Freewheeling Concept:
Hybrid benefits for manual transmissions at low cost

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Abstract: Despite the rapid development of highly efficient automated transmissions, the high demand for vehicles with lower cost manual transmissions seems set to continue for the foreseeable future. The challenge remains to bring the efficiency benefits of hybrid features such as regenerative braking, engine off sailing and electric creep to this significant segment of the market.

Adding a freewheel or one way clutch into the manual transmission enables inherent decoupling of the vehicle from the engine during over-run phases and avoids slowing the vehicle down unnecessarily with engine and driveline drag.

This paper proposes a mild hybrid version of the freewheel system as an alternative to current e-clutch hybrid system. Significant cost and CO_2 savings benefits will be highlighted with focus on high volume manual transmission markets. DSD will define solutions for the mechanical integration with dynamic simulation studies used to highlight methods to overcome the key challenges of controlling the take up of the one-way device and the implementation of a lock out system.

Keywords: Freewheeling, Hybridisation, Coasting

1. Introduction

Due to the short-term mandatory 2020 CO_2 emission targets for new passenger cars and light-commercial vehicles, reducing levels of CO_2 emissions is one of the major challenges facing current OEMs. The European Union has set emissions targets such that 95% of newly registered vehicles must emit less than 95 g/km of CO_2 in 2020 imposing 100% compliance in 2021. This equates to a fuel consumption of approximately 4.1 l/100 km of petrol or 3.6 l/100 km of diesel [7].

An obvious way to achieve such targets is through the manufacture and sale of ultra-efficient hybrid and electric vehicles capable of operating in zero emissions modes. This, however, is not a viable option if such vehicles account for only a small proportion of the total vehicles on the road. Mass-market uptake of latest hybrid and electric vehicle technology remains slow, making up a small percentage of worldwide light duty vehicle sales [1]. Highly efficient transmission technologies provide another option for CO_2 emissions reduction but despite a steady growth in vehicles fitted with dual clutch, CVT and efficient automatic technologies, manual transmissions still make up approximately 50% of all vehicles sold worldwide (Figure 1). In Europe this is even more apparent with approximately 70% of consumers preferring manual transmissions. One of the reasons for this being the additional cost; automatic/automated transmission typically cost around 1000€ more [1].

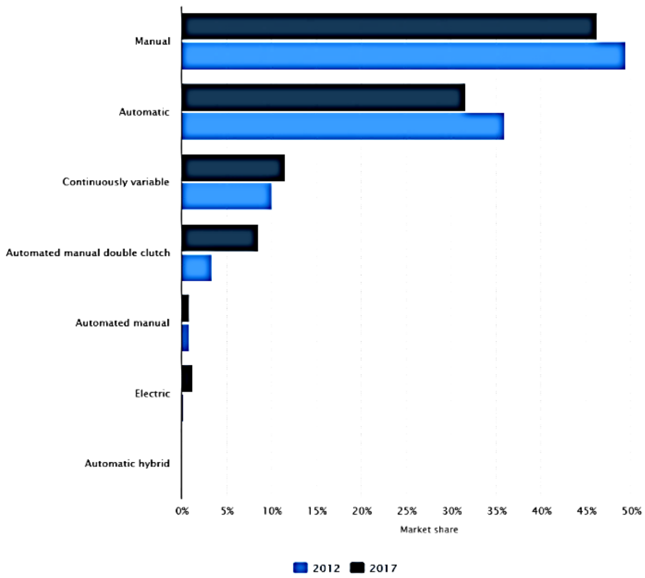

Figure 1: Worldwide vehicle sales by transmission type [1]

It is clear that in order to realise global CO_2 emission targets, hybrid features and technologies need to make their way into the dominating low cost manual transmission market.

Clutch by wire or e-clutch systems coupled with mild electrification of the powertrain offers a potential solution to this challenge. This configuration however requires the integration of a high-force actuation system with sensors, which must work in conjunction with an ECU to monitor and control. This results in a significant on-cost to the transmission piece price.

Another option, which can be realised at a relatively low cost, is adding a freewheel or one way clutch into the manual transmission. A freewheel device can permit decoupling of the wheels from the engine during over-run phases, when the engine stops transmitting positive torque. This decoupling avoids decelerating the vehicle unnecessarily with both engine *and* driveline frictional forces. The freewheeling transmission is not a new concept, it was put into production by Saab in the 1960's to help improve off throttle 2-stroke engine lubrication but, at the time, suffered issues with driver perception despite demonstrating the expected improvements in engine durability and driveline efficiency[2].

With improvements in electric motor design the opportunity to integrate a motor to generate the lost engine braking torque, provides a concept to addressing the negative driver perception that hindered Saab back in the 1960s. Aside to this, it would be possible to capitalise on regenerative energy benefits common to a modern mild hybrid system. It must be noted, however, that if this was the case, the electric motor must be located downstream of the freewheel device.

This paper proposes a mild hybrid version of the freewheel system as an alternative to current e-clutch hybrid system. Cost and CO_2 savings will be highlighted and DSD will define solutions for the mechanical integration. Dynamic simulation studies are used to highlight methods to overcome the key challenges of controlling the take up of the one-way device.

2. Freewheel

A one-way freewheel clutch or sprag clutch, as mentioned previously, resembles a roller bearing, but instead of cylindrical rollers, non-revolving asymmetric figure-eight shaped "sprags" are used to provide contact between inner and outer races. When the unit rotates in one direction, the rollers slip or freewheel. However, due to the sprag shape (see Figure 2), when the unit rotates in the opposite direction, the rollers tilt slightly, producing a wedging action causing the inner and outer race to bind due to friction. Minimal backlash can be achieved as the sprags are spring-loaded. Sprag clutches are commonplace in many industrial applications including roller coasters and elevation conveyor belts where the focus there is on anti-rollback.

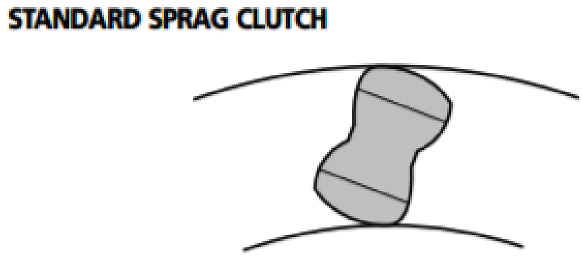

Figure 2: Pictorial representation of a standard sprag clutch showing sprag located between inner and outer race [3]

Within the automotive industry, sprag clutches have been predominantly used in automatic planetary transmissions. General Motors' "Turbo Hydramatic" transmissions have used freewheeling technology as a method of allowing the transmission to smoothly change gears under load [2]. Integration of a freewheel device in this configuration eliminates the need to accurately control the engagement and disengagement of shifting members. However, as will be discussed in this paper, there is an opportunity to introduce a freewheel device to a manual transmission to serve as a mechanism to decouple the engine from the transmission input or output (depending on its installation location) and take advantage of the benefits of a common automated transmission and hybrid feature; coasting.

Coasting is a condition that occurs when the engine over-run torque is decoupled from the wheels as the driver removes their foot from the accelerator pedal. This process allows the engine to return to idle speed or even be switched off. Decoupling allows the momentum of the vehicle to carry it further than it would if coupling was maintained; this has the potential to save fuel. If the brake, accelerator pedal or the gear selector lever is operated, the engine can be restarted and the clutch re-engaged to allow torque transfer to the wheels. The benefits of coasting in terms of reducing CO_2 emissions have been quantified in the new World Light Vehicle Test Procedure (WLTP). According to figures provided by Getrag-Ford Transmissions GmbH; the WLTP has less stop time but allows up to 18 percent CO_2 saving by coasting with the engine either at idle or stopped completely[4]. Figure 3 shows the regions of the new WLTP cycle that can capitalise from the CO_2 saving benefits of coasting.

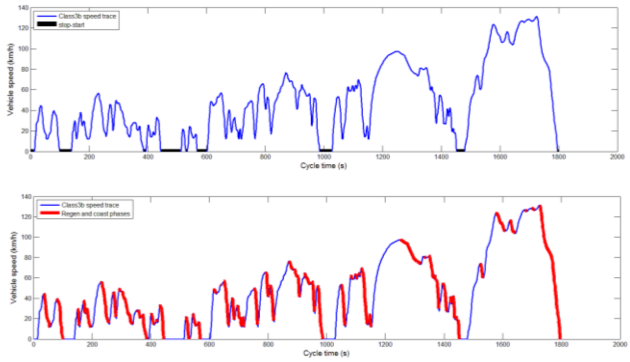

Figure 3: Class 3 World Harmonised Light Duty Emission Cycle showing potential coasting regions in red.

Some manufacturers, have already introduced vehicles to the market with the coast function active on their automatic and dual-clutch transmission systems. This has been shown to save around 3-5 percent CO_2 compared to a strategy of running with a locked clutch with the engine in fuel cut [5][6]. Incorporating coasting capabilities in manual transmissions can be a significant enabler to CO_2 savings in a much larger market segment.

The inclusion of a freewheel device to enable coasting in manual transmissions offers the potential for further CO_2 reductions through the integration of an electric motor capable of allowing torque assist, filling and regeneration in applicable regions. The electric motor can be used to simulate the typical braking feel of the engine if deemed necessary whilst at the same time recovering energy. The motor can additionally provide some support by delivering a level of creep torque for very small driver demands thus avoiding continual engine speed-shuttling when the driver is attempting to maintain low vehicle speeds. The size of the motor will depend on its location and whether it can take advantage of transmission ratios.

With regards to the powertrain layout, as mentioned previously, the freewheel device must be engine side of the point at which the electric motor is coupled in order to enable the electric motor to provide regenerative braking and torque assist functions. Although not essential, it is desirable to provide an automated locking mechanism for the freewheel to prevent engine and transmission decoupling in instances such as extended periods of hill descent which can benefit from engine braking being restored.

3. Mechanical Integration

With respect to the powertrain layout, there are a few locations in which the freewheel device can be integrated into the manual transmission system. A summary of these options with their respective benefits and costs have been discussed below:

Layshaft Integration (Figure 4):

Benefits – E-Motor downstream of the transmission and engine, therefore no requirement to overcome transmission and engine drag losses.
Costs – Control of engine torque must account for engine and transmission dynamics and drag losses.

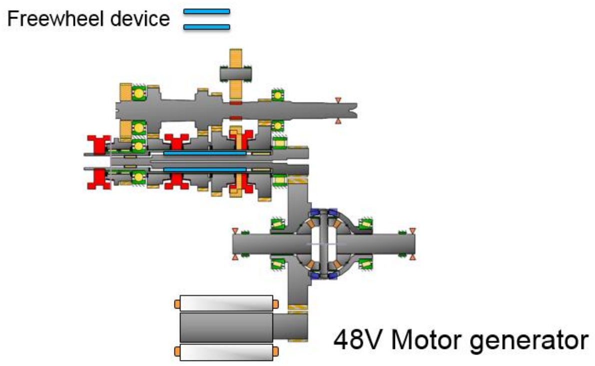

Figure 4: Potential transmission layout for Layshaft freewheel configuration on example 5 speed manual

Inputshaft Integration (Figure 5):

Benefits – E-Motor can be located on the inputshaft, therefore can benefit from transmission ratios in regeneration and torque assist functions.
Costs –E-Motor must also overcome transmission dynamics and drag losses.

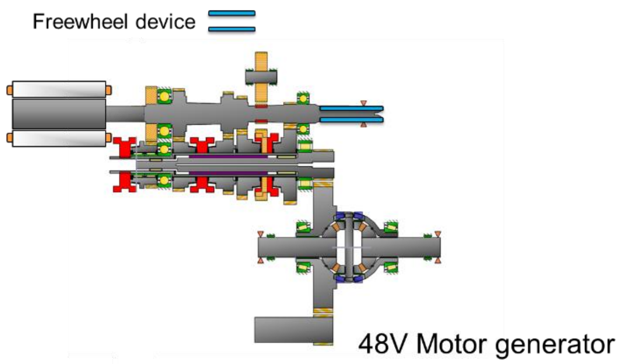

Figure 5: Potential transmission layout for inputshaft freewheel configuration on example 5 speed manual

This paper will focus on the inputshaft mounted freewheel device based on the electric motor benefiting from the transmission ratio as shown in figure 5. This configuration means the electric motor can be smaller, therefore potentially reducing the associated costs for implementation.

One of the concerns associated with freewheel devices used in manual transmissions is the point at which the freewheel takes up torque after it has previously been freewheeling. This paper will show that this can give rise to significant driveline oscillations. A series of tip in and out drive cases will be evaluated in simulation to highlight the effects of a freewheel device on the driveline dynamics and how the addition of an engine speed controller can reduce these driveline oscillations.

4. Dynamic Simulation Model

1D torsional dynamic simulation techniques were used to investigate the response of the powertrain with respect to positioning the freewheel device on the inputshaft. A full driveline and vehicle model representative of a 6 speed manual transmission was created, which using representative data for inertias, torsional stiffness properties of shafts and springs, gear ratios and backlashes enabled the effects of the inclusion of a sprag clutch to be investigated. The model layout can be seen in Figure 6 and comprised the following features:

- Engine represented with an inertia
- Dual Mass Flywheel stiffness properties
- Dry clutch
- Sprag Clutch/Freewheel – viscous coupling between clutch and transmission only transferring torque during positive rotation
- 6 speed manual transmission with oil drag torsional stiffness properties, inertia and gear mesh backlash
- Differential casing with splines and gear ratio and mesh backlash, representative stiffness properties
- Prop shaft dynamics with shaft torsional stiffness properties
- Wheel dynamics with longitudinal stiffness and tyre-road interaction (magic formula)
- Vehicle model including aerodynamic drag

The analysis documented in this paper involved the prescribed crankshaft torque represented by a torque vs time profile, simulating the tip in of the throttle. Torque was ramped up over a 0.5 second period from engine drag torque up to full torque starting at 2500rpm in a fixed 3rd gear. Torque amplitude was then reduced and increased sequentially to demonstrate the effect of the freewheel device on the response of the powertrain and the drive performance. The clutch was locked for this analysis.

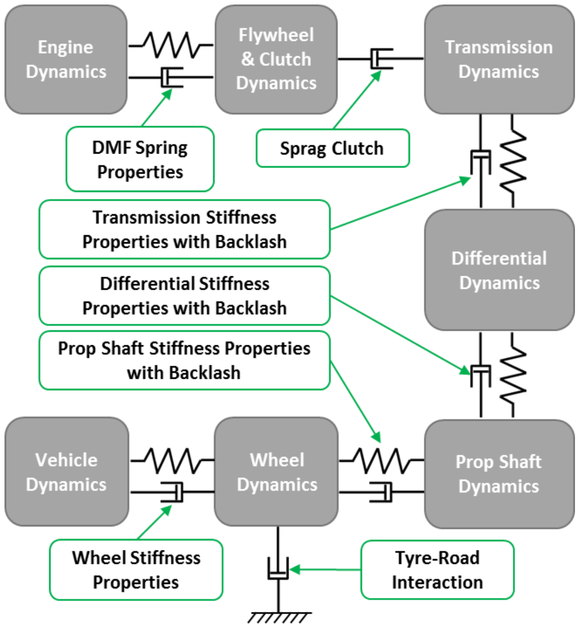

Figure 6: Schematic diagram of the 1D torsional model

5. Simulation

The drive cases defined below were performed on the following powertrain configurations to observe their effects on the driveline behaviour:

- Tip in tip out without freewheel device
- Tip in tip out with freewheel device on inputshaft
- Tip in tip out with freewheel device on inputshaft and engine torque controller

Figure 7 demonstrates the driveline behaviour without mechanical integration of a freewheel device. This is what one would expect to observe in a conventional non hybridised manual transmission.

As can be seen, once the torque is removed during the tip out phase, the wheels are driving the engine through the driveline ratio. This coupling prevents the engine speed from dropping to idle, the resulting engine and transmission inputshaft speeds are equal. During this phase the engine is in fuel cut and the engine drag is adding to the road load to decelerate the vehicle. As the engine speed approaches idle, fuel will be injected to maintain its speed at the idle speed setpoint. With the additional inertia from the engaged driveline, the engine will be required to increase its fuelling quantity to provide more torque in order to maintain the idle speed, this can be shown in Eqn.1 where T_{Clutch} is the additional driveline torque in a coupled system.

$$I_{Eng}\ddot{\theta}_{Eng} = T_{Eng} - T_{Eng_{fric}} - T_{Clutch} \qquad \textit{Eqn.1}$$

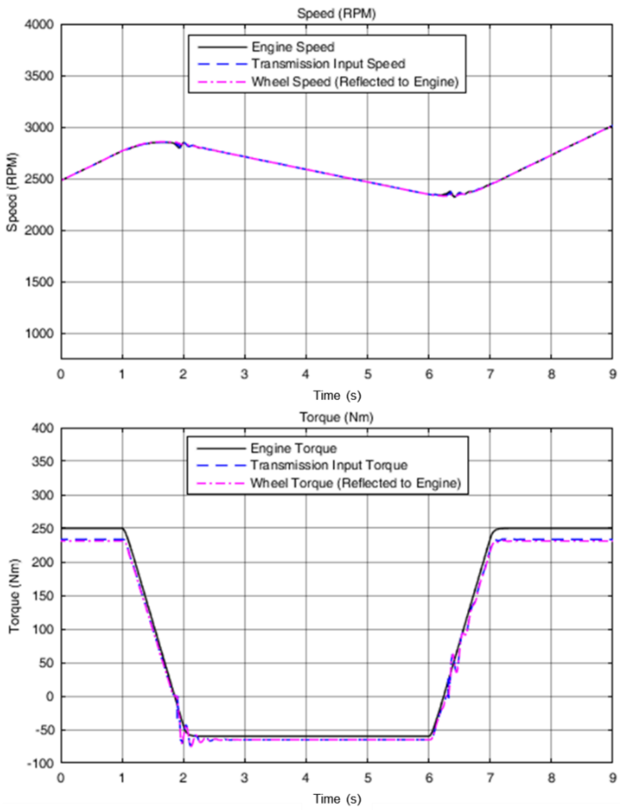

Figure 7: Plot of Speed and Torque of the Engine, Transmission input and Wheel (reflected to engine) during a tip out and tip in of the throttle without a freewheel device

With a freewheel device on the transmission inputshaft, the engine and the transmission are decoupled during over-run conditions, this can be seen in Figure 8. With the engine decoupled from the driveline, the engine decelerates back to idle speed due to its own friction torque. This decoupling removes T_{Clutch} from equation 1. It is possible here to switch the engine off completely to save the additional fuel that is required to keep the engine speed at idle and benefitting from further CO_2 savings.

When the freewheel device transfers positive torque during the tip in phases, large oscillations can be observed as there is no control of the synchronisation of the engine and transmission inputshaft speeds. The high rate of change of speed differential between the engine and the transmission input shaft gives rise to high levels of jerk once coupling begins. Jerk is an undesirable state, and easily perceived by the driver due to the abrupt changes in vehicle acceleration. In automatic transmissions the torque converter will naturally damp these oscillations and in DCTs this behaviour can be controlled by slipping the friction clutches.

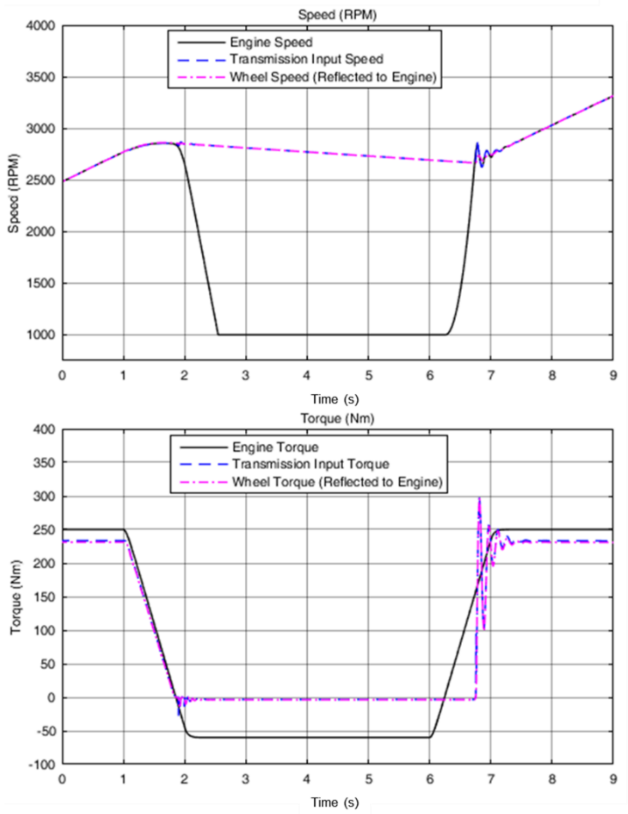

Figure 8: Plot of Speed and Torque of the Engine, Transmission input and Wheel (reflected to engine) during a tip out and tip in of the throttle with a freewheel device

With the addition of an engine speed controller realised via torque modulation, significant improvements can be made to the re-engagement feel of a freewheel device and the resulting levels of driveline oscillations.

A torque controller was implemented within the model to provide a smooth transition as recoupling occurs. The controller limits the rate of the crankshaft torque to reduce the level of driveline speed oscillations and subsequently - jerk. Figure 9 demonstrates the effect of the controlling crankshaft torque during the tip in phase. The level of oscillation in the transmission and wheel torque traces are greatly reduced, with the rate of change of the engine and transmission speed differential also decreased.

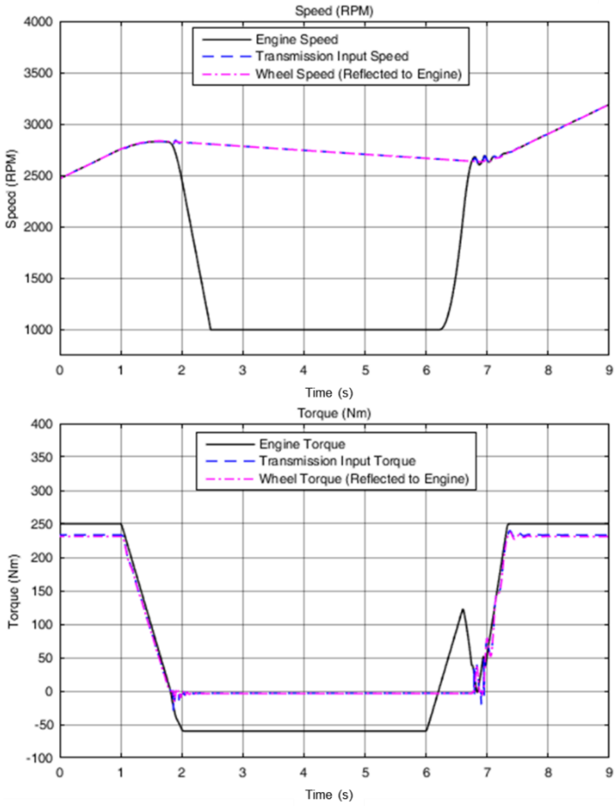

Figure 9: Plot of Speed and Torque of the Engine, Transmission input and Wheel (reflected to engine) during a tip out and tip in of the throttle with a freewheel device and torque control.

As previously mentioned, jerk is an undesirable state easily perceived by the driver if the change in the rate of acceleration is too high. Figure 10 shows the vehicle acceleration during the tip in analysis for two different powertrain configurations:

- The manual transmission system without the freewheel device.
- The manual transmission system with the freewheel device and torque control

The comparable rates of acceleration between the two powertrain configurations demonstrates the potential of including a freewheel device with torque control.

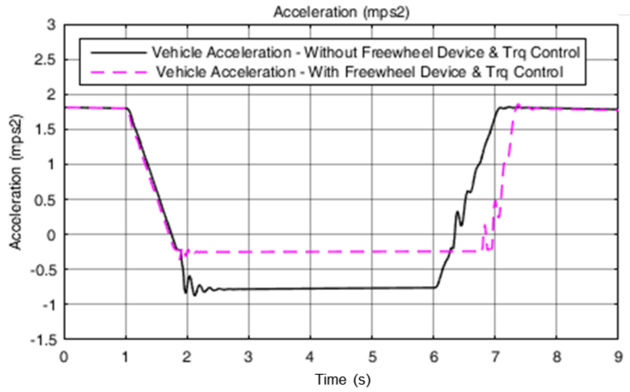

Figure 10: Plot of vehicle Acceleration without a freewheel device and with a freewheel device and torque controller during a tip out and tip in of the throttle.

Figure 10 also shows the drawbacks of integrating a freewheel device. With a conventional manual transmission, if the friction clutch is locked, when the driver demands positive torque, it is felt much sooner than a system incorporating a freewheel device due to the absence of time needed to synchronise the engine and inputshaft speed. If the latency is large enough, this could compromise the functional safety of the system, presenting vehicle level hazards such as late acceleration. The latency in the freewheel system can be improved by increasing the rate at which engine torque is increased in the speed synchronisation phase or by introducing an electric motor to provide positive torque during this delay.

The combination of a freewheel device and electric motor within the powertrain also enables additional benefits such as:

Torque Fill: The electric motor can provide positive tractive torque to overcome any delays incurred by synchronising the engine and transmission inputshaft speeds. When the driver demands torque, the electric motor can provide this torque instantaneously to respond to the driver's intentions. During this time the engine can be synchronising its speed with the inputshaft in preparation to take over the torque delivery from the electric motor. A secondary benefit to this strategy is that by controlling the electric motor torque the effect of backlash during torque reversal can be mitigated.

Creep: At low engine and vehicle speeds the electric motor can be used to provide a level of creep torque while the engine is able to sit at idle with no additional inertia from the engaged driveline.

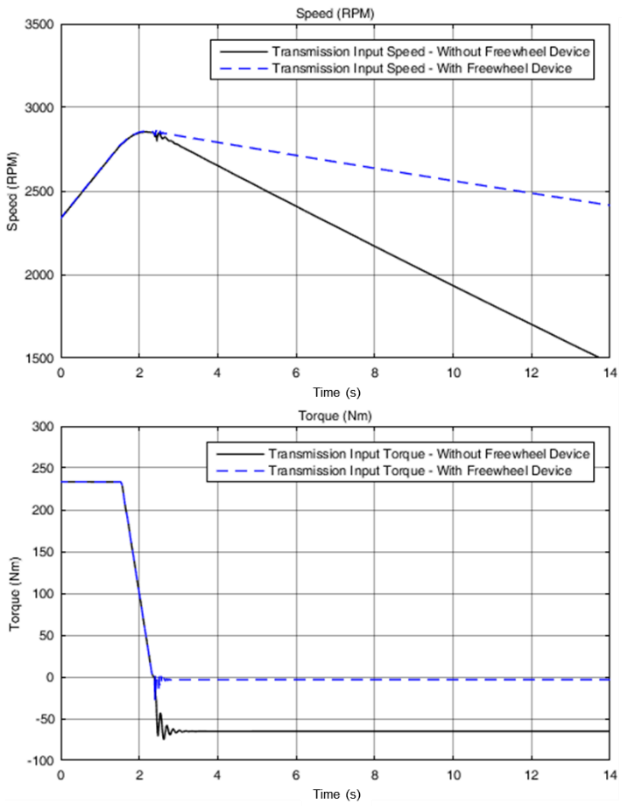

Figure 11: Plot of Speed and Torque of the, Transmission input during a tip out of the throttle with and without the freewheel device

Figure 11 shows a closer look at the effect of integrating a freewheel device into the driveline. The plot shows the transmission speed and torque traces with and without a freewheel device integrated. As the freewheel device decouples the engine from the driveline, the engine friction torque is removed from the system, hence a reduced rate of decay of the inputshaft speed and less negative torque. It is in this region that the electric motor can, as discussed previously, be used to recover energy from the powertrain, enabling the rate of decay of the transmission inputshaft speed to match that of the conventional coupled system. Alternatively, the electric motor can be used provide positive torque during the over-run condition to reduce the level of vehicle deceleration further than just decoupling and allow the coasting period to carry the vehicle further before reapplication of the accelerator pedal is required. The two strategies will require coordination to enable the most efficient use of the electric motor within its capabilities while delivering a consistent driving experience.

6. Conclusion

In this paper we have discussed the benefits and drawbacks of integrating a freewheel device into a manual transmission.

Hybrid vehicles must increase their sales numbers if it to be the only option for meeting the global 2020 CO2 emissions targets. Other technologies must be explored if their uptake remains slow. A freewheel device integrated into a manual transmission presents one of many viable options that can go some way to meeting these emissions targets by enabling CO2 reducing features in a dominating market segment. Coasting is one of those features and a powertrain incorporating both a freewheel device and electric motor can extend the CO2 saving benefits through energy recovery and torque fill to prolong the coast period.

The point at which the freewheel device stops freewheeling and begins to transfer torque remains a key area of focus to ensure that the driver experience does not deteriorate. Simulations using a 6 speed driveline model shows that engine speed control via torque modulation can drastically reduce the driveline oscillations at the coupling point when comparing it to an uncontrolled system.

Speed control can also present some challenges such as increased system latency. The time spent synchronising the engine speed with the inputshaft speed after an increase in driver demand torque can be detrimental to a driver's perception of vehicle responsiveness. An electric motor integrated into the transmission can overcome this latency by 'filling' in the torque gap as soon as driver demand torque is detected. In addition to this it can provide other hybrid features such as regenerative braking to mimic what the driver would expect from a conventional manual.

7. Acknowledgement

We would like to thank Simon Shepherd and Pedro Zabala who were involved in the simulation data collection and review.

8. References

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