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Analysis of Dual and Quad Axle Mounted Motor Drivetrain Performance

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Abstract

This paper explores the benefits in terms of efficiency, performance, safety and features that a drivetrain using dual and/or quad inboard axle-mounted motors has over that of a single-motor electric drivetrain. Several methods for improving efficiency by taking advantage of the possibilities of axle-mounted motors are explored and presented as an inventory of possible power request scenarios. It is argued that axle-mounted drivetrains can provide a number of safety and convenience features over that of a single-motor electric drivetrain while maintaining or increasing electrical efficiency.

To adequately compare axle-mounted drivetrains with single-motor drivetrains, a standard certification cycle that includes cornering must be developed. With potential gains of up to 25% overall drivetrain efficiency, this is the most vital future research presented by this paper for verification of concepts presented.

Keywords: Control System, Efficiency, Energy Consumption, Powertrain, Student Project

1 Introduction

With the resurgence of electric drive vehicles in the transportation industry in the last decade, automobiles are seeing the most radical drivetrain changes in history. Electric motors are simple and can be scaled to a wide variety of design power requirements with minimal detriment to operating efficiency, while their gasoline counterparts require extremely complex control systems just to sustain efficient operation. Rather than satisfy a driver's tractive power demand with a single power source, multiple electric motors allow a vehicle to split the demand over several components.

Improving the efficiency of electric drivetrains is an important engineering problem that faces full electric vehicles. Current battery technology cannot compete with a conventional gasoline vehicle in terms of useable energy storage and "refill" time, so even small improvements in the "fuel economy" of an electric vehicle are important.

The VEV1 developed by the student team Voltaic Drive Systems in 2011 demonstrated a prototype drivetrain which used axle-mounted BLDC motors that independently drive each wheel. This type of drivetrain eliminates the mechanical differential necessary to split the power from a single motor to both sides of a vehicle, and it allows explicit control over the power sent to each wheel of the vehicle. This type of drivetrain also offers benefits such as traction control, 0-pt turning, improved safety from faster steering response, and more. These features may be a deciding factor for consumers to purchase an EV instead of an ICE vehicle as their next automobile.

When combined with high-torque motors, a vehicle design can even avoid using a single-speed gearbox for each motor saving on weight, efficiency, and complexity. Two-wheel and Four-wheel versions of this drivetrain are shown in Figure 1 and Figure 2 below.

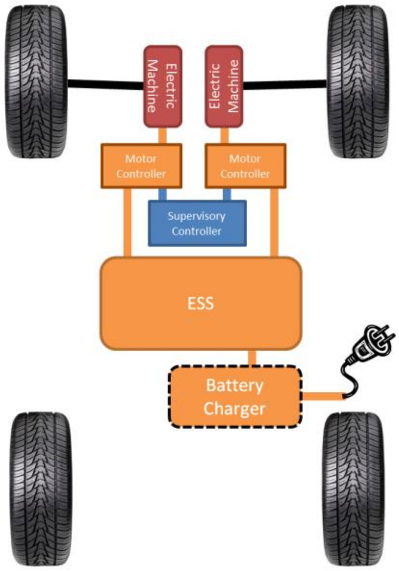


Figure 1: 2WD Axle-mounted motor drivetrains

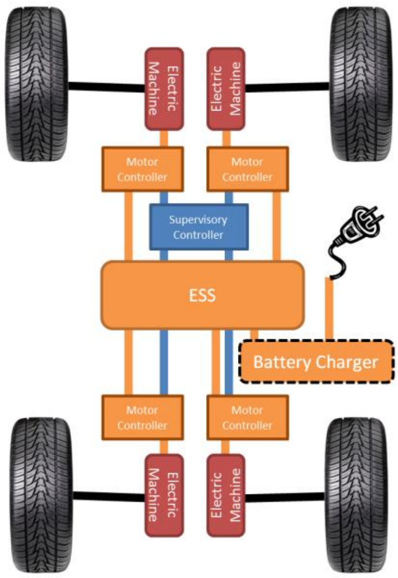


Figure 2: 4WD Axle-mounted motor drivetrain

Unique drivetrains such as 2WD and 4WD axle-mounted drivetrains require control strategies that can take advantage of embedded control of electric motors in strategic ways to improve performance in a variety of categories. This paper will use basic calculations from an energy standpoint to verify the possibility of improved efficiency, show possible traction control methods, and discuss a variety of other benefits of axle-mounted drivetrains.

2 Methods, Assumptions, Test Model

By starting with hand calculations to explore the possibility of efficiency gains of an axle-mounted motor system, a theoretical estimate of the efficiency gain limit has been determined. To evaluate the effectiveness of the control strategy alone, efficiency gain is the difference between the overall drivetrain efficiency before and after control scheme alteration.

This report assumes that electric motor scaling is possible without significant changes to efficiency characteristics. The motor parameters remain similar enough for comparison as identical motors with only the power characteristics scaled.

In this report, individual wheel speeds are assumed to be a function of turning radius, vehicle width, and vehicle speed. Wider vehicles and vehicles with a tighter turning radius demonstrate a more significant difference in the individual wheel speeds between the left and right sides of the vehicle at a given turning radius.

The motor explored in this paper is similar to the YASA-750 high torque axial flux motor developed at Yasa Motors from Oxford, England.

The motor's characteristics and example efficiency map are in Table 1 and Fig. 3 below.

Table 1: Test Platform Motor [1]

Motor Type	YASA-750
Peak Power Rating	100kW
Peak Torque	750 N-m
Peak Current	360 Amps
Voltage	380 V

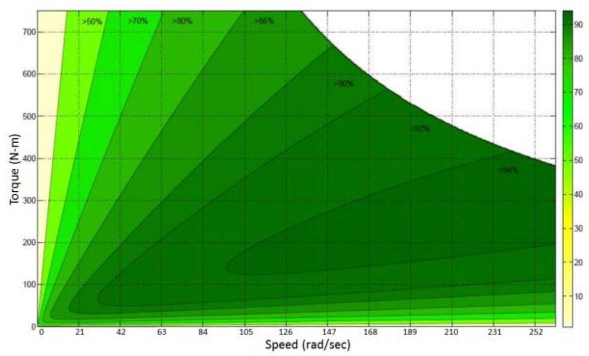


Figure 3: Efficiency Map for YASA-750 [1]

The 2WD axle-mounted test platform will consist of two of the motors described above. The 4WD test platform will have four.

For each motor there is a separate inverter of matching power. A suitable inverter would be a Sevcon Gen4 Size 8 at 380V per motor. There is a supervisory controller that monitors wheel speeds, throttle or braking request, steering angle and other variables. The supervisory controller uses these values to calculate and delegate power requests to individual motors. A prototype supervisory controller with adequate computing power and connectivity would be a dSPACE MicroAutoBoxII controller.

2.1 Vehicle Platform

The test platform modelled in this report is described by Table 2 below.

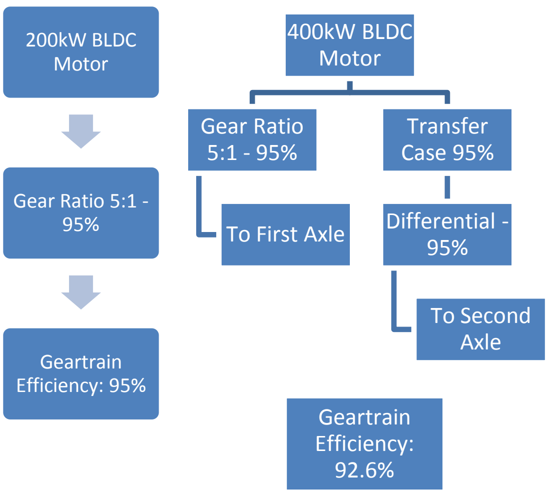
Table 2: Test Platform specifications

Width	73 in
Wheelbase	107.8 in
Turning Circle	37.4 ft
Wheel diameter	16”

The test platform is indicative of a generic full size sedan. The wheel diameter used is smaller than an average consumer vehicle to justify eliminating the gearbox between motor and wheel for the test platform.

2.2 High-Level Power Flow

The baseline vehicle is powered by a single electric motor of equal design power to the sum of all axle-mounted motors. It is assumed that the baseline vehicle has a transaxle for each axle with an average efficiency of 95%, and a transfer case for 4WD vehicles with an average efficiency of 95%.



2WD Baseline AWD Baseline

Figure 4: High-Level Power Flow Charts

Axle-mounted motors provide freedom from geartrain efficiency losses by entirely avoiding them. Contingent on maintaining an identical operating efficiency of the motor in each drivetrain, axle-mounted motor drivetrains offer a baseline efficiency increase of up to a 7.4% before implementing the control strategies introduced in the next section.

2.3 Efficiency

There are two main strategies which are explored in this paper to increase efficiency with axle-mounted motor drivetrains. The first deals with varying the tractive power distribution between the left and right side of the vehicle. This strategy can be applied for axle-mounted drivetrains with two or four wheel drive. The second works on the principle of varying the power distribution between the front and rear axles in a four-motor drivetrain to stay in more efficient operating regions. Both strategies can be used together on 4WD axle mounted drivetrains for the maximum efficiency increase.

2.3.1 Left-Right Control Variation

Certification cycles for current production automobiles give a measure of the fuel consumption during a standard drive cycle in a straight line, but they do not account for cornering. When considering a system with multiple axle-mounted motors, cornering must be included to examine the operating point differences between each side of the vehicle and analyse consumption.

After examining the difference in operating points between the left and right sides of the vehicle, it may be valuable to develop a control scheme that can calculate which motor should be satisfying most of the tractive power demand based on the difference in operating points.

Rather than attempting to develop a certification cycle representative of a typical driver which includes steering, the results of this paper will be presented as an inventory of the range of efficiency gains in different scenarios. The main variables which will be examined are steering angle, speed, and tractive power.

Take for example a vehicle equipped with two axle-mounted motors. At a given speed in a straight line each motor satisfies half of the tractive power demand and may be operating at an efficiency of 80%, shown in Figure 5 below.

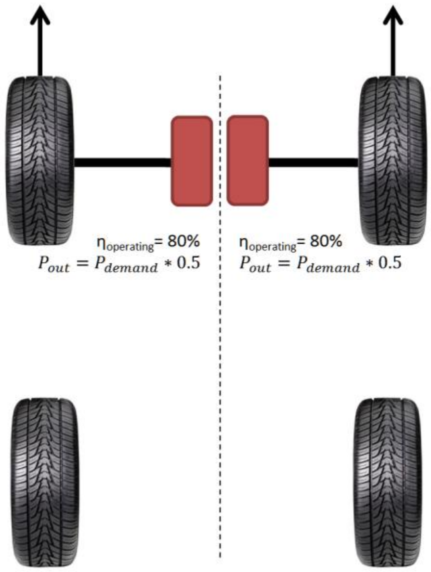


Figure 5: Traveling in a straight line

If a steering angle is introduced, one motor may be operating around 70% while the other is now able to provide power at ~90% efficiency. Rather than continuing to satisfy the total tractive power request with a 50/50 split between both motors, it is valuable to satisfy a higher portion of the power demand with the motor at a higher efficiency state, while satisfying the remainder of the power request with the motor at a lower efficiency state to prevent significant course alteration. This case is shown in Figure 6 below.

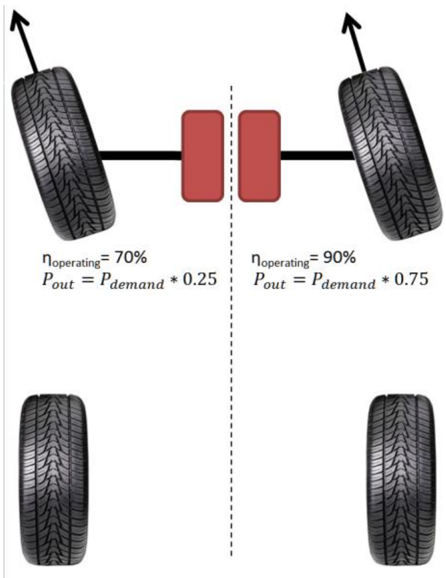


Figure 6: Traveling with a turning angle

2.3.2 L-R Control Variation Example

Consider a vehicle moving at a constant 27 mph in a straight line, resulting in a motor speed of 60 rad/sec. The black rectangle shows the operating column for this speed in Figure 8 below. In this state, both electric motors produce the same amount of power at the same efficiency.

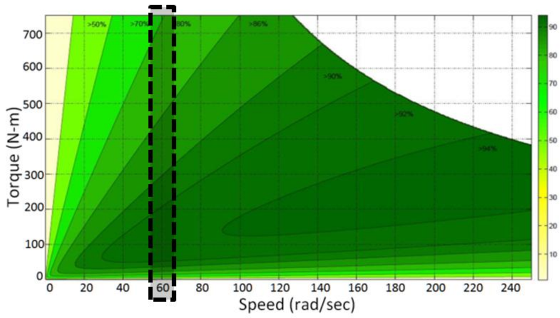


Figure 7: Constant speed straight line

The vehicle traveling at the same speed but with the steering wheel locked to one side will cause a difference in the operating RPM between each motor. This difference is calculated using the turning circle traced by the rear axle of the test platform. The inside motor is now operating at ~48 rad/sec and the outside motor is operating at ~72 rad/sec. Two scenarios in which the tractive power demand is split equally to the L and R motors for this speed are shown for the straight-line and the steering locked case in Figure 8 below.

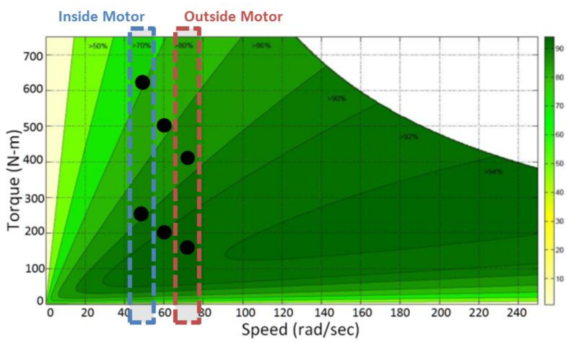


Figure 8: Efficiency map with overlayed example operating columns

By examining the operating columns now available to each motor, it can be determined whether or not it is valuable to unequally load the driving motors to satisfy the tractive power demand. There are two mechanics that improve efficiency by shifting power. First, the motor operating at a higher efficiency can be favoured for satisfying the power demand. Second, changing the loading to each motor can potentially change the operating efficiency favourably.

For a tractive power request of 24kW, a power balance of 65% to the outside motor and 35% to the inside motor is chosen. This choice improves operating efficiency of the inside motor while maintaining the efficiency of the outside motor at the same time as shifting more demand to the more efficient motor.

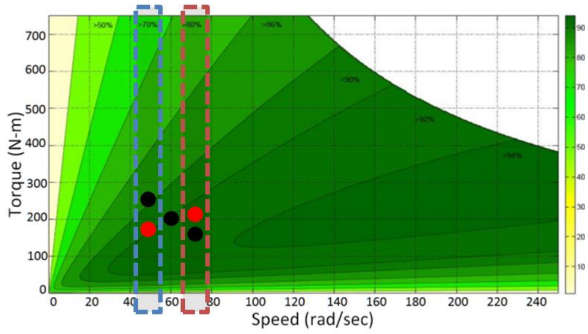


Figure 9: Operating shift example

In this case, the outside motor is operating around 6% more efficient than the inside motor, and shifting power demand off of the inside motor improves its operating efficiency by almost 4%. Before the L-R power variation is applied, the weighted average motor efficiency is ~89.5%. Using the power shift of 65/35, the overall powertrain efficiency is improved to 91.5% for a gain of 2% efficiency.

2.3.3 Front-to-Back Control Variation

On quad axle-mounted motor drivetrains, as with other drivetrains which include separate power sources on separate axles, the vehicle controller is able to operate a single axle at high efficiency rather than both axles at lower efficiencies.

2.3.3.1 Axle Power Split Strategy

In some quad axle-mounted motor drivetrains the power specification of each motor will be identical. For low power demands, it may be most efficient to only power one axle. Increasing that power demand at the same speed could require operation of both axles for maximum efficiency. This effect is demonstrated in Figure 10 and Figure 11 below.

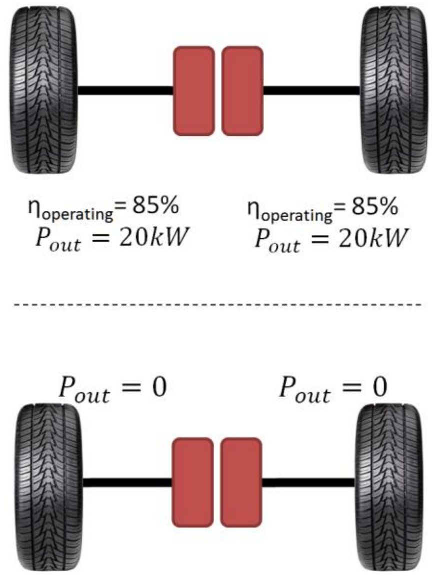


Figure 10: 40kW power request η=85%

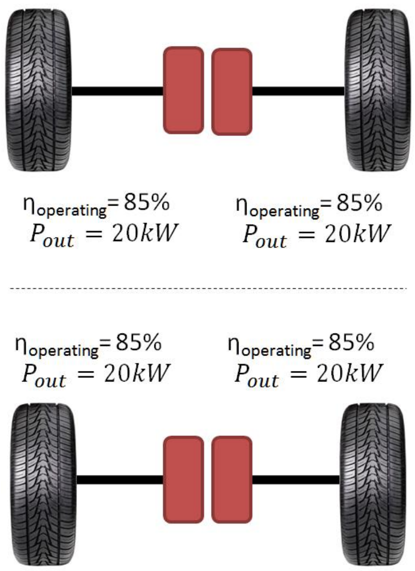


Figure 11: 80kW power request η=85%

2.3.3.2 Design Variation between axles

Quad axle-mounted motor vehicles can take advantage of the axle power balancing in their design. Rather than designing a vehicle with identical powertrains on both axles, the power specifications of a single axle's motors can be changed to introduce additional efficient power zones.

For example, a given two-axle electric drivetrain has axle design powers of 150kW (75kW + 75kW) and 250kW (125kW+125kW). There are now three distinct efficiency regions which should be taken advantage of, described below.

1. For power demands below the power at peak efficiency of the low power axle, that axle should be controlled to satisfy the power demand alone.
2. For power demands between this value and the power near peak efficiency of the high power axle, use the high power axle alone.
3. For power demands above this value, split the power to each axle by the ratio of their design powers.

There is also some blending between these regions to avoid jolting the driver. These design powers should be chosen to satisfy the highest density of power requests during certification cycles.

2.3.4 F-B Control Variation Example

First, we compare a 4WD test platform where the power demand is split equally between both axles to the 4WD test platform with the power delivered to each axle controlled separately. Each axle's design power is 200kW.

As an example, a vehicle is traveling at 27 mph, causing a motor speed of 60rad/sec. The resulting efficiency for low power requests is shown in Figure 12 below.

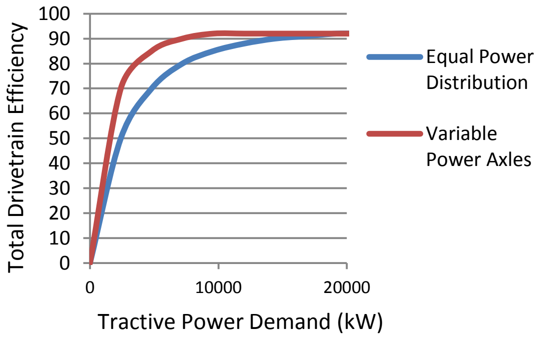


Figure 12: Efficiency versus motor power request at 60 rad/sec motor speed

At power requests below the power output at peak efficiency of a single axle, the variable power control vehicle will only use a single axle to satisfy the demand, while the equal power distribution vehicle will be operating all four motors at lower efficiency.

Taking advantage of the ability to control power between each axle, the design power of each axle can be altered to provide a greater boost while under a single axle's power demand at peak efficiency. This is demonstrated by Figure 13 below using axle powers altered to 150kW and 250kW.

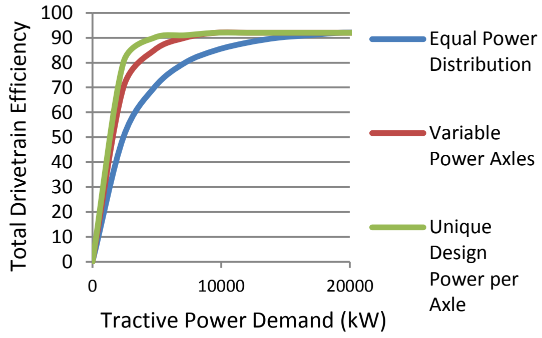


Figure 13: Efficiency versus motor power of equal powered axles, variable power, and variable power with different design powers

For lower power demands, efficiency is based on the low design power axle. For medium demands, efficiency is based on the high design power axle. For larger demands, the power is split between both axles based on the ratio of their design powers.

3 Results

Inspecting the efficiency charts shows distinct regions where L-R and F-B control variation is valuable for the test platform.

3.1.1 L-R Control Variation Results

To demonstrate the maximum improvement in drivetrain efficiency, a full inventory of locked-steering efficiency improvements with a power distribution ratio of 1:0 (100% power to outside wheel) is shown below in Figure 14.

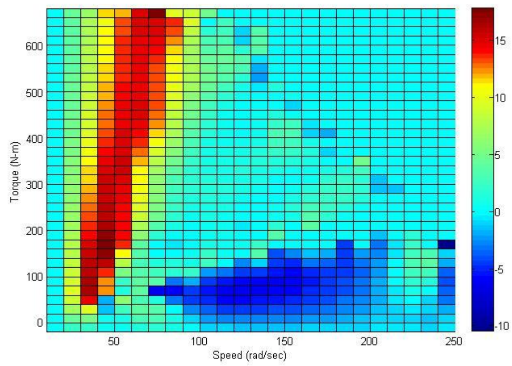


Figure 14: Weighted Average Motor Efficiency at locked steering with full power to outside wheel

There is a distinct zone at low speed and high torque in which L-R torque variation is beneficial to drivetrain efficiency with a maximum improvement of 18%, or a maximum of 9kW power savings at 750N-m and 70 rad/sec. However, at high speeds and low torque requests shifting power to the outside wheel is undesirable, resulting in an overall loss in efficiency. Inspecting the efficiency map for the test platform motor reveals the cause; the outside wheel is initially operating at a lower efficiency than the inside. By changing strategy to shift power to the inside wheel, efficiency improvements are seen in the high-speed low torque zone of Figure 15 below.

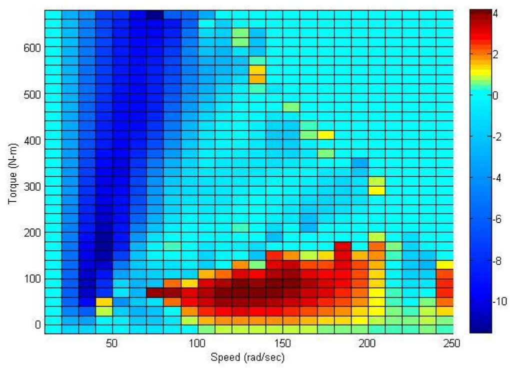


Figure 15: Weighted Average Motor Efficiency at locked steering with full power to inside wheel

Shifting power to the inside wheel at high-speed low torque operation provides a maximum efficiency boost of 4%, or a maximum of 1kW at 150 rad/sec. It should also be noted that the combination high speed with a locked steering wheel is rarely encountered. In such a case the efficiency of the vehicle drivetrain may be less important than the stability and control of the vehicle, which would likely change if power was shifted to the inside wheel.

3.1.2 F-B Control Variation Results

For a test platform with equal-power axles at 200kW each (100kW+100kW), the efficiency improvement of using F-B control variation is inventoried by Figure 16 below.

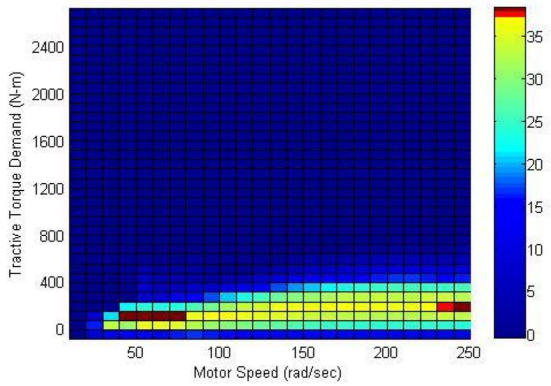


Figure 16: F-B, equal axle power, total tractive power demand vs motor speed

As discussed, there are significant gains in efficiency during low-torque requests. There is a maximum of 38% efficiency gain, or a maximum power savings of of 19kW at 250 rad/sec (112mph) and 200N-m torque.

The efficiency gains resulting from F-B control variation on a test vehicle with different axle design powers of 100kW (50kW+50kW) and 300kW (150kW+150kW) are shown in Figure 17 below.

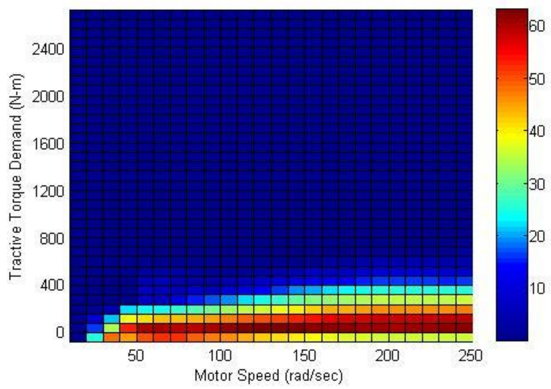


Figure 17: F-B, design powers of 100kW and 300kW, total tractve power demand vs motor speed

The efficiency improvements of using F-B power variation on the test platform of different axle design powers is significantly more than the improvement due to power variation alone. There is a maximum of 63% efficiency gain, or a maximum power savings of of 31.5kW at 250 rad/sec (112mph) and 200N-m torque.

Due to the different design powers of each axle, there are three separate peak efficiency operating torques at any given speed, increased from two. For a tractive torque request, the efficiency peaks in equal power axle vehicles are at ~200 N-m and ~300N-m. For different design-power axles, the peaks are at ~100 N-m and 325 N-m, giving a wider spread of high efficiency points when a single axle is powered.

3.1.3 Combined L-R and F-B

More exploration must be done to manage corner-to-corner power blending in 4WD axle-mounted vehicles, but a general blending based on the two presented power splitting strategies can be applied for a reasonable improvement.

To combine the effects of L-R variation with F-B variation, the improvement efficiency plots are added together to create a new overall drivetrain efficiency plot. In a locked-steering scenario, the resulting improvement in overall drivetrain efficiency, including L-R variation and F-B variation, is shown in Figure 18 below.

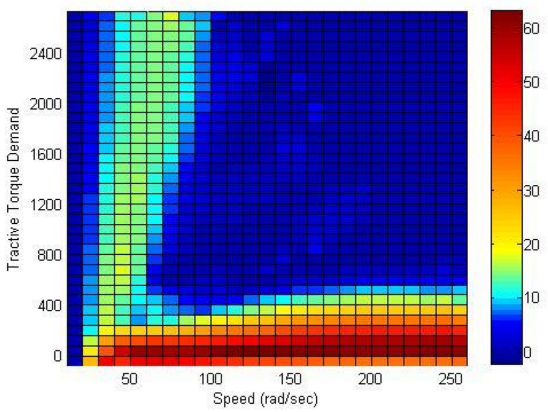


Figure 18: Combined Strategies Efficiency Improvement over single motor

The largest efficiency gain is a result of F-B axle variation for low torque requests at high speeds. In this figure, L-R power variation is not implemented for high-speeds to avoid altering vehicle dynamics.

3.2 Other Considerations

The benefits of axle-mounted motor drivetrains are only highlighted by the possibility of improved drivetrain efficiency. To consumers, it will be the sum of all features that dictates the final decision about what new vehicle to buy. Offering a range of unique features, vehicles with axle-mounted motors may be able to fare well in the current automotive market.

Safety features are an extremely valuable selling point. Vehicles with an axle-mounted motor drivetrain have abilities that improve safety over conventional vehicles.

3.2.1 0-pt turning

Axle-mounted motors enable explicit control not only of the power supplied to each wheel explicitly, but they also over the rotation of each wheel. More precisely, the driver can be given control over the direction of rotation of the wheels on each side of the vehicle, enabling the possibility of zero-point turning on everyday automobiles, making parallel parking possible in tighter spots than on a conventional vehicle.

3.2.2 Torque vectoring and Traction Control

By increasing the amount of power to the outside wheel, vehicles equipped with axle mounted motors can show improved steering response because of the additional forces acting to cause rotation of the vehicle. In terms of safety, this can decrease lane change maneuver time, potentially reducing the chance of an accident.

Traction control is the act of monitoring and automatically adjusting power output to the road, and in rare cases to individual wheels. With axle-mounted motors, the performance of such a system can be improved by allowing the supervisory controller explicit control over the power to each wheel individually.

3.2.3 Backup System

Should one of the electric motors fail, axle-mounted motor drivetrains naturally have a backup system which can allow the driver to continue vehicle operation in a “limping” state to get off of the road to a safe place before stopping.

4 Conclusions

The range of an affordable electric vehicle is arguably the largest deterrent to potential customers deciding between gas or electric. By improving drivetrain efficiency, axle-mounted motor drivetrains can help mitigate this roadblock by more effectively using the limited battery capacity available in an electric vehicle. The additional features of axle mounted motors (zero-point turning, explicit advanced traction control) can be used to provide an additional draw for potential customers.

Axle mounted motor drivetrains offer a baseline 5%-7% increase in operating efficiency due to the lack of geartrain losses. Additionally, left-right power variation and front-back power variation offer a theoretical maximum efficiency gain of

18% and 63% respectively. The main mechanic of efficiency gain is effectively a widening of a drivetrain's high-efficiency operating region due to intelligent satisfaction of power demand by multiple motors. More exploration must be done to optimize power shift ratio in scenarios where the steering wheel is only partially turned.

Vehicle stability must be addressed further for implementation of axle-mounted motor drivetrains. With an aggressive power shifting strategy for efficiency, vehicle dynamics may become unpredictable to a driver who is used to a standard drivetrain. More effort must be placed on ensuring that the vehicle travels on the driver's intended path due to unintended power variance across the vehicle.

5 References

[1] *YASA-750*, [Online]. Available: http://www.yasamotors.com/technology/products/yasa-750. [Accessed 12th January 2012].

6 About the Authors

Trevor Fayer is a Masters student in Mechanical Engineering at the University of Washington. He currently acts as Team Leader and GRA for the UW EcoCAR2 team, UW Advanced Vehicle Works. With over forty people on this team, Trevor leads the design of a PHEV with the mission of fostering the next generation of automotive engineers from the University of Washington.