

Optimal Powertrain Lock-Up Transients for a Heavy Duty Series Hybrid Electric Vehicle

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Abstract: Fuel optimal lock-up transients for a heavy duty series hybrid electric vehicle are studied. A mean value engine model is used together with numerical optimal control to investigate the interplay between electric machine, gearbox and engine with its turbocharger dynamics in particular how they influence the manner and rate at which the engine should be controlled in order to reach a synchronized speed with the gear-box, enabling lock-up. This is studied both for prescribed gear-box speeds, simulating a mechanical transmission, and with gear-box speed an optimization variable, simulating a continuously variable transmission. The optimal engine transients and their duration are seen to be dictated by the stationary efficiency of the different drivetrain modes, showing that the ratio between the efficiencies of the electric and mechanical path dominates the dynamics and have a greater effect than the engine and turbocharger dynamics. In particular the transition between the modes is as fast as possible when the conventional powertrain is the most efficient and as slow as possible when the engine-generator set is more efficient. This points out that the stationary efficiency maps can be used in a central way for the control design of lock-up transients.

Keywords: Electric motor, engine, turbo, gearbox, fuel consumption, dynamic optimization.

1. INTRODUCTION

In a series hybrid electric vehicle (SHEV) there are two separate power paths to the wheels, one from fuel and one from the battery, compared to just one for a conventional vehicle, see Fig. 1. This has the advantage that the combustion engine operation is separated from the power requirement of the vehicle Guzzella and Sciarretta (2013). For vehicles with a transient work pattern this is advantageous since the combustion engine can be optimized to avoid its more inefficient operating regions. Further it offers the possibility to recuperate energy with the electric machine (EM). A drawback of the SHEV configuration is the multiple energy conversions going from the engine to the wheels. If the battery is unused the vehicle is being driven by the engine-generator combination (GenSet). Assuming constant efficiencies and wheel power P_{wh} , and battery unused, the power required from the engine for a SHEV vs. a conventional vehicle can be computed as:

$$P_{ice,SHEV} = \frac{P_{wh}}{\eta_{EM}^2} \quad (1)$$

$$P_{ice,conv} = \frac{P_{wh}}{\eta_{GB}} \quad (2)$$

However, the SHEV not only suffers from one extra energy conversion compared to a conventional vehicle, the efficiency of an EM is normally lower than that of a mechanical gear-box (GB), meaning that the engine efficiency at $P_{ice,SHEV}$ has to be substantially higher than at $P_{ice,conv}$ for the extra conversions to be worth

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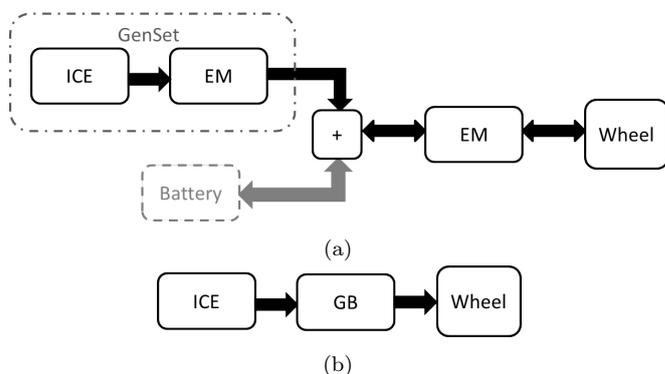


Fig. 1. Architecture and energy paths of a) a series hybrid powertrain (the battery is not used here) b) a conventional powertrain with the clutch locked.

it. In stationary type operation when the battery remains relatively unused, e.g. highway driving, this is normally not the case.

To circumvent the drawback of an extra energy conversion the SHEV can be equipped with a mechanical drive, like in the RunWise® (Parker, 2010), where the engine of the SHEV can be mechanically connected to the wheels. This gives the advantage of using the SHEV mode during transient phases of the driving, and conventional mode when it is the most efficient.

During stationary operation the efficiency maps of the different energy converters can be used to compute both the optimal operating point as well as which mode is the most efficient see Yoo et al. (2009); Cairano et al. (2013); Halme

and Suomela (2012); Sezer et al. (2011). If a change in mode is optimal, going from SHEV to conventional driving, the engine has to be controlled to reach the synchronous speed of the gear-box. How to perform this transient is an open question, i.e. how to perform the lock-up in a fuel efficient way, especially if the engine is turbocharged. In transient operation the slow turbocharger dynamics can limit the rate of change in load and speed that can be achieved, often referred to as turbocharger lag, see Rakopoulos and Giakoumis (2009). Further the freedom to select engine speed in SHEV mode also opens the question if this freedom can be exploited when performing the lock-up transients.

1.1 Contributions

The contributions of this paper is how to control the engine, electric machine, and transmission to perform transmission lock-up transients for a series-hybrid in a fuel optimal way. The study is performed using numerical optimal control and a detailed MVEM incorporating both engine and turbocharger dynamics as well as emptying and filling of the manifolds, investigating the interplay between the engine with its turbocharger dynamics and the electric machine and transmission in optimal lock-up transients. The study is conducted for two cases: one where the gear ratios, i.e. the possible engine speeds, are fixed, and one where the target engine speed itself is optimized. Further the impact of the efficiency ratio between the mechanical and electrical drivetrain is also studied.

1.2 Paper Outline

Section 2 gives an overview of related research. Section 3 presents the scenario, Section 4 presents the mean value engine model used in the study, while Section 5 presents the problem studied and Section 6 the numerical solution path. Section 7 presents the results before the concluding remarks in Section 8.

2. RELATED RESEARCH

Two examples investigating optimal control of series hybrids including transient effects are Nino-Baron et al. (2011); He and Yang (2005). In Nino-Baron et al. (2011) only the engine speed dynamics of the naturally aspirated GenSet are considered and in the optimization the systems stationary efficiency maps are used, and in He and Yang (2005) a model for the fuel consumption increase from the stationary map, due to the transients, is used in the optimization to account for transient losses.

In related articles, concerning optimal transient control of diesel engines, different optimization methods are used to minimize fuel and/or pollutants during transient operation for known engine speeds, see Benz et al. (2011); Kyrtatos et al. (2003); Asprión et al. (2014) or, as in Nilsson et al. (2012) the optimal engine operating point trajectory for a known engine power output trajectory is derived using Willans-line efficiency model with a first order delay torque reduction representing the turbocharger dynamics.

Of the discussed papers only two papers study fuel optimal control of the diesel engine in transient operation, with the freedom to select engine speed. Both papers use

relatively simple models, either neglecting turbocharger dynamics Nino-Baron et al. (2011) or using a Willans-line approach Nilsson et al. (2012).

The approach here is to use a mean value engine model (MVEM) that captures the system dynamics and numerical optimal control to find optimal open loop control laws. This approach is getting common and there are several recent studies that have applied the same approach, see e.g. Benz et al. (2011); Asprión et al. (2014); Nezhadali and Eriksson (2016).

3. LOCK-UP SCENARIO

The scenario studied is that the vehicle is driven in series hybrid mode by the GenSet and EM, at constant speed, a speed that requires $P_{ref} = 100$ kW at the wheels. At some instant a lockup is commanded, then the GenSet speed is to be controlled so that engine speed will match the gearbox input speed, matching vehicle speed and selected gear, so that the clutch can be closed without clutching losses and torque jerks in the driveline. Then the GenSet and electric motor hands over the driving torque to the mechanical path, i.e. clutch and gearbox.

4. MODEL

A mean value engine model (MVEM) is used to investigate the optimal control actions. MVEMs is a family of control oriented models that has a compact representation of the system and describes the dynamics on the time scales that are connected to the control actions. Therefore they are well suited for optimal control studies.

The engine and generator models used can be downloaded in the **LiU-D-El**-package from Vehicular systems software (2014) and is described in detail as MVEM₂ in Sivertsson and Eriksson (2014). The model describes a powertrain consisting of a 6-cylinder diesel engine with a fixed-geometry turbine with a wastegate for boost control, and a generator mounted on the crank shaft. The states of the mean value engine model (MVEM) are engine and turbocharger speeds, $\omega_{ice/tc}$, and inlet and exhaust manifold pressures, $p_{im/im}$. The controls are injected fuel mass, u_f , wastegate position, u_{wg} , generator power, P_{gen} , and gear box mechanical power at the clutch, P_{GB} . The engine model consists of two control volumes, intake and exhaust manifold, and four restrictions, compressor, engine, turbine, and wastegate. On the engine there is a generator that is parameterized from the generator efficiency map.

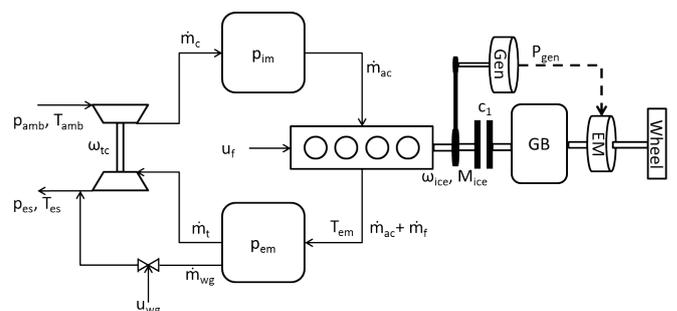


Fig. 2. Structure of the powertrain. The modeled components as well as the connection between them.

The engine and generator model is developed and validated in Sivertsson and Eriksson (2014). In this study the MVEM based GenSet is augmented with a clutch, gear-box (GB) and an electric motor (EM), connected to a vehicle through the Wheel as shown in Fig. 2. The GB and EM are modeled as constant efficiencies, η_{GB} and η_{EM} , and the clutch is modeled as a switch taking the potential values zero (clutch open, engine disconnected) and one (clutch closed, engine connected). Since the vehicle is running at constant speed in the scenario the vehicle is modeled as a load of constant power P_{ref} . The governing differential equations of the powertrain are shown below. To show the structure the states are collected in the vector $x = [\omega_{ice}, p_{im}, p_{em}, \omega_{tc}]$ and the control inputs are shown individually:

$$\frac{d\omega_{ice}}{dt} = \frac{P_{ice}(x, u_f) - P_{mech}(P_{gen}) - c_1 P_{GB}}{\omega_{ice} J_{GenSet}} \quad (3)$$

$$\frac{dp_{im}}{dt} = \frac{R_a T_{im}}{V_{im}} (\dot{m}_c(x) - \dot{m}_{ac}(x)) \quad (4)$$

$$\frac{dp_{em}}{dt} = \frac{R_e T_{em}(x, u_f)}{V_{em}} (\dot{m}_{ac}(x) + \dot{m}_f(x, u_f) - \dot{m}_t(x) - \dot{m}_{wg}(x, u_{wg})) \quad (5)$$

$$\frac{d\omega_{tc}}{dt} = \frac{P_t(x)\eta_{tm} - P_c(x)}{\omega_{tc} J_{tc}} \quad (6)$$

The efficiency and torque characteristics of the GenSet model, as well as the stationary optimal lines for the engine and GenSet, are shown in Fig. 3. For a complete list of the symbols used in the paper, see Tables 1-2.

Table 1. Symbols used

Symbol	Description	Unit
p	Pressure	Pa
T	Temperature	K
ω	Rotational speed	rad/s
\dot{m}	Massflow	kg/s
P	Power	W
E	Energy	J
V	Volume	m^3
R	Gas Constant	J/(kg · K)
$u_f, u_{wg}, P_{gen}, P_{GB}$	Control signals	mg/cycle, -, W, W
J	Inertia	$kg \cdot m^2$
BSR	Blade speed ratio	-
ϕ	Fuel-air equivalence ratio	-
λ_{min}	Air-fuel smoke-limit	-
T_{sw}	Switching time	s

Table 2. Subscripts used

Index	Description	Index	Description
ice	Engine	$GenSet$	Engine-Generator
im	Intake manifold	em	Exhaust manifold
c	Compressor	ac	After compressor
t	Turbine	wg	Wastegate
f	Fuel	tc	Turbocharger
a	Air	e	Exhaust
gen	Generator-electrical	$mech$	Generator-mechanical
ref	Reference	$c, surge$	Compressor surge-limit
amb	Ambient	pwt	Powertrain
GB	Gear-Box	EM	Electric motor

5. PROBLEM FORMULATION

As mentioned above the problem studied is that the vehicle is at stationary speed, a speed that requires $P_{ref} = 100$ kW at the wheels. Initially it is being driven by the GenSet and EM. The GenSet speed is optimized to be the most efficient speed for P_{ref} . Since it is stationary operation, it should be

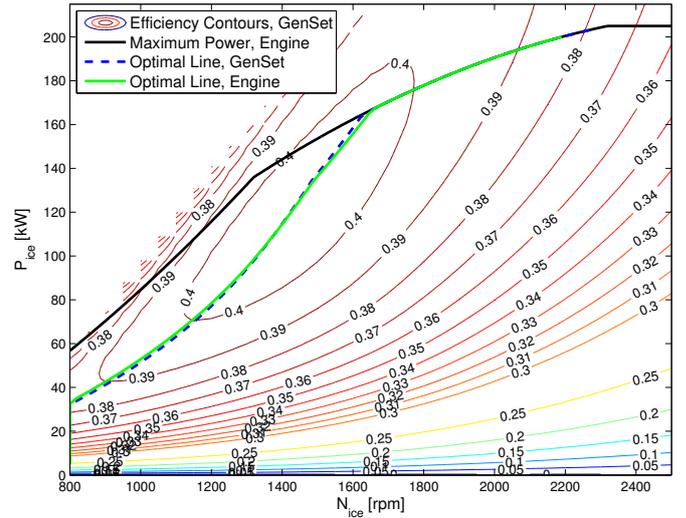


Fig. 3. The characteristics of the powertrain model.

more efficient to go to lock-up and drive as a conventional vehicle. The optimal control problem formulated is fuel optimal engine transients, going from SHEV mode to lock-up and conventional mode. This is formulated as a two-phase optimal control problem. In phase 1 the GenSet is driving the vehicle and the engine speed is free, and in the second phase the engine speed is fixed and the vehicle is in conventional mode. The switching time between the phases T_{sw} is also optimized.

In the first phase the clutch is open and the phase starts with the GenSet in stationary operation, the phase ends when the synchronous speed, ω_{GB} , is reached. The clutch is then closed so in the second phase $\omega_{ice} = \omega_{GB}$ and $P_{gen} = 0$. The final operating point of the second phase is required to be stationary. The problem is formulated mathematically as:

$$\begin{aligned} \min_{u(t)} \quad & \int_0^{T_{sw}} \dot{m}_f(x(t), u_f(t)) dt + \int_{T_{sw}}^T \dot{m}_f(x(t), u_f(t)) dt \\ \text{s.t.} \quad & \dot{x}(t) = f(x(t), u(t)) \\ & (x(t), u(t)) \in \Omega(t) \end{aligned} \quad (7)$$

where x is the state vector of the MVEM, \dot{x} is the state equations (3)-(6), u is the control vector $u = [u_f, u_{wg}, P_{gen}, P_{GB}]$, and T is the maximum allowed time for the lock-up process. The two phases are limited by the following constraints:

Phase 1 Constraints

$$\begin{aligned} x(0) &= x_0, & \omega_{ice}(T_{sw}) &= \omega_{GB} \\ P_{gen}(t) &= \frac{P_{ref}}{\eta_{EM}}, & c_1 &= 0, & P_{GB}(t) &= 0 \end{aligned} \quad (8)$$

Phase 2 Constraints

$$\begin{aligned} \dot{x}(T) &= 0, & \omega_{ice}(t) &= \omega_{GB} \\ P_{GB}(t) &= \frac{P_{ref}}{\eta_{GB}}, & c_1 &= 1, & P_{gen}(t) &= 0 \end{aligned} \quad (9)$$

Further state continuity is enforced, i.e. the initial states of phase 2 have to be equal to the final states of phase 1, the time at which the phase switch occurs, T_{sw} is also a parameter to be optimized. At the final time T the system must have reached a steady state point, so that the driving

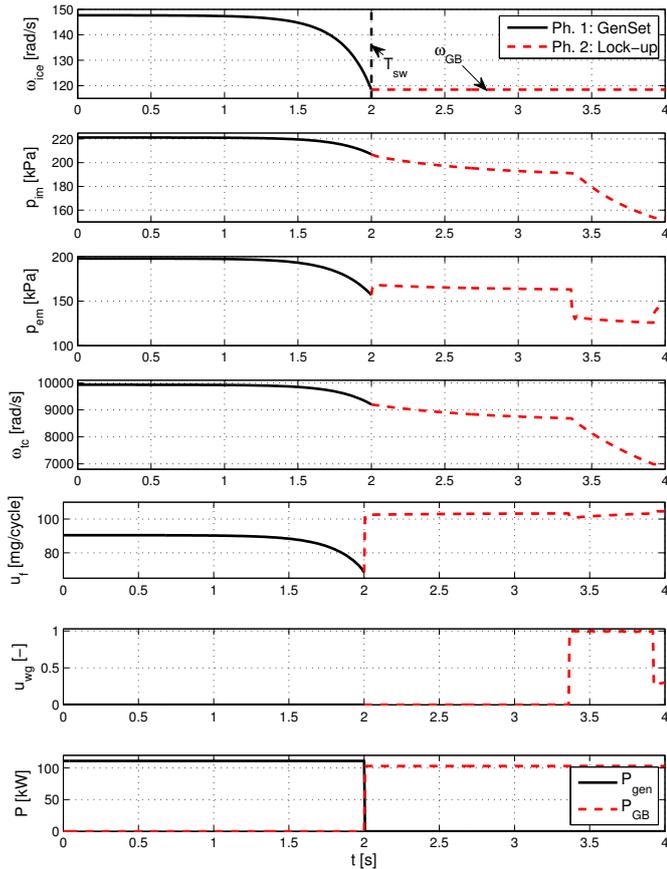


Fig. 4. The nature of the problem considered. Two phase problem solved using an MVEM and numerical optimal control.

power will be able to maintain the constant speed. The nature of the problem is shown in Fig. 4.

The gear-box speed ω_{GB} is given by the wheel speed and the gear ratios. In this paper the problem is solved for 11 different ω_{GB} , $\omega_{GB,vec}$, evenly spaced in the operating range of the engine, simulating an 11 gear GB. The problem is also solved with ω_{GB} as a variable to be optimized, simulating a continuously variable transmission CVT.

In an SHEV there is little meaning in departing from the stationary optimal line, depicted in Fig. 3. Therefore given η_{EM} the optimal ω_{ice} and states for the corresponding P_{gen} is found, and x_0 is set to be equal to the state values. In order to prevent solutions where the final state is in a poor efficiency region T_{sw} is limited so that phase two is always at least one second long.

The constraints common to both phases are the actuator and state limits, as well as constraints imposed by the components, such as maximum power of the engine, P_{ice} , surge-limit of the compressor, $\Pi_{c,surge}$, blade speed ratio-limit of the turbine, BSR , as well as environmental constraints, i.e. an upper limit on ϕ set by the smoke-limiter, expressed as:

$$\begin{aligned}
 u_{min} &\leq u(t) \leq u_{max}, & x_{min} &\leq x(t) \leq x_{max} \\
 P_{ice}(x(t), u(t)) &\leq P_{ice,max}(x(t)), & \phi(x(t), u(t)) &\leq \frac{1}{\lambda_{min}} \\
 BSR_{min} &\leq BSR(x(t), u(t)) \leq BSR_{max}, & \Pi_c &\leq \Pi_{c,surge}
 \end{aligned} \tag{10}$$

6. NUMERICAL SOLUTION

The software package that is used to solve the optimal control problem numerically is CasADi Andersson (2013). First the problem is discretized using Radau collocation with three collocation points in each control interval. The states are thus approximated with a third order polynomial, whereas the controls are approximated by a second order polynomial in each control interval. The states are required to be continuous over each control interval boundary, whereas the controls are allowed to be discontinuous. The resulting nonlinear program (NLP) is solved using IPOPT, Wächter and Biegler (2006), with the MA57 linear solver from the HSL package, HSL (2013). In this paper 25 control intervals per second is used, deemed to be a good balance between problem size, control freedom, as well as numerical accuracy for the integration routine. The total duration to be optimized is fixed to $T = 4$ s, found to be sufficiently long for the transients studied. A NLP solver such as IPOPT cannot guarantee global optimality, care has been taken to ensure that the resulting solutions are good local minima. This is done by varying the initial guesses and ensuring that the associated solutions all converge to the same optimum.

7. RESULTS

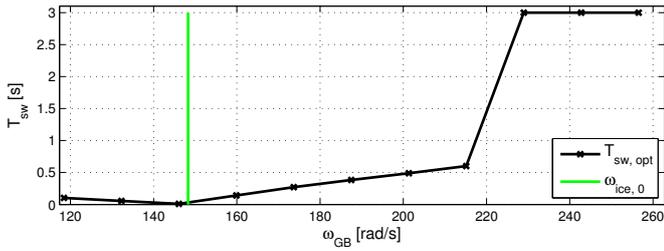
The problem described by (7)-(10) is solved using CasADi. The EM and GB efficiencies are set to what is considered reasonable values $\eta_{EM} = 0.9, \eta_{GB} = 0.97$, Guzzella and Sciarretta (2013), highlighting the fact that a mechanical gear is more efficient than an electric motor.

7.1 Lock-up transients for fixed gear

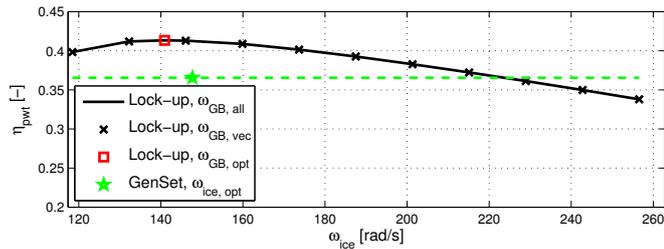
In Fig. 5a the optimal switching time for $\eta_{EM} = 0.9, \eta_{GB} = 0.97$ and the potential gear-box speeds $\omega_{GB,vec}$ are shown. The basic behavior has three essential phases: one deceleration/acceleration phase, one adjustment phase to meet the end constraints, and a waiting phase. There is a dicotomy in the solution, i.e. it has two categories, ω_{GB} above or below 220 rad/s, above the waiting phase is at the beginning while below it is placed in the end.

For $\omega_{GB} < 220$ rad/s the switching time occurs as soon as possible. For speeds lower than $\omega_{ice,0}$ the solution is to cut fuel as much as possible, respecting the BSR limit, and decelerate to ω_{GB} . The time to the switch is a function of how far a way, in terms of engine speed, ω_{GB} is. For speeds higher than $\omega_{ice,0}$ but lower than 220 rad/s the solution is to inject as much fuel as possible, respecting the maximum power limit, and accelerate to ω_{GB} . The duration is thus a function of how far a way, in terms of engine speed, ω_{GB} is.

For $\omega_{GB} > 220$ rad/s the solution changes character. Instead of going to lock-up as fast as possible, the solution is to wait and go to lock-up as late as allowed. The solution



(a) Optimal switching time as a function of ω_{GB} . Also shown is the initial speed of the GenSet. The switching time gets longer when the deviation from $\omega_{ice,0}$ gets bigger as it takes longer time for the GenSet to decelerate or accelerate. There is a switch in characteristics that related to when the engine speed gets so far from the optimal line that the electric path is more efficient than the combined efficiency of the engine and transmission.



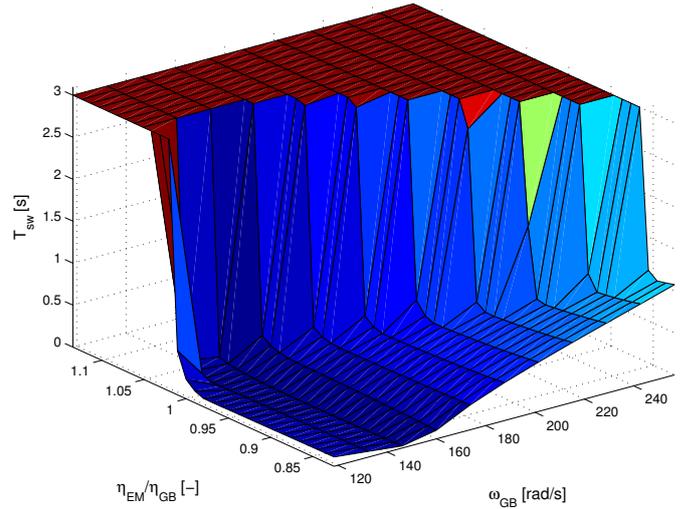
(b) Stationary efficiencies for two different modes of the powertrain at 100 kW. The optimal GenSet speed and efficiency is marked with a star and the dashed line marks the GenSet efficiency of the optimal point for 100 kW. The efficiency of the mechanical transmission gets lower efficiencies when the engine speed deviates from the optimal point.

Fig. 5. Dynamic solution and stationary analysis for $\eta_{EM} = 0.9, \eta_{GB} = 0.97$.

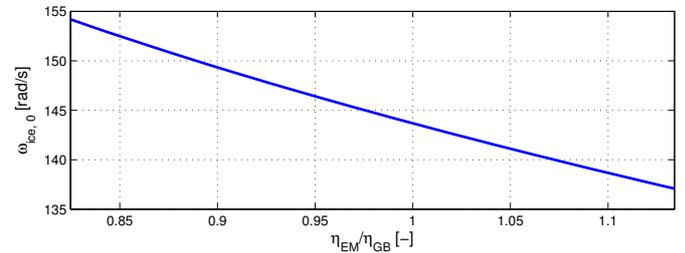
then stays in GenSet mode for the first two seconds and then start an acceleration towards ω_{GB} and going to lock-up at $T_{sw} = 3$ s. The acceleration is close to the optimal line and limited by the maximum engine power. The solution does not follow the stationary optimal line exactly since if the duration of this acceleration increases the time spent at the peak efficiency point, i.e. the starting point, decreases. Instead the acceleration is quite aggressive mostly limited by the maximum power and a trade-off between efficiency and duration.

Why the solution changes character can be explained by looking at Fig. 5b. For all $\omega_{GB} < 220$ rad/s the powertrain efficiency is higher in lock-up mode than in GenSet mode, whereas for $\omega_{GB} > 220$ rad/s the GenSet is more efficient, i.e. the switching time can be decided by just looking at the stationary efficiency. The active constraints also suggest that the most important aspects are that the injected fuel can not be negative and the maximum power can not be exceeded.

Drivetrain efficiencies impact on the switching time To investigate how sensitive the solution are to the drivetrain efficiencies the same problem is solved for a series of η_{EM} between 0.8 and 1.1. Of course efficiencies over 1 are not reasonable, however it also corresponds to relative drivetrain efficiencies η_{EM}/η_{GB} between 0.82 and 1.13 which should illustrate the behavior when which drivetrain is the most efficient, electric or mechanical, changes.



(a) Optimal T_{sw}



(b) Optimal starting engine speed as a function of relative efficiency.

Fig. 6. Relative efficiency and gear-box speed impact on the optimal switching time as well as the optimal starting engine speed.

The optimal switching time as a function of relative efficiency and gear-box speed, as well as the optimal starting speed as a function of relative efficiency, are shown in Fig. 6a and Fig. 6b. The optimal T_{sw} as a function of drivetrain efficiency ratios and ω_{GB} follow the same trend as in Fig. 5a. For almost all efficiency ratios and ω_{GB} the optimal solution is either to lock-up as fast as possible or as late as possible, following the discussion in Section 7.1. There are a few exceptions occurring when the difference in efficiency between lock-up and GenSet, is close to zero. Then the solution is instead dictated by how long it takes to accelerate along the engine optimal line, shown in Fig. 3, to ω_{GB} .

7.2 Lock-up transients for free gear

So far the optimal lock-up time and transients have been investigated for a set of prescribed gear-box speeds, i.e. for a fixed gear-box. A still open question is to which gear-box speed the engine should be controlled if the selection was completely free, like in a CVT, and if this affects the switching time. Therefore the same optimal control problem is solved for a series of drivetrain efficiency ratios, as in previous section, but with ω_{GB} as a parameter to be optimized.

The optimal switching time as function of η_{EM}/η_{GB} is shown in Fig. 7a. T_{sw} is as before either as short as possible or as long as possible. As with the fixed gear study, the behavior can be explained by looking

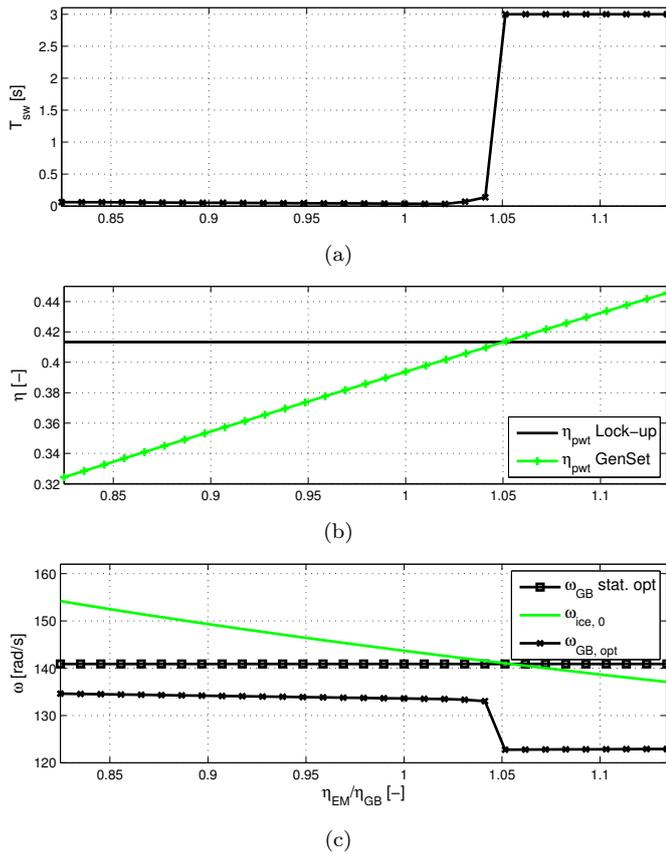


Fig. 7. a) Optimal switching time with optimized gear-box speed. b) Stationary analysis of the two energy paths c) Initial and final engine speed, compared to stationary optimal.

at the stationary efficiency of the powertrain in the two different configurations. In Fig. 7b the peak efficiency of the powertrain in GenSet and lock-up modes is shown. Since η_{GB} is fixed and ω_{GB} is constant the peak powertrain efficiency in lock-up mode is constant. The peak powertrain efficiency in GenSet mode is dependent on η_{EM} and thus increases as η_{EM}/η_{GB} increases. When the peak powertrain efficiency as a GenSet is higher than in lock-up mode T_{sw} goes from being as short as possible to being as long as possible.

Looking at Fig. 7c the optimal ω_{GB} doesn't follow the stationary analysis. For all efficiency ratios the optimal target speed is different from what a stationary analysis would have predicted. For high efficiency ratios the stationary efficiency would predict an acceleration, but instead a deceleration is optimal. This is since by decreasing the engine speed kinetic energy is removed from the engine powertrain and used to produce output power. If the target efficiency is not that much lower than the stationary optima the deceleration itself compensates for the difference in efficiency, especially for the case with $T_{sw} = 3$ s since this point will only be held for 1 s. In Fig. 8 the change in fuel consumption by optimizing ω_{GB} instead of just selecting the stationary optima is shown. The difference increases with the efficiency ratios and is especially high for the higher ratios. This is since the stationary peak efficiency is at a higher speed than $\omega_{ice,0}$, requiring an acceleration, whereas the optimal solution is a deceleration. The longer

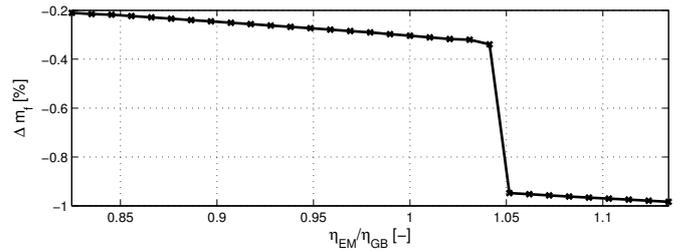


Fig. 8. Gains of optimizing ω_{GB} vs. stationary optimal ω_{GB} .

the duration spent in lock-up though, the smaller this difference should be and in the limit it should be optimal to go to the stationary optimal ω_{GB} .

7.3 Results and Discussion

Summarizing all the results it is seen that the ratio between the efficiencies of the mechanical and electrical paths have the most influence on the solution while no significant effects of the engine and turbocharger dynamics, apart from the natural fueling and power limits, can be seen. With fixed gear-box speed the optimal lock-up time depends, as expected, on the required change in engine speed. However for reasonable drivetrain efficiencies the lock-up time is as low as possible. The solution is thus to accelerate/decelerate the engine as fast as the constraints allow. The main constraints active are lower limits on fuel injection as well as the maximum power. For higher electrical efficiencies, or higher gear-box speeds, the solution shifts character and the switching time is as long as possible. This is due to the GenSet mode being more efficient than the lock-up mode, the acceleration is a trade-off between speed and efficiency. The only special case seen is when the efficiencies are almost equal. Then the switching time is dictated by how long it takes to perform the transient along the optimal line.

With optimized gear-box speed the behavior is similar. For reasonable drivetrain efficiencies lock-up mode is more efficient and the engine transient is as fast as possible. The optimal gear-box speed is however not the same as the stationary optimal. This is due to that if ω_{GB} is lower than the $\omega_{ice,0}$ the kinetic energy of the engine can be used to produce output power, decreasing the total consumption. An effect that decreases for longer durations.

The absence of effects of the turbocharger dynamics can seem surprising. Since optimal lock-up transients are studied the engine starts in steady-state in high load, a load where the inlet manifold pressure and turbocharger speed are required to be high. The solution then follows the most limiting constraint, for accelerations this is the engine's maximum torque line and not the smoke-limiter. At 100 kW the compressor delivers enough air to the engine so that the fuel injection can reach the maximum torque point without violating the smoke limiter. This is an effect of the turbocharger matching and the results can therefore be different if a different engine is used or if a lower load is studied. However, the method and model presented here are still applicable and can be adjusted to study other matchings and operating points.

8. CONCLUSIONS

In this paper fuel optimal lock-up transients for a heavy duty series hybrid electric vehicle are studied. An MVEM, together with numerical optimal control, is used to investigate the interplay between the electric machines, transmission, and engine with its turbocharger dynamics during a clutch lock-up transient. Particular attention is given to their influence on the manner and rate at which the engine should be controlled in order to reach a synchronized speed with the gear-box, enabling lock-up. This is performed both with prescribed gear-box speeds, simulating a mechanical transmission, and with gear-box speed an optimization variable, simulating a CVT.

The results show that the ratio between the efficiencies of the electric and the mechanic paths have the most influence on the transients while the engine is less important but its limitations influence the dynamics of the lock-up control of the engine. For reasonable efficiencies and synchronous speeds the efficiency of the mechanical drive is higher than that of the GenSet, the lock-up therefore occurs as fast as possible. If the opposite is true, the GenSet drive being more efficient, the lock-up transient occurs as late as possible, because it is more efficient to stay in electric mode. The only exception is for very similar drivetrain efficiencies where the transient duration depends on how long it takes to accelerate along the optimal line. This indicates that the stationary efficiency maps contain enough information to find the fuel optimal control for torque lock-up transients.

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