

Combining Hybrid Electric Technology with Multi-axle Drivelines

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ABSTRACT

The paper presented herein, combines various aspects of hybrid electric powertrain technology with the mechanics of multi-axle drivelines. Starting with a review of why automotive engineers desire to implement electrified powertrain technology, the paper will then explore the reasons for multi-axle drivetrains and finally, will explore the benefits and challenges of combining hybrid-electric and multi-axle driveline technology.

INTRODUCTION

1. Why do automotive engineers want to implement electric drivetrain systems on road vehicles?
2. Second, why multi-axle drives?
3. Third, how can drive train electrification and multi-axle drives be combined, so as to result in the most advantageous configuration?

Mechanical drive trains suffer the disadvantage of compelling the engine to operate at other than the most efficient RPM for the power it is developing at any given moment.

For every operating condition, a vehicle requires a certain amount of power. Also for every value of power within an engine's capability, there will be an operating speed at which efficiency reaches its maximum value ([Figure 1](#)).

Conventional manual and automatic transmissions offer a limited number of fixed gear ratios. Therefore the engine is generally not operating at the optimum RPM for the power output required by a given operating condition. Mechanical continuously variable transmissions have been devised, and in some cases used on small vehicles. However, such transmissions do not by themselves offer the advantages of stored energy for launch assist and regenerative braking.

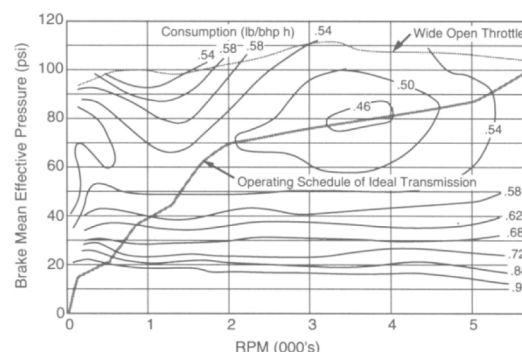


Figure 1. A typical specific fuel consumption map
(Gillespie, Thomas, *Fundamentals of Vehicle Dynamics*,
©Society of Automotive Engineers Inc., 1992, page 32)

Because the automotive engineering community would like to attain more flexible drivetrain management, hybrid electric (and also hydraulic) systems have been developed and implemented in production. Series, parallel, input power-split, and compound-split hybrid configurations have been developed.

Question 2 concerns multi-axle drives. Such systems offer several advantages which include improved traction in poor operating conditions, and could also offer control and optimization of wheel slip and steering forces. There are also disadvantages, such as the extra weight of transfer cases, drive shafts, and powered axles where there would normally be unpowered axles.

Many 4×4 vehicles have used part-time transfer cases, whereby the (usually) front axle is not driven except when needed. When activated, such systems compel front and rear axles to rotate at the same speed. This is good or at least not harmful, when operating in conditions where the tires can

easily rotate (or slip) relative to the surface they are in contact with.

However, a hard road tends to compel multiply driven axles to rotate at different speeds, owing to slight differences in average effective rolling radius among different axles even when nominal tire radius is the same for all wheels. The resulting conflict between drive train and road (Kinematic discrepancy) wastes energy owing to non-optimum wheel slip, and results in driveline stresses and accelerated tire wear.

Hence with multi-axle drivelines intended for full time operation (such as tandem drive axles on 6×4 tractor/semitrailer trucks), an interaxle differential is provided to allow driven axles to rotate at different speeds. While a multi-axle driveline without interaxle differentials compels all driven axles to rotate at the same speed (or, at fixed speed ratios), a multi-axle driveline with interaxle differentials compels a fixed torque proportioning between or among driven axles. A disadvantage of unrestrained (open) interaxle differentials is that if any drive axle encounters low traction coefficient μ , tractive effort will be limited not only on that axle but also on other driven axles.

Accordingly, multi-axle drivelines with interaxle differentials are usually equipped with differential locks or other means (i.e., viscous couplings) to limit speed differences (hence increase tractive effort) when any axle loses traction. Such systems still suffer the disadvantage of fixed torque distribution, which results in other than optimum proportioning of drive torque as circumstances and needs vary.

Also a viscous coupling wastes energy whenever there is a speed difference, owing to continuous fluid shearing and consequent friction.

It will be the goal of this paper to explain how drive train electrification can address the shortcomings of mechanical transmissions and drivelines as described above. It is the author's intention to unite electric drive systems with ideas and concepts developed for mechanical multi-axle drivetrains.

REVIEW OF CURRENT ELECTRIC DRIVE TRAIN SYSTEMS

Various electric drive systems have been studied and utilized in the transportation industry. For road vehicles, many such systems drive only one axle.

The series hybrid configuration consists of an engine driving a generator, which in turn provides electric power to one or more traction motors, which in turn are coupled or geared to axles or wheels. Electric storage batteries may be provided to

absorb regenerated braking energy and subsequently augment engine/generator power in accelerating the vehicle, or to meet other short-time power needs such as hill-climbing.

This configuration has been implemented for ~70 years on Diesel-electric railroad locomotives. While it has not been practical to utilize storage batteries to recover and reuse braking energy¹, the series configuration offers the railroad industry the following advantages:

- More convenient packaging, as one does not have to allow for mechanical alignment of engine, transmission, interaxle differentials, propulsion shafts and gearing to the drive axles.
- One can drive all four or all six axles of a locomotive, without the complex system of interaxle differentials necessary with a mechanical drive system to avoid compelling any two or more axles to revolve at the same speed^{2,3}.
- The combination of generator and traction motors acts as a continuously variable transmission in that one can load the prime mover (engine) in such a way that, at whatever RPM the engine is running, it is operating at maximum efficiency. Or, operate at the most efficient RPM for the power output required at any given moment.
- Direct current series-wound traction motors produce high torque at low RPM. Although their maximum torque is limited, they do have close to ideal torque versus speed characteristics. Hence Diesel locomotives from the very beginning had high drawbar pull for a given prime mover power rating (i.e., the equivalent of a large first gear ratio in a mechanical transmission). This advantage is retained with alternating current motors used in the latest electric and Diesel-electric locomotives.
- Finally, even when braking energy is not recovered and reused, one may operate traction motors as generators for braking. The electric power thus generated, is converted to heat by resistance grids. This reduces brake wear, although air brakes are still required.

Packaging is an important design consideration for railroad locomotives, because all axles must be driven to fully utilize locomotive weight as an agent in enabling traction. Therefore the series electric drive configuration is preferred for this application, if for no other reason than to avoid the engineering problems that would result from attempts to drive four or six axles any other way.

Outside the railroad industry, there are disadvantages with the series hybrid electric drive configuration. With road vehicles, there are seldom more than two driven axles rather than four or six⁴. The most notable disadvantage of the series configuration is that energy is lost in both the generator and traction motors. Also, the generator traction motors, and

power electronics must be sized for peak torque (which is roughly proportional to current) and power requirements to meet design objectives for speed, payload, acceleration and maximum grade. This results in weight, cost and fuel economy disadvantages. Hence with road vehicles, parallel and power-split hybrid drive configurations have been the preferred approach.

A 4×2, parallel hybrid configuration is shown in [Figure 2](#) below:

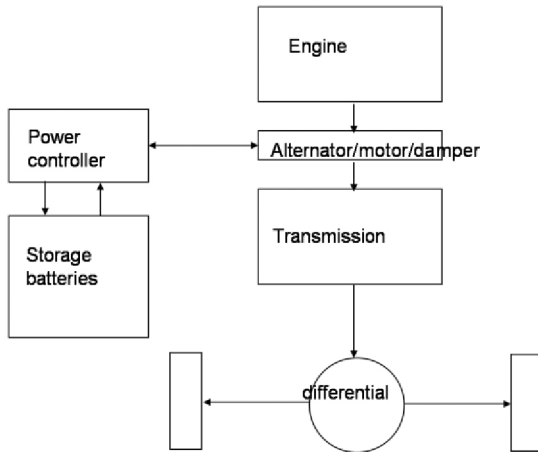


Figure 2. Parallel Hybrid Configuration (Drawing created by author)

There is only one electrical machine, a combination alternator/starter motor/traction motor, which serves the following functions:

- Drive motor, to augment engine torque during acceleration or hill climbing.
- Generator, to provide vehicle electric power in place of the traditional belt-driven alternator. In generator mode, it can function as a driveline retarder (regenerative braking). When the vehicle is parked with the transmission in neutral, the engine may be operated to drive the generator and thus provide electric power for such purposes as operating power tools.
- Starter motor, to start the engine.

This system improves fuel economy⁵ in the following ways:

1. Torque assist from the motor/generator enables aggressive torque converter lockup strategy.
2. When slowing down (or maintaining speed when going downhill), the electric machine acts as a driveline retarder. The electric power thus generated is not converted into heat and dissipated, but is used to recharge batteries. This power is then available to assist the engine during peak power demands.

3. Fuel to the engine is cut off when the vehicle slows to a stop, as at traffic lights or intersections. As soon as the operator takes his or her foot off the brake pedal and places it upon the accelerator pedal, the engine is quickly restarted. This reduces overall fuel consumption, by eliminating unnecessary engine idling.

Utilizing a parallel rather than a series configuration, avoids the need to size electrical components to handle full power and torque requirements⁶. Also only one electric machine is required, thus reducing the weight, cost and volume relative to what would be required for a series hybrid system.

As the electric machine is located between engine and transmission, it is referred to as a pre-transmission parallel hybrid. The basic concept shown in [Figure 2](#) has been utilized in pickup trucks, passenger cars and also for a Class 4 truck⁷. Locating the motor/generator ahead of the transmission eliminates the need for it to develop high torque at low speeds, i.e., the transmission amplifies propulsion (or, regenerative braking) torque at low vehicle speed for the motor/generator as well as for the engine.

The shortcomings of this configuration are as follows:

- For rear wheel drive vehicles in regenerative braking mode, the electric machine only retards the rear axle. It would be advantageous to provide regenerative braking on the front axle as well, since this is where most braking effort occurs.
- The only way such vehicles can be equipped for four wheel drive is to use a mechanical transfer case (See [Figure 3](#)). The electric machine, when operating as a generator, retards the front as well as the rear wheels with regenerative braking force distribution determined by transfer case gearing. One cannot control regenerative braking on front and rear wheels independently.
- If a transfer case and front drive axle are provided but without an interaxle differential, one could then use 4×4 only when positive engagement is either required or at least not harmful. If the transfer case does have a differential, the rear to front gear ratio (u_d) is fixed at whatever value the differential gearing provides.

ALTERNATIVE PROPOSALS

One alternative is the rear wheel drive parallel hybrid configuration described above, with the front wheels provided with one or two traction motors (See [Figures 4](#) and [5](#)).

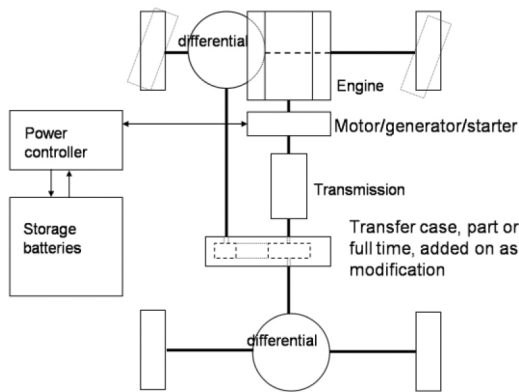


Figure 3. 4x4 drivetrain based on 4x2 parallel hybrid
(Drawing created by author)

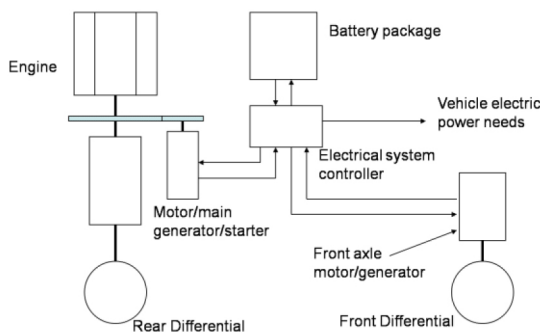


Figure 4. Parallel/Series 4x4 hybrid electric drive system

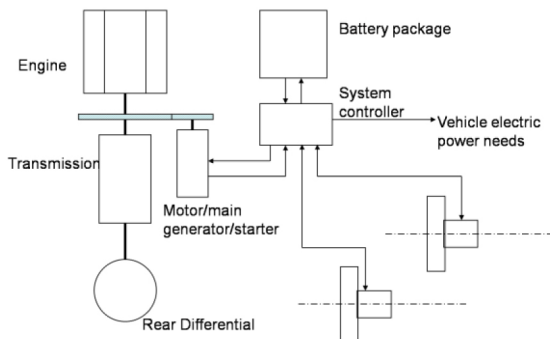


Figure 5. Parallel/Series 4x4 hybrid electric drive system with separate motor for each front wheel
(Drawings created by author)

This configuration offers the following advantages:

1. Packaging convenience. For front engine/rear wheel drive vehicles, the packaging problems resulting from having to provide a transfer case and drive shafts to the front and rear axles are avoided. For passenger buses with a rear-mounted engine driving the rear wheels, one can attain four wheel drive without having to allow space for a drive shaft from rear to front.
2. The motor(s) driving the front wheels can be used for regenerative braking as well as propulsion.

3. One can vary driving or braking torque on the front wheels independently of the rear wheels. Therefore one has the equivalent of a full-time transfer case with variable torque proportioning ratio. The possibility therefore exists to adjust the equivalent u_d ⁸ so as to maximize efficiency at all times. For straight-ahead operation, the ratio of circumferential wheel forces $F_{x2}/F_{x1} = T_2 r_1 / T_1 r_2$, where T_2 and T_1 denote drive torque on the rear and front axles respectively while r_2 and r_1 denote effective rolling radii of the rear and front axles. If one assumes $r_1 = r_2$, the ratio F_{x2}/F_{x1} is simply u_d . For a firm (paved) road, best traction performance occurs when the ratio of wheel forces F_{x2}/F_{x1} is equal to R_{z2}/R_{z1} or u_G , the ratio of normal loads (weights) on the rear and front axles⁹. Therefore, assuming r_1 and r_2 are equal, the optimum u_d is equal to or greater than u_G . For operation on unpaved (dirt) roads, maximum efficiency occurs if wheel slip S_δ is equalized between front and rear wheels. If one assumes circumferential wheel force follows a linear relationship $F_x = K_a S_\delta$, and again assuming that rolling radii for front and rear axles are equal, then for maximum efficiency $u_d = K_{a2}/K_{a1}$, where K_{a1} and K_{a2} are the longitudinal stiffness for the front and rear tires.

4. Varying u_d so as to direct a sufficient percentage of drive torque to the front wheels is helpful during steering, because when there is a steering angle δ one can control front wheel lateral driving force $F_{y1}^a = (R_{x1} - F_{x1}) \tan(\delta)$ by controlling front wheel straight-ahead force F_{x1} , which in turn is given as follows:

$$F_{x1} = fW \frac{1 + u_G \cos \delta}{(1 + u_G)(1 + u_d \cos \delta)} \quad (1)$$

Where

R_x = wheel resistance to forward motion,

f = coefficient of rolling resistance,

W = total vehicle weight (i.e., sum of weights on front and rear wheels).

When turning around a corner at low speed, it is desirable to select u_d such that at a given u_G , F_{x1} is greater than R_{x1} during steering, or at least no less.

5. The overall drive system can be designed so that when rear wheel slip is detected, drive torque to the rear wheels is reduced. Likewise if the front wheels were to lose traction, electric power to the front traction motor would be reduced. With separate front wheel motors, power to the wheel with the least traction would be selectively reduced. The objective under low traction conditions is to operate each wheel at a