicle performance
Peak motor torque at low speeds	Launch torque requirements for maximum loading and maximum grade
	Curb climb torque with fully loaded vehicle
Continuous motor torque at low speeds	Crawling on grade with fully loaded vehicle with trailer
Peak motor power	0-100 km/h acceleration time
	Acceleration capability at high cruising speeds
Continuous motor power	Cruising at maximum vehicle velocity
	Cruising at high speeds on grades with fully loaded vehicle with trailer
Gear ratio	Launch torque requirements, curb/climb torque
	0-100 km/h acceleration time
	Maximum vehicle velocity

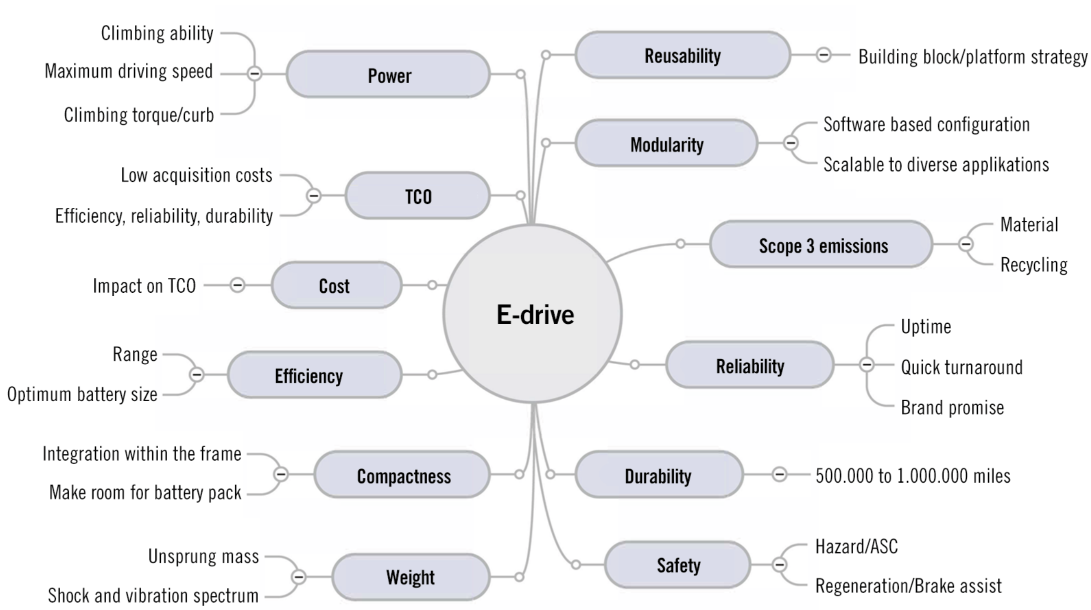
TABLE 1 System parameters and the affecting vehicle performance (© BorgWarner)

SYSTEM DESIGN OPTIMIZATION PROCESS

As shown in **FIGURE 1**, there are entire sets of requirements covering for example reusability, scalability, and emissions. Since the challenge is to optimize against competing metrics, a Multi Objective Optimization (M-O-O) method is deployed, an example of such an approach is outlined in **FIGURE 2**.

BorgWarner designed and built several electrified axle (e-axle) solutions utilizing the optimization processes described. The two designs presented here meet a variety of vehicle require-

FIGURE 1 Design space metrics for heavy-duty e-axle (© BorgWarner)



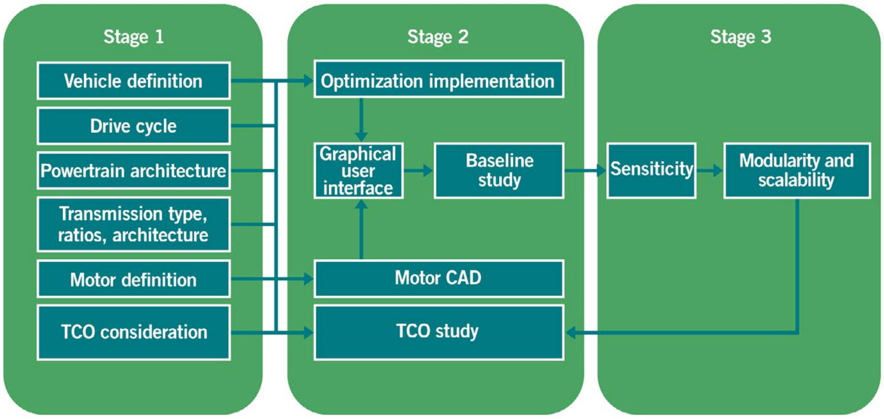


FIGURE 2 Multi objective optimization process (© BorgWarner)

ments for different applications. One solution utilizes a front drive e-axle with a separate rear drive e-axle, the second solution applies a single rear drive e-axle. The designs and specifications of both solutions are provided in the following descriptions.

TWO-AXLE DESIGN

BorgWarner has implemented an all-wheel drive system with two fully integrated e-axles to meet vehicle platform requirements for a range of MD trucks. The design space spanned a wide range of gross vehicle weight, and functional class, **TABLE 2**. The prime objective of the design was to maximize the scale of production and serve the vehicle space with component-commonality. A, B, C, D and E designate the different configurations. The system was designed to achieve all low speed with high torque maneuvers, and top speed and highway speed towing capabilities.

Traditional ring and pinion axle assemblies are standard designs for the current production trucks. This relatively radially slim architecture was a difficult challenge to replace with electric drive componentry. The vehicle package space allows for cross vehicle orientation of the motor axis, with an additional large gear reduction ratio. The developers resolved these constraints with the use of stacked planetary gearing architecture similar to automatic transmissions. The drive motor design was adapted from current technology to a radially concentric design. This architecture is implemented for both front and rear axle assemblies.

The front axle was designed with a 16:1 reduction gear ratio from motor output to wheel input. For the larger and heavier applications, a 17:1 ratio was selected. For the rear axle, a single 16:1 gear ratio was selected to achieve all at-speed drive functions. To achieve low speed drive functions, an auxiliary additional gear ratio of 48:1 was included. The torque path of the drive is mechanized through a simple dog clutch, and the gearbox is shifted with an additional motor actuator and shifting cam.

The overall system was designed for synchronized range shifting. Shift motor capability provides for Electronic Control Unit (ECU) controlled shifting combined with drive motor synchronization for torque interrupted on-the-fly range shifts. In addition, the mechanical architecture provides for integrated park actuation utilizing an actuator and external vehicle system control.

The interior permanent magnet motor from BorgWarner is designed for 800-V power system compatibility. In tight integration with the mechanical geartrain design, a 280-mm armature design was developed from current technology to achieve the high torque and power drive loads required for MD trucks. The electric drive circuit is designed to sustain 800 A peak current and 450 A continuous current. The motor is cooled using an auxiliary pump providing oil cooling flow.

The 380-kW silicon carbide-based axle-mounted inverter is compatible

	Parameter	Unit	Pick-up (Class 3)	Cab chassis (Class 5)	Pick-up (Class 5)	Utility (Class 6)
Vehicle weight	Gross axle weight front	kg	2900	2800	2900	3300
	Gross axle weight rear	kg	5600	5300	5600	6900
	Gross vehicle weight	kg	6000	8000	8400	10,100
	Gross combination weight	kg	14,000	16,800	23,000	23,000
E-axle design	Front axle Pkg	-	A			B
	Rear axle Pkg	-	C	D		E
	Front gear ratio	-	16:1			17:1
	Rear gear ratio	-	Two-speed: 16:1/48:1			
	Front/rear motor	-	Interior permanent magnet machine, stator with 280 mm outer diameter			
	Inverter	-	800-V SiC			
	Motor power	kW	425 (peak), 310 (continuous)			

TABLE 2 Two-axle design solutions (© BorgWarner)

with 800-V system architecture and is able to support both the peak and continuous current demands of the motor. The inverter package was developed for compact electromechanical integration directly on the beam axle assembly. **FIGURE 3** illustrates the front and rear axle assembly exterior packages.

The system is optimized to achieve best efficiency, thereby reducing energy consumption, and achieving the desired range with a smaller battery pack. **FIGURE 4** shows the total system efficiency graph for the rear axle when gear 2 (ratio 16:1) is active. The system efficiency calculated includes the efficiencies of the inverter, electric motor, and transmission. The system has a peak efficiency of 94 % and a large region of efficiency greater than 92 %.

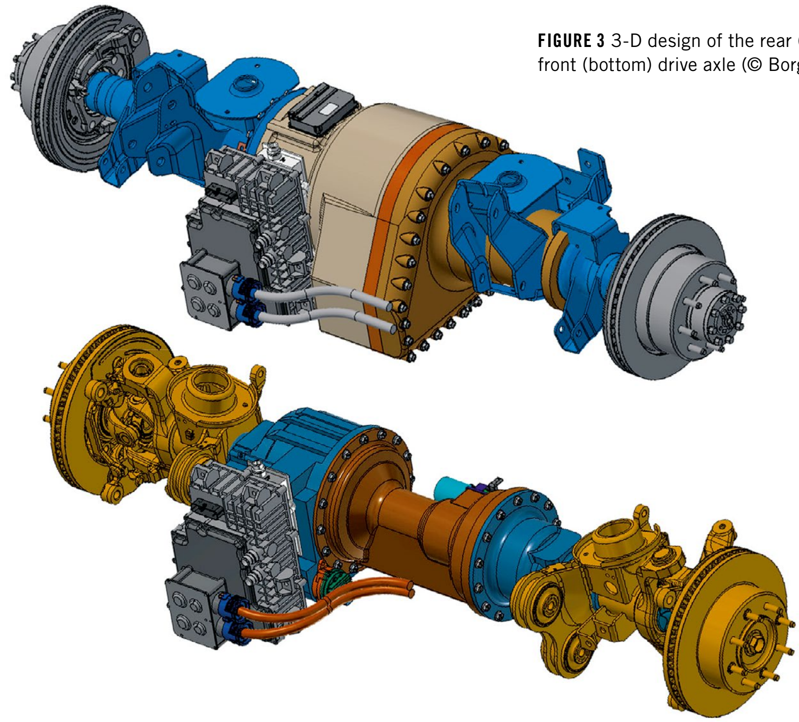


FIGURE 3 3-D design of the rear (top) and front (bottom) drive axle (© BorgWarner)

SINGLE-AXLE DESIGN

A single-axle proof-of-concept drive was also designed and built, which consists of an electric beam axle with two electric motors including reduction gears, each driving one wheel (dual motor). This configuration incorporates two planetary gear sets interconnected by a chain set. This arrangement yields three reduction stages, culminating in a high overall ratio in a compact space. The design is executed within a parallel shaft configuration. The key parameters of the single e-axle design as well as the demonstration vehicle parameters are given in **TABLE 3**.

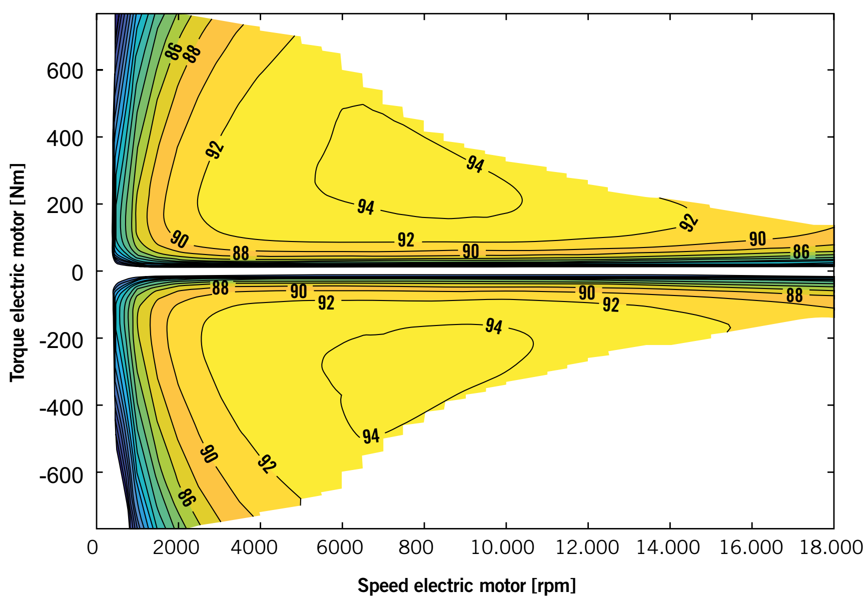


FIGURE 4 System efficiency for rear drive axle in gear 2 (ratio 16:1) (© BorgWarner)

DEMONSTRATION VEHICLE

The development vehicle chosen was the 2021 Ford F550 Super Duty Crew Chassis XL dump truck. This base model comes equipped with a naturally aspirated 7.3-l V8 gasoline engine with dual equal variable camshaft timing and port fuel injection, and a ten-speed automatic transmission. The objective was to build a rear-wheel drive prototype vehicle with the new e-axle that not only matches but surpasses the performance and capabilities of the stock vehicle. The dual motor prototype provides a peak output torque of 13,000 Nm and a maximum vehicle speed of 137 km/h.

In addition to the e-axle, three battery packs with a total capacity of 99 kWh were installed. Due to the significant impact of ambient temperatures on the efficiency and performance of BEVs, the vehicle was equipped with a purpose-developed thermal management system with high-voltage coolant heaters for the battery and cabin.

SIMULATED PERFORMANCE RESULTS

In this section, some performance results are shown for on-vehicle testing on the demonstration vehicle as well as simulated performance using a model of this vehicle and applying both the single-axle and the two-axle solution. The intention here is not to show the comparison between the two e-axle solutions, as these were developed based on different sets of requirements. Instead, it gives a sense of how different drive solutions and their specification impact the system performance.

	Parameter	Unit	Value
Vehicle weight	Curb weight	kg	4850
	Gross vehicle weight	kg	8850
	Gross combination weight	kg	12,700
E-axle design	Gear ratio	-	22:1
	Motors	-	2x high-voltage hairpin stator with 220 mm outer diameter
	Inverter	-	800-V SiC
	Motor power	kW	285 each 570 total
Battery	Voltage	V	800
	Capacity	kWh	99

TABLE 3 Key parameters of the single e-axle design (© BorgWarner)

The single axle solution is designed by looking at the component availability and packaging on an already built vehicle. Whereas the two-axle solution was designed for a set of new vehicle variants (from class 3 to class 6 trucks). So, this dual axle powertrain is oversized for the vehicle considered and only considered in the simulation.

FIGURE 5 shows the tractive force diagram for the vehicle, with solid lines for the peak output and dotted lines for the continuous output. The actual motor output at the wheels (considering 95 % transmission efficiency) is plotted for both single-axle and two-axle systems. The black curves show the traction output from the single-axle system. The blue curves show the traction output of the two-axle system. For the two-axle solution, the vehicle is using the normal driving gear (second) on the rear. The red curves show the two-axle output when rear gear 1 is active. This is only activated at certain special maneuvers when there is a very high wheel torque requirement.

BorgWarner has developed a vehicle system simulation toolset [1] which helps to analyze efficiency and performance for various vehicle architectures. The same tool was used in this case to evaluate the acceleration performance of the selected vehicle configurations.

FIGURE 6 shows the simulated acceleration times from 0 to 100 km/h for the two vehicle configurations considered. The test was carried out at different loading conditions, namely the curb weight, the gross vehicle weight, and the gross combination weight. The single-axle performance is in the acceptable range for the vehicle segment. However, the two-axle drive performs very well, bringing down the acceleration time to half in comparison to the single-axle drive. This is mainly due to the over-sized powertrain for the given vehicle having almost double the system power compared to the single-axle drive. Also, due to two driving axles, it can bring more tractive force without slipping the tires. The intention here is to show the simulation capability and visualize the system power impact on the acceleration performance.

ON-VEHICLE PERFORMANCE RESULTS

FIGURE 7 shows the comparison of the acceleration times from 0 to 100 km/h of the simulation results and the on-vehicle measurements for the single-axle vehicle. Also, the performance of the ICE powered stock vehicle is shown

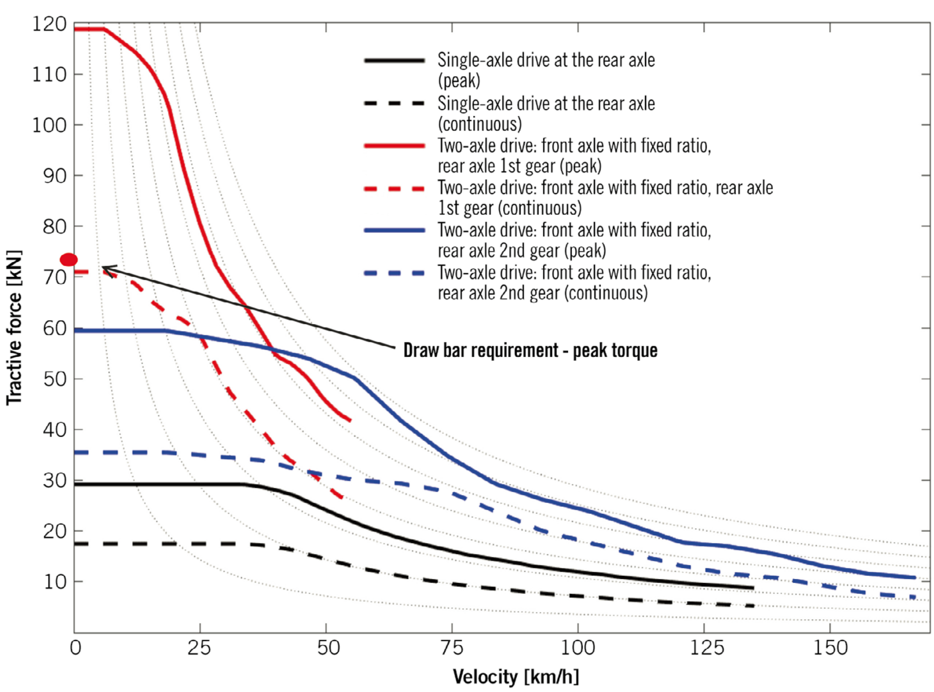


FIGURE 5 Tractive force comparison single-axle versus two-axle drive (© BorgWarner)

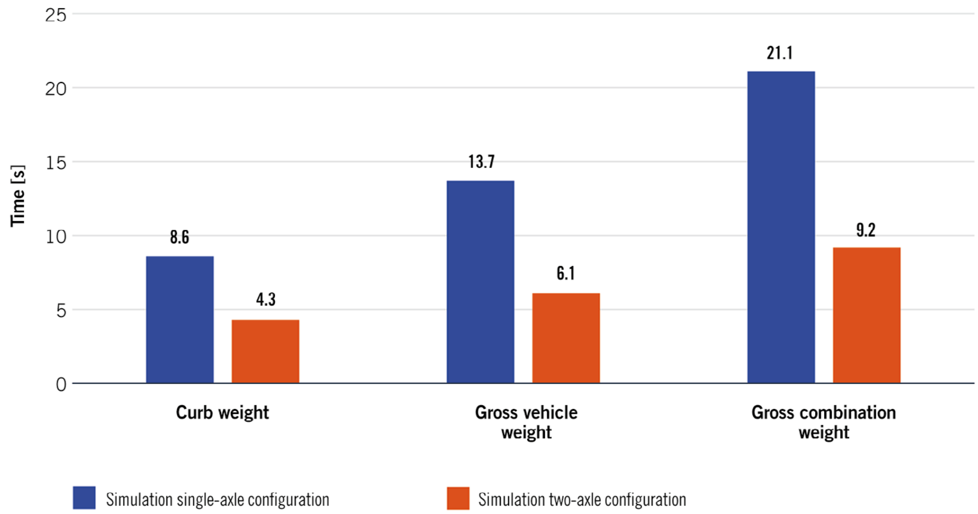


FIGURE 6 Simulated acceleration time in seconds from 0 to 100 km/h for the single-axle and two-axle configuration (© BorgWarner)

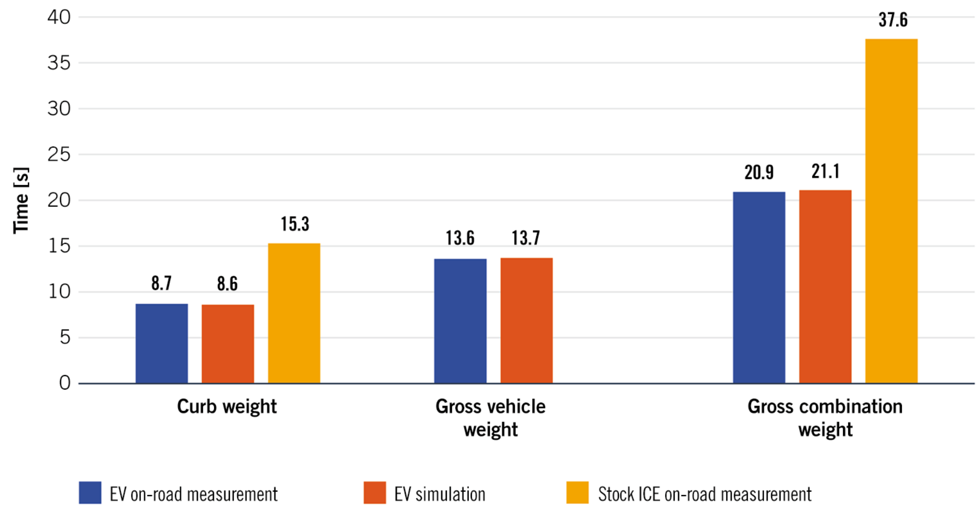


FIGURE 7 Single-axle acceleration time in seconds from 0 to 100 km/h; test measurement versus simulation versus stock vehicle (ICE) (© BorgWarner)

to give a feel of how much the e-axle improves the acceleration due to its high zero speed torque. The close match with less than 1 % deviation between measurement and simulation shows the model and the system parameters used in the simulation perform well.

CONCLUSIONS

The experience with electrified propulsion systems applied to medium duty commercial vehicles shows that with a broad knowledge of BEV components and overall vehicle systems, solutions can be created that meet customer targets as well as or better than ICE drives. The electric solutions not only reduce tailpipe emissions, but also provide faster low speed torque response and drastically improved NVH leading to better operator productivity and job satisfaction. Initially, the primary driver for electrifying vehicles in this class may has been to reduce their carbon footprint. However, based on the findings above, BorgWarner believes that drivers will also favor battery-electric over combustion-powered vehicles, once they have more experience with them in their daily work.

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