Optimal Transient Control and Effects of a Small Energy Storage for a Diesel-Electric Powertrain

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Abstract: Optimal control of a diesel-electric powertrain in transient operation as well as effects of adding a small energy storage to assist in the transients is studied. Two different types of problems are solved, minimum fuel and minimum time, with and without an extra energy storage. In the optimization both the output power and engine speed are free variables. For this aim a 4-state mean value engine model is used together with a model for the generator losses as well as the losses of the energy storage. The considered transients are steps from idle to target power with different requirements on produced energy, used as a measure on the freedom in the optimization before the requested power has to be met. For minimum fuel transients the energy storage remains unused for all requested energies, for minimum time it does not. The minimum time solution is found to both minimize the response time of the powertrain and also provide good fuel economy. For larger requested energies with energy storage the response time is immediate, with an energy storage of only 10-20Wh.

Keywords: Optimal Control, Diesel-Electric Powertrain

1. INTRODUCTION

In off-highway applications applications the diesel-electric powertrain, such as the BAE Systems TorqE$^{\text{TM}}$, see Fig. 1, offers the potential to increase the performance and lower the fuel consumption, due to the lack of mechanical link between the diesel engine and the wheels. Through this electrification of the powertrain the engine speed can be chosen freely which also enables the powertrain to produce maximum power from standstill. This in combination with the torque characteristics of the electric motors can thus increase performance and potentially lower fuel consumption, especially in transient operation.

In previous papers it is studied how to best take advantage of the extra freedom available in the diesel-electric powertrain, see Sivertsson and Eriksson (2012a,b). This paper extends the results obtained by including a model for the generator losses as well as a small energy storage. In other related articles on optimal transient control of diesel-engines different optimization methods are used to minimize pollutants during transient operation for known engine speeds, see for instance Benz et al. (2011) or, as in Nilsson et al. (2012) the optimal engine operating point trajectory for a known engine power output trajectory is derived. The diesel engine is modeled as an inertia with a Willans-line efficiency model and the optimal solution is found using dynamic programming and Pontryagins maximum principle. Due to the complexity of the nonlinear model used in this paper such methods aren't feasible. Instead the problem is solved using Tomlab/PROPT which uses pesudospectral collocation methods to solve optimal control problems.

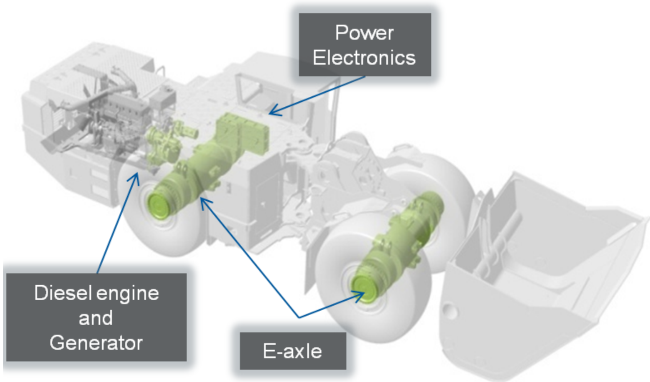

Fig. 1. BAE Systems TorqE$^{\text{TM}}$ powertrain.

The contribution of this paper is the study of the optimal control from idle to a target energy for two different criteria with the engine output power and engine speed considered free variables during the transient, with and without an energy storage to assist in the transient. To also be able to study how large the energy storage should be, the size is not fixed. A nonlinear, four state, four input mean value engine model (MVEM) is used in the study. This MVEM incorporates the turbocharger dynamics as well as the nonlinear multiple input-multiple output nature of the diesel engine. The model is implemented with continuous derivatives to facilitate analytical derivatives during the numerical solution of the optimal control problem.

2. MODEL

The modeled powertrain consists of a 6-cylinder 12.7-liter SCANIA diesel engine with a fixed-geometry turbine and a wastegate for boost control, equipped with a generator and energy storage. The states of the MVEM are engine speed, ω_{ice}, inlet manifold pressure, p_{im}, exhaust manifold pressure, p_{em}, turbocharger speed, ω_{tc}, charge in the energy storage, q, and produced energy of the powertrain, E_{gen}. The controls are injected fuel mass, u_f, wastegate position, u_{wg}, generator power, P_{gen}, and power from the energy storage, P_{batt} The engine model consists of two control volumes, intake and exhaust manifold, and four restrictions, compressor, engine, turbine, and wastegate. The control volumes are modeled with the standard isothermal model, using the ideal gas law and mass conservation. The engine and turbocharger speeds are modeled using Newton's second law. The governing differential equations of the MVEM are:

$$\frac{d\omega_{ice}}{dt} = \frac{1}{J_{genset}}(T_{ice} - \frac{P_{mech}}{\omega_{ice}}) \quad (1)$$

$$\frac{dp_{im}}{dt} = \frac{R_a T_{im}}{V_{im}}(\dot{m}_c - \dot{m}_{ac}) \quad (2)$$

$$\frac{dp_{em}}{dt} = \frac{R_e T_{em}}{V_{em}}(\dot{m}_{ac} + \dot{m}_f - \dot{m}_t - \dot{m}_{wg}) \quad (3)$$

$$\frac{d\omega_{tc}}{dt} = \frac{P_t - P_c}{\omega_{tc} J_{tc}} - w_{fric}\omega_{tc}^2 \quad (4)$$

Where $\dot{m}$ denotes massflows, $T_{im/em}$ temperatures, J inertia, V volume, R gas constants, P powers, and T_{ice} torque, with connections between the components as in Fig 2. There are also two summation states, to keep track of the produced energy as well as the energy storage usage, expressed as:

$$\frac{dq}{dt} = -I_{batt} \quad (5)$$

$$\frac{dE_{out}}{dt} = P_{out} \quad (6)$$

For more details on the submodels used as well as the parameters and constants, see Sivertsson and Eriksson (2012a). For more in-depth information on diesel engine modeling see Eriksson (2007); Wahlström and Eriksson (2011). The model used is the same as presented in Sivertsson and Eriksson (2012a) but augmented with a model for the generator losses as well as a model for the energy storage collected from Guzzella and Sciarretta (2007) and shown below.

2.1 Energy Storage

The energy storage is modeled as an equivalent circuit according to:

$$I_{batt} = \frac{U_{oc} - \sqrt{U_{oc}^2 - 4R_i P_{batt}}}{2R_i} \quad (7)$$

The model for the energy storage has two tuning parameters, U_{oc} and R_i, with assumed values shown in Table 1.

2.2 Generator

Inspired by eq. 4.15 in Guzzella and Sciarretta (2007) the generator is modeled according to:

Table 1. Parameters used in the generator and energy storage models

Symbol	Description	Value	Unit
U_{oc}	Open-Circuit Voltage	750	V
R_i	Internal Resistance	0.5	Ω
$c_{gen,1}$	Generator parameter	$5.3727 \cdot 10^{-3}$	–
$c_{gen,2}$	Generator parameter	$1.6537 \cdot 10^{-7}$	–
$c_{gen,3}$	Generator parameter	14.1957	–
$c_{gen,4}$	Generator parameter	$2.6887 \cdot 10^{2}$	–

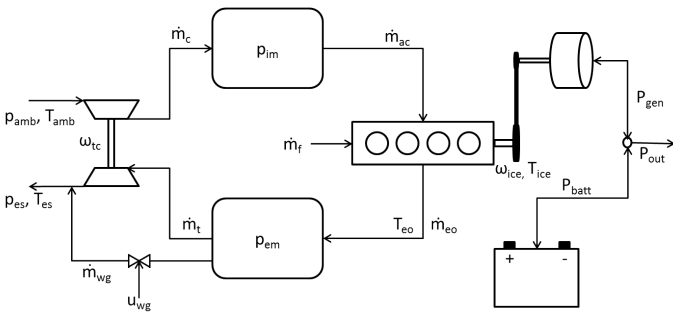

Fig. 2. Structure of the MVEM. The modeled components as well as the connection between them.

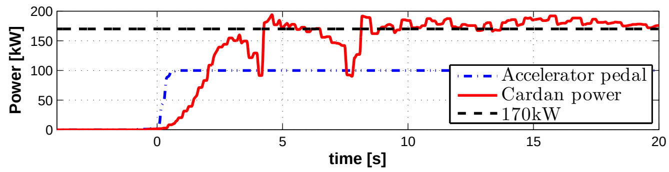

Fig. 3. Cardan power for a step from idle measured on one of the considered applications.

$$P_{loss} = P_{gen}^2\left(\frac{c_{gen,1}}{\omega_{ice}^2} + c_{gen,2}\right) + \omega_{ice}c_{gen,3} + c_{gen,4} \quad (8)$$

$$P_{mech} = P_{gen} + P_{loss} \quad (9)$$

$$P_{out} = P_{gen} + P_{batt} \quad (10)$$

P_{gen} is the electric power, P_{mech} the mechanical power of the generator, and P_{out} is the output power of the powertrain. P_{mech} has two limits, one for peak power and one for continuous power, seen in Fig. 4. The generator model has four tuning parameters, $c_{gen,1-4}$, with values tuned to fit the efficiency map of the generator, see Table 1.

3. PROBLEM FORMULATION

In Fig. 3 a performance test for one of the considered applications of the BAE Systems TorqE^{TM}is shown. This test is a step from idle to constant output power, an output power that is then held. In order to evaluate the potential of the diesel-electric powertrain on this type of test, two optimal control problems are formulated, minimum time and minimum fuel, as follows:

$$\begin{aligned} &\min \int_0^T \dot{m}_f \, \mathrm{dt} \qquad \text{or} \qquad \min\ T \\ &\text{s.t.} \quad \dot{x} = f(x, u), \end{aligned} \quad (11)$$

where x is the states of the MVEM and $\dot{x}$ is defined by (1)-(4). The studied transients are steps from idle to a target power subject to constraints imposed by the components, such as maximum torque and minimum speed, as well as environmental constraints, i.e. a limit on ϕ_λ set by the smoke-limiter. The constraints are:

$$\begin{array}{ll} x(0) = \text{idle}, & \dot{x}(T) = 0 \\ T_{ice} \leq T_{ice,max}(\omega_{ice}), & \omega_{ice} \geq \omega_{ice,min} \\ \phi_\lambda \geq 0, & P_{out}(T) = P_{req} \\ P_{mot,peak} \leq P_{mech} \leq P_{gen,peak}, & 0 \leq P_{out} \leq P_{req} \\ P_{mot,cont} \leq P_{mech}(T) \leq P_{gen,cont}, & E_{out}(T) = E_{req} \\ P_{batt} = 0 \text{ or } P_{batt}(T) = 0, & q(T) - q(0) = 0 \end{array} \quad (12)$$

The problem in (11)-(12) is how to control the diesel-electric powertrain in order to be able to satisfy the operators power request, either as fast as possible, or as fuel efficient as possible, where E_{req} can be interpreted as a measure on the amount of freedom given to the powertrain, in terms of produced energy, before the operators power request has to be met and a stationary point has to have been reached. The generator is allowed to exceed the continuous mechanical power limit during the transient, but not the peak mechanical power limit. The end stationary point however, has to be less than or equal to the continuous limit. In order to study effects of adding a small energy storage to assist during the transients the problem is solved with both $P_{batt} = 0$ and with P_{batt} as a free variable. In order to ensure that $\dot{q}(T) = 0$, $P_{batt}(T) = 0$ in both cases. Since U_{oc} and R_i are independent of q only the relative depletion is of interest, the initial q-level is thus set to zero.

Since the computational complexity of the problem increases with the number of states, neither q nor E_{out} are implemented as states, instead they are replaced by the following constraints:

$$\int_0^T I_{batt}\, dt = 0, \text{ and } \int_0^T P_{out}\, dt = E_{req} \quad (13)$$

4. POWER TRANSIENTS

The results for a step from idle to target power for the two criteria, with and without secondary energy storage, are shown in Fig. 4-5. There it is seen that the results from Sivertsson and Eriksson (2012a) hold even when a model for the generator losses is added. The main characteristic of the solution is more dictated by the maximum torque-line and the smoke-limiter than by the efficiency of the engine. Whereas the minimum time solution follows the smoke-limiter until the end, the minimum fuel solution ends with cutting fuel as the stationary point is approached. Then the wastegate is actuated to get stationarity.

A big difference between the two criteria is how the energy storage is used. The minimum time solution uses the generator in motoring mode for the first 0.15s, accelerating the engine, and thus increasing the backpressure and consequently turbocharger speed. It then switches to generating mode, recharging the energy storage. The minimum fuel solution switches operating mode for the generator three times. First it uses the generator in motoring mode, helping accelering the engine. It then goes over to charging the energy storage, charging it to a level over zero, a buffer later used to assist in the acceleration towards the end of the transient.

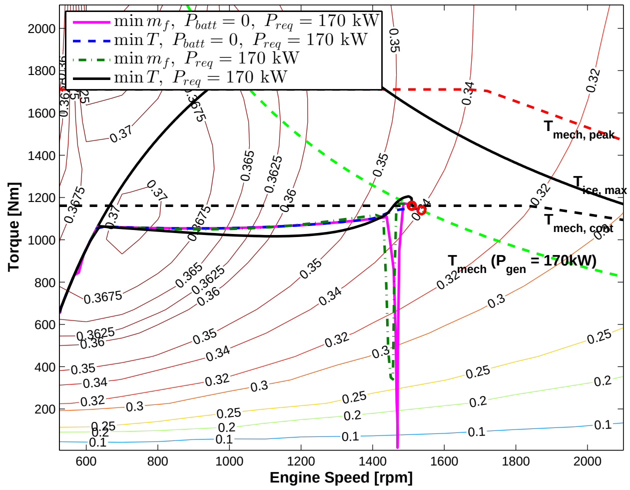

Fig. 4. Engine torque and speed plot for a step from idle to target power for minimum time and minimum fuel, with and without assistance from the energy storage. The efficiency contours are for the generator set.

Table 2. Change in time and fuel consumption for a power step with the addition of a small energy storage. All results relative $\min T$, $P_{batt} = 0$. $\Delta q_{max} = \max q - \min q$.

	$\min m_f$ $P_{batt} = 0$	$\min m_f$	$\min T$ $P_{batt} = 0$	$\min T$
$\Delta T[\%]$	2.3	-1.4	0	-11.4
$\Delta m_f[\%]$	-2.9	-3.1	0	4.3
$\Delta q_{max}[Wh]$	0	0.5	0	2.8

In Table 2 the change in time and fuel consumption compared to $\min T$, $P_{batt} = 0$, which is used as a baseline throughout the paper, is shown. Without the use of an energy storage the minimum fuel uses 3% less fuel than the minimum time, however this comes at the price of a 2% time increase. Adding an energy storage has only slight effects on the fuel economy, however the time duration decreases so the minimum fuel solution is actually faster than the baseline. The biggest effects can be seen when time is minimized, the time consumption decreases with 11% but at a price of 4% increase in fuel consumption.

5. SOLUTION PATH

In order to ensure that the number of collocation points doesn't affect the characteristic of the solution all problems are solved for 50, 75, 100, and 125 collocation points. For the problems studied here the characteristics of the solution remain intact, so the problem could be solved with less than 125 collocation points. However in the plots shown 125 collocation points are used regardless of length of the solution.

When solving minimum fuel required energy problems with PROPT the solution is often very oscillatory. Therefore the sum of the squared state derivatives with the weight w is added to the cost function, see (14). The problem is first solved with $w = 0$ to benchmark the later solutions. Then the problem is solved iteratively first with a large w which is then decreased, with the solution for the last w hot-starting the next. In the ideal case w

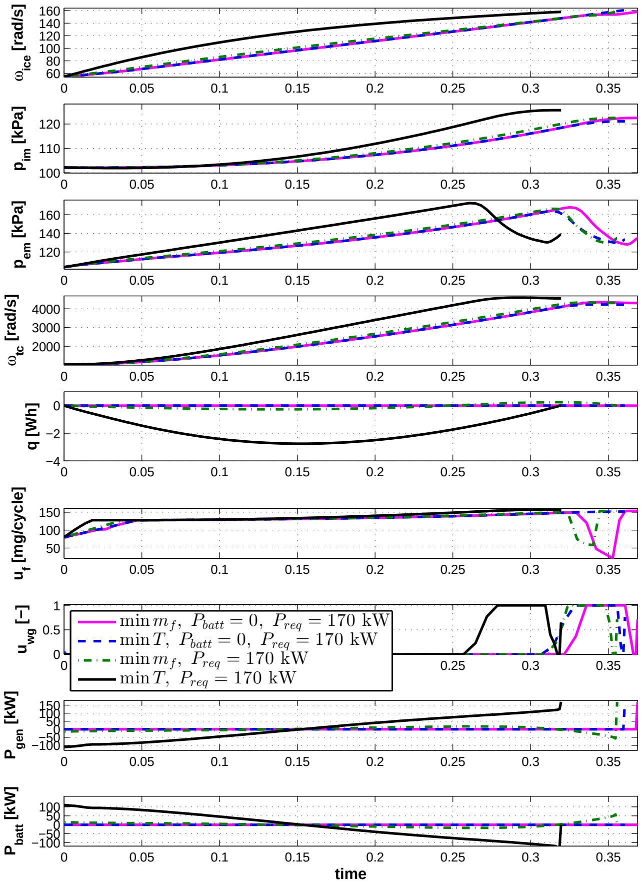

Fig. 5. States and controls for a step from idle to target power for minimum time and minimum fuel, with and without assistance from the energy storage.

is decreased all the way to zero, and a smooth solution is obtained. This does not always work, and when not, a smooth solution with the lowest fuel consumption is selected. The worst case change from this technique is less than 0.7‰ in fuel consumption and 3% in time.

$$\min m_f + w \int_0^T \dot{x}'\dot{x}\, dt \qquad (14)$$

An interesting property of the minimum time formulation is that above a certain E_{req} the solution is not unique. For lower E_{req} the solution is limited by the available engine power, but when the pressures and speeds have reached a level where it can produce more than the requested power the solution is no longer unique. This occurs for $E_{req} \approx 300$ kJ. This is because the output power is limited below the maximum power of the engine, resulting in several solutions where the excess energy is stored as kinetic energy in the engine itself, and thus resulting in an oscillatory solution, see Fig. 6. A method for handling this is developed. First time is minimized and then a second problem is solved where fuel is minimized, according to the strategy previously discussed, with $T \leq \min T + \epsilon$, where ϵ means that the minimum time is rounded up to the nearest 10 microsecond. The obtained solution is both smooth and with lower fuel consumption without affecting the duration, seen in Fig. 6.

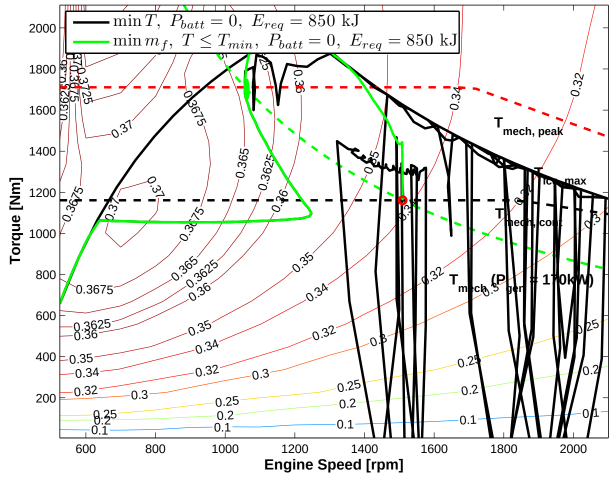

Fig. 6. For higher E_{req} the minimum time solution is not unique. Both trajectories have the same duration, but the fuel consumption differs by 10.6%.

6. ENERGY TRANSIENTS

6.1 Minimum Time

In Fig. 7 solutions to the minimum time formulation is shown. The minimum time, $P_{batt} = 0$, solutions first accelerate the engine and then apply a step in generator power and, if they are long enough(roughly $E_{req} \geq 340$ kJ), wander towards the point of peak efficiency for producing 170 kW stationary, see Fig. 9. It then stays there using the wastegate to control the engine. The transients end with the wastegate closing, and acceleration to meet the final constraints. The wastegate is then actuated to get stationarity. For lower E_{req} the control is similar but instead of accelerating towards a stationary point the control is to wander towards the peak power of the engine and follow this line towards the end operating point.

For shorter horizons ($E_{req} \leq 170$ kJ) the transients start with the generator being used in motor mode, accelerating the engine. The control then goes over to both the generator and energy storage producing power, the end phase of the transient is then to produce power with the generator and recharging the energy storage. The wastegate then opens to reduce the backpressure and also intake manifold pressure, controlling the air flow so that the torque limit is fulfilled with u_f smoke-limited, see Fig. 7. For longer horizons the phases are similar, but the time when the generator is used in motoring mode is short, roughly 0.05s, and power from the energy storage is used as output power from the start. The genset then accelerates towards a stationary point on the peak mechanical power limit for the generator. The engine speed of this operating point decreases with the increasing horizon length, providing better efficiency. As seen in Fig. 7, the $P_{batt} > 0$ phase is similar for $E_{req} = [510\ 850]$ kJ. For the longer horizons there is then more time to recharge the energy storage. The gain of this is two-fold, the efficiency of the genset is better at lower engine speed and also a lower P_{batt} means less losses in the battery. The wastegate is actuated to maintain the operating point with u_f smoke-limited, and $P_{batt} < 0$, recharging the energy storage. The wastegate

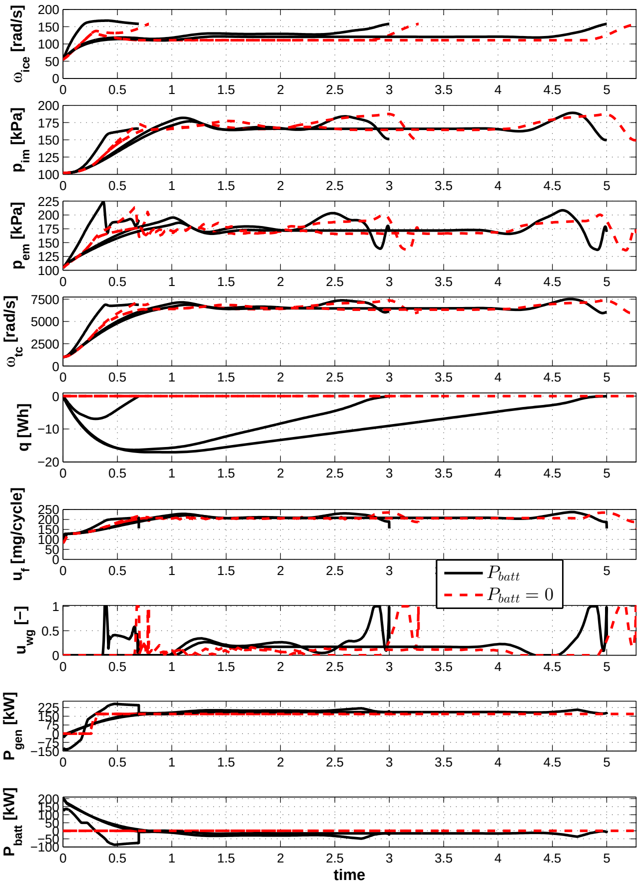

Fig. 7. Minimum time solutions for $E_{req} = [85, 510, 850]$ kJ with and without $P_{batt} = 0$. The minimum time solutions use the energy storage to accelerate the engine as well as to produce output power.

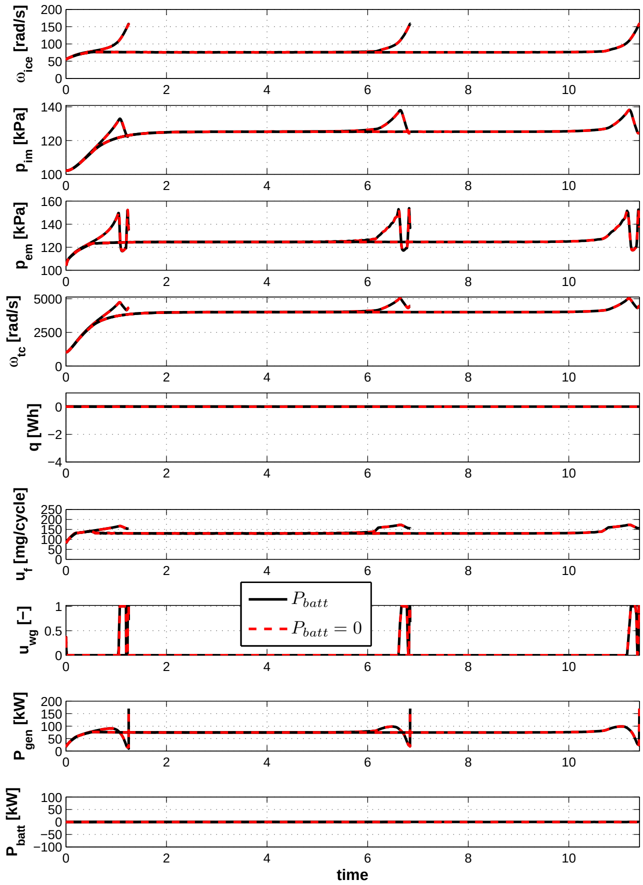

Fig. 8. Minimum fuel solutions for $E_{req} = [85, 510, 850]$ kJ with and without $P_{batt} = 0$. None of the minimum fuel transients use the energy storage.

is then closed during the final transient to meet the end constraints, opening towards the end to get stationarity.

6.2 Minimum Fuel

In the transients studied here, with the E_{req} used, the energy storage is never used in the minimum fuel transients, see Fig. 8. The transients are also insensitive to different energy horizons, the difference is mainly how large part of the transient is spent to put the genset in a position to meet the final constraints. All solutions accelerate the engine, whilst generating power, and move towards the region of peak efficiency for the genset, see Fig. 9. It then stays there until the end of the transient, where an acceleration to meet the end constraints is performed. The wastegate remains closed throughout the transient except for some actuation at the end to get stationarity in the turbocharger speed and intake and exhaust manifold pressures.

7. RESULTS

To make the results comparable all controls are augmented so they produce 850 kJ. This is achieved by holding the final controls until the target energy has been reached. Looking at the consumptions in Table 3 one can see that compared to the reference trajectory the fuel consumption, for the minimum fuel case, decreases linearly with increasing E_{req}, however the time consumption instead increases linearly. So for instance for $E_{req} = 340$ kJ fuel optimal control has the potential to decrease the fuel consumption by 4%, at a price of 41% time incease. There are some slight variations in duration between the case with and without $P_{batt} = 0$, this difference is however small.

For $\min T$, $P_{batt} = 0$ the decrease in time increases with E_{req} up to 170 kJ, it then remains constant, the consumption is however decreasing. For the case of $E_{req} = 340$ kJ the decrease in fuel consumption is almost 3% and the decrease in time consumption is almost 2%.

The duration of the $\min T$ transients decrease with increasing E_{req} up to 340 kJ after which it remains constant. This is because after this the powertrain can deliver the requested power from the start, eliminating all response time. For the longer transients the control also result in a fuel consumption decrease that increases with E_{req}, for the shorter horizons the use of the energy storage however comes with a small consumption penalty. The consumption reduction is always lower with energy storage, than without when time is minimized. The size of the energy storage is also found to increase with E_{req}, it is however very small just up to 20Wh, or 72 kJ, for the horizons studied.

8. CONCLUSION

In this paper optimal control for a diesel-electric powertrain with and without the use of an energy storage to assist during the transients is studied. In order to just study the transients the charge in the energy storage is required to be the same at start and end. For minimum fuel problems the energy storage remains unused. The control consists of two phases, first it accelerates to the region of peak efficiency for the genset where it stays until the end of the transient where it accelerates to meet the end constraints.

In the minimum time case the energy storage is used both to accelerate the engine and to produce output power. For larger E_{req} the solution has a stationary phase on the peak limit of the generator, both with and without energy storage. The stationary point for the solution with energy storage is higher in engine speed since the energy storage has to be recharged. This results in a slightly higher consumption compared to the case without energy storage, but for horizons of 340 kJ and higher the consumption still is lower than the reference trajectory and also faster.

The fuel consumption for the minimum fuel formulation decreases linearly with increasing E_{req}, but the time penalty for this quite quickly becomes relatively large. There is also a driveability aspect since the solution stays in the region of peak efficiency for a large part of the transient, producing a power lower than the requested. It however produces power from the start. The minimum time solutions first accelerate the engine before it starts to produce power. For longer energy horizons, this response time is small, roughly 0.1s before it reaches the requested power. This could still be perceived as strange. It is seen that adding a small energy storage can reduce this delay, and even remove it completely for larger requested energies, with an energy storage of just up to 20Wh. Also the minimum time formulation not only decreases the response time of the powertrain, it also decreases fuel. For the case without energy storage the minimum time controls just increase the consumption with roughly 1.5% compared to minimum fuel, despite being substantially faster.

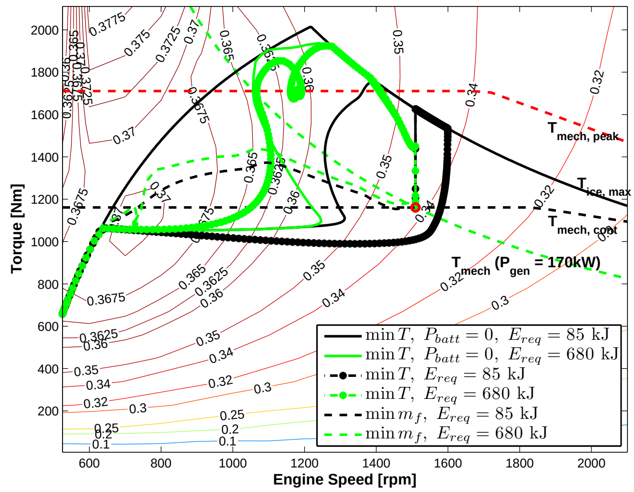

Fig. 9. Torque and Engine speed plot for different E_{req} and criteria, with and without energy storage.

Table 3. Change in fuel consumption and duration of the different strategies compared to the reference trajectory. $\Delta q_{max} = \max q - \min q$.

$E_{req}(T)$		$\min m_f$ $P_{batt}=0$	$\min m_f$	$\min T$ $P_{batt}=0$	$\min T$
	$\Delta T[\%]$	0.2	-0.1	0	-0.9
-	$\Delta m_f[\%]$	-0.7	-0.7	0	-0.5
	$\Delta q_{max}[Wh]$	0	0.5	0	2.8
	$\Delta T[\%]$	7.3	7.2	-1.3	-3
85kJ	$\Delta m_f[\%]$	-1.6	-1.6	-0.2	1.1
	$\Delta q_{max}[Wh]$	0	0	0	6.9
	$\Delta T[\%]$	11.5	11.5	-1.6	-4.1
127.5kJ	$\Delta m_f[\%]$	-2	-2	-0.6	1.3
	$\Delta q_{max}[Wh]$	0	0	0	9.7
	$\Delta T[\%]$	17.4	17.1	-1.7	-5.1
170kJ	$\Delta m_f[\%]$	-2.3	-2.3	-1.3	1.5
	$\Delta q_{max}[Wh]$	0	0	0	12.6
	$\Delta T[\%]$	41	40.8	-1.7	-6.7
340kJ	$\Delta m_f[\%]$	-3.8	-3.8	-2.7	-0.9
	$\Delta q_{max}[Wh]$	0	0	0	15.9
	$\Delta T[\%]$	65	65	-1.7	-6.7
510kJ	$\Delta m_f[\%]$	-5.2	-5.2	-3.9	-2.5
	$\Delta q_{max}[Wh]$	0	0	0	16.4
	$\Delta T[\%]$	88.8	88.5	-1.7	-6.7
680kJ	$\Delta m_f[\%]$	-6.7	-6.7	-5.2	-4
	$\Delta q_{max}[Wh]$	0	0	0	16.7
	$\Delta T[\%]$	112.7	112.7	-1.7	-6.7
850kJ	$\Delta m_f[\%]$	-8.2	-8.2	-6.5	-5.3
	$\Delta q_{max}[Wh]$	0	0	0	17.1

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