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Evaluation of Turbocharger Power Assist System Using Optimal Control Techniques

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ABSTRACT

In the paper we employ numerical optimal control techniques to define the best transient operating strategy for a turbocharger power assist system (TPAS). A TPAS is any device capable of bi-directional energy transfer to the turbocharger shaft and energy storage. When applied to turbocharged diesel engines, the TPAS results in significant reduction of the turbo-lag. The optimum transient strategy is capable of improving the vehicle acceleration performance with no deterioration in smoke emissions. These benefits can be attained even if the net energy contribution by the TPAS during the acceleration interval is zero, i.e., all energy is re-generated and returned back to the energy storage by the end of the acceleration interval. At the same time the total fuel consumption during the acceleration interval may be reduced. These results are compared to the "conventional" vehicle (without TPAS) and to the case when the supplemental energy is applied directly to or taken directly from the crankshaft as in a parallel hybrid vehicle configuration. Comparison with the conventional vehicle and with the parallel hybrid vehicle reveals the mechanism by which TPAS can reduce pumping losses at the initial phase of acceleration thereby improving fuel economy.

INTRODUCTION

Turbocharged diesel engines are widely used in the transportation industry around the world and have a significant penetration into passenger car market in Europe due to their superior fuel economy. Despite their fuel efficient operation, diesel engines have two important drawbacks, namely, the turbo-lag on the performance side and oxides of nitrogen (NOx), particulate (PM) as well as smoke on the emissions side. These two performance objectives are interrelated and sometimes conflicting, resulting in a difficult control and design tradeoff. The introduction of additional hardware can address and potentially alleviate this tradeoff. Advanced after-treatment systems (such as Lean NOx Catalysts or Diesel Particulate Filters) can relax the feedgas emission constraints and advanced turbocharger concepts can provide additional degrees of freedom to optimize the engine response during fast changes in fueling level.

For example, the no-visible smoke requirement in passenger cars imposes lower bounds on the engine air-to-fuel ratio. These bounds are ensured by limiting the fuel rate during tip-ins. The fuel limiting, in turn, results in an increased turbo-lag and degradation of the vehicle acceleration response at tip-ins. This tradeoff between feedgas smoke and vehicle acceleration can be resolved by supplementing the engine power during acceleration by auxiliary means. Typical auxiliary systems are the electric power supplies attached to the crankshaft or the driveshaft as in a parallel hybrid vehicle configuration shown in Figure 1(a). Several parallel hybrid configurations have been studied both in industry [9] and in academia [2]. A novel way of supplementing the engine power and directly addressing the turbo-lag is to apply electric power to the turbocharger shaft utilizing a Turbocharger Power Assist System (TPAS) as illustrated in Figure 1(b).

A turbocharger power assist system (TPAS) is any device capable of supplying torque to the turbocharger shaft in the motoring mode and absorbing power from the turbocharger shaft and storing it when engaged in the regenerative mode. The energy storage can be achieved, for example, in a battery. The TPAS can be engaged at tip-ins to rapidly raise the turbocharger speed and fresh air delivery to the engine, thereby, increasing engine torque output with no deleterious effect on smoke. At higher speeds and loads, the TPAS can play the role of a conventional wastegate; it regulates the boost pressure, while at the same time, it charges a battery (regenerative mode). This energy would normally be wasted as a portion of the exhaust gas bypasses the turbocharger when the wastegate opens.

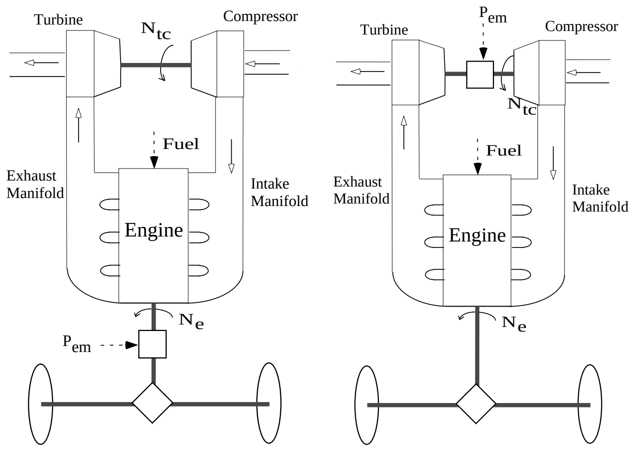

Figure 1. Diesel engine with (a) an electric motor in a parallel hybrid configuration and with (b) a turbocharger power assist system (where P_{em} denotes the supplemental power).

Several devices that can function as a TPAS are currently under development by several manufacturers. These include electrically actuated *Dynacharger* developed by TurboDyne, Inc., [8] and a *TurboGenerator* developed by the AlliedSignal, Inc., [10]. AlliedSignal, Inc., has also reported the use of a similar device for a turbocharger in a fuel cell application [4]. In [1] an electric generator integrally coupled with the turbocharger shaft is used to generate additional power for the vehicle electric requirements. For the viability of the TPAS concept there is a need for a significant innovation in motor, battery, and power electronic technologies that will enable reliable operation at very high rotational speeds (up to 180,000 rpm) typically encountered in small turbocharger applications.

Proper assessment of the cost/benefit tradeoff of new hardware components (such as a TPAS) and of subsystem level requirements is not possible unless the new component operation is optimally coordinated with the overall system. The feasibility study and development of operating strategies for hybrid powertrains often proceeds on a steady-state basis. That is, appropriate regions in terms of engine (or vehicle) speed and demanded powertrain torque are identified where the ancillary power is applied or the energy is regenerated. In this paper we take a different approach. Specifically, we ensure that both the application of the ancillary power and the energy regeneration take place over a single transient event. Due to the transient character of these performance objectives the optimization problem takes the form of an optimal control problem. This optimal control problem can be first solved numerically off-line utilizing a control-oriented model of the powertrain system. The results from the optimal control problem serve as an initial assessment of the technology and are especially important in guiding the system re-design and configuration. Additional analysis of the resulting optimal trajectories may provide critical guidelines for the development of the on-line control strategy, see [6].

In this paper we use optimal control techniques to assess the benefits of supplemental power addition at the turbocharger shaft. In the initial assessment, the objective is to minimize the time for a vehicle acceleration in a fixed gear to a specified final velocity. The problem is solved under two constraints: (i) the maximum power supplied or regenerated from the TPAS is limited, and (ii) the total power absorbed minus the power regenerated from the TPAS at the end of the acceleration is less than or equal to zero. This last constraint is imposed to avoid energy storage depletion, but it makes the optimal control problem difficult. The air-to-fuel ratio is constrained to a sufficiently high value to avoid visible smoke. Fixed gear acceleration tests are often used to characterize car "highway passing" performance or a "launch" performance from idle, see e.g. [7].

A detailed mean-value model of a diesel engine in conjunction with a generic model of power addition at the turbocharger shaft is utilized in this study. The optimal pattern of the supplemental power addition and regeneration is characterized. It involves adding power in the initial phase of the acceleration and regenerating the energy in the final phase of the acceleration. A sizeable reduction in the acceleration time as compared to the conventional vehicle is obtained even under the constraint of less than zero energy consumption by the TPAS. At the same time no deleterious effect on fuel consumption is observed and visible smoke is avoided. A brief comparison with the parallel hybrid is also made and it reveals a similar mechanism with which the TPAS can reduce pumping losses and improve the engine volumetric efficiency. In the last sections we investigate the sensitivity of the results due to changes in (i) maximum power limit, (ii) combined turbocharger/TPAS rotational inertia, and (iii) motoring/regenerating efficiencies. Finally, we demonstrate that the characteristics of the nominal optimal trajectory remain essentially unchanged if we consider limits on the magnitude of the maximum torque that the TPAS can deliver or absorb. This additional information on the TPAS is incorporated in the optimal control framework through the use of appropriate constraints on state and control variables.

PRELIMINARIES

POWERTRAIN MODEL

The study is based on a mean-value model of a turbocharged diesel engine [5]. The engine model, assuming zero exhaust gas recirculation (EGR) and fixed geometry turbocharger, has six states. The assumption of zero exhaust gas recirculation is not restrictive because EGR is typically disabled during aggressive acceleration phases. The four states represent the density and pressure dynamics in intake manifold and exhaust manifold. Specifically, p stands for gas pressure (kPa) and ρ for gas density kg/m^3. The subscript 1 identifies the intake manifold and the subscript 2 identifies the exhaust manifold. Consequently, these four states are p_1, ρ_1, p_2, ρ_2. The fifth state is the turbocharger rotor speed, N_{tc} (rpm), and the sixth state is the engine crankshaft speed, N_e (rpm). The state vector with these six entries is denoted by x.

The engine speed, N_v, is generated by a vehicle model. The load torque on the engine crankshaft is calculated from the aerodynamic and rolling resistance forces on the vehicle and known (fixed) gear ratio. Then, the engine acceleration is proportional to the difference between the engine brake torque and the load torque.

The cycle averaged fueling rate, W_f (kg/hr), is generated by the control system:

$$r = W_f .$$

The power supplied by the TPAS to the turbocharger shaft, P_{em}(kW), is a control input to the system:

$$u = P_{em} .$$

The power is absorbed from the turbocharger shaft if u is negative. Hence,

$$\frac{dN_{tc}}{dt} = \frac{P_t - P_c + P_{em}}{I_{tc} N_{tc}} ,$$

where, P_t (kW), is the power generated by the turbine, P_c (kW), is the power consumed by the compressor and I_{tc} is the turbocharger inertia in appropriate units. The supplemental power directly affects the rate of change in turbocharger speed, N_{tc}, which, in turn, affects the compressor and turbine mass airflow and the pressure in the intake and exhaust manifolds. The effects of the TPAS on the intake and exhaust manifold pressures propagate through the cylinder breathing process and can alter the engine volumetric efficiency and the pumping losses.

In a realistic situation the power that can be delivered or absorbed by the TPAS is subject to constraints. For example, if an electric motor and a battery are used, the TPAS maximum power is limited by the battery state of charge and motor characteristics. In particular, the maximum power may be a function of the turbocharger rotational speed. In this study our main interest is in understanding fundamental issues in supplemental energy addition with a view towards the specification of the subsystem level requirements. Hence, in the first part of the paper only a fixed maximum power constraint is assumed. We later illustrate how additional constraints of maximum torque limit or motor efficiency can be included into the optimization analysis.

From the fundamental laws of mass and energy conservation for intake and exhaust manifolds and from the torque balance on the turbocharger shaft and on the crankshaft we obtain the equations for the engine and the vehicle in the following general form

$$\frac{dx}{dt} = f(x, u, r) .$$

SMOKE-LIMITED ACCELERATION

Maximum acceleration with no visible smoke is enforced by restricting the fueling rate, W_f, when the total cylinder intake air flow, W_{1e}, is not sufficient. Specifically, if $W_{f,req}$ is the fueling rate requested by the driver through interpretation of the pedal depression then the actual fueling rate delivered to the engine, W_f, is

$$W_f = \min\left\{\frac{W_{1e}}{\phi_{cr}}, W_{f,req}\right\}.$$

The critical in-cylinder air-to-fuel ratio value, ϕ_{cr}, that guarantees visible smoke-free combustion is assumed to be equal to $\phi_{cr} = 25$. If we neglect any traction limitations, it is obvious that the maximum vehicle acceleration with non-visible smoke operation is achieved with an active fueling rate limit, $r(t) = W_f(t) = W_{1e} / \phi_{cr}$.

The vehicle acceleration performance can, thus, be improved by increasing the engine intake airflow, W_{1e}, and allowing more fuel to be burned in the engine without generating visible smoke. This can be achieved by improving the engine volumetric efficiency because the engine intake airflow, W_{1e}, is proportional to the engine volumetric efficiency, η_{vol}. As we discussed in the previous section, the TPAS has the potential to improve the engine volumetric efficiency through its effects on the intake and exhaust manifold pressures. Moreover, the TPAS can reduce the pumping losses by reducing the pressure difference between the exhaust and intake manifolds, $p_2 - p_1$. Reduction in pumping losses directly affects the engine brake torque, τ_e, during acceleration.

OPTIMAL ACCELERATION WITH TPAS

MINIMUM-TIME PROBLEM FORMULATION

The optimization objective is to determine the time trajectory of the supplemental power, P_{em}, that results in minimum acceleration time to a specified final velocity for a fixed gear ratio. In addition, two constraints are considered. Specifically, the total energy consumption by the TPAS during the acceleration interval must be less than zero, and, P_{em} cannot exceed the maximum power limit. That is, all the energy spent by the TPAS has to be regenerated and returned back to the energy storage (such as a battery or a flywheel) by the end of the acceleration period to be available for future use. The acceleration is assumed to take place with the fuel limiter active.

Mathematically, the problem is formulated as follows:

Determine a continuous trajectory

$$P_{em}(t) = u(t), \ 0 \le t \le T,$$

and the terminal time, T, so that the cost (which is the terminal time)

$J(u,T) = T$ is minimized

subject to

- the maximum power limit equal to u_{max}

$$|u(t)| \le u_{max}, \ 0 \le t \le T,$$

- acceleration on the fueling rate limiter

$$r(t) = W_{1e}/\phi_{cr},$$

- total energy consumption being less than zero

$$\int_0^T u(t)dt \le 0,$$

- final vehicle speed is equal to the desired one (equivalent to constraint on final engine speed equal to N_e^d when gear is fixed)

$$g(u,T) = N_e(t) - N_e^d = 0,$$

- diesel engine and vehicle dynamics

$$\frac{dx}{dt} = f(x(t), u(t), r(t)), \quad x(0) = x^0, \ \ 0 \le t \le T.$$

Here x^0 is the initial equilibrium, e.g. corresponding to the powertrain states in neutral idle when $N_e(0) = N_e^0, \quad r(0) = r^0$, and, $u(0) = 0$.

NUMERICAL OPTIMIZATION PROCEDURE

In the optimization process, T, is adjusted and, consequently, the time interval over which the dynamical equations are integrated varies. It is much easier, however, and more convenient to set up simulations over a fixed time interval. Hence, we transform the problem to an equivalent fixed time problem where T enters as a parameter into the dynamical equations. The transformation involves re-scaling time,

$$\sigma = t/T.$$

In the scaled time, the model is

$$\frac{dx}{d\sigma} = Tf(x,u,r), \ x(0) = x^0, \ 0 \le \sigma \le 1.$$

The optimization objective is still to minimize T which is now a parameter in the model.

The next step involves representing u using a finite number of appropriate basis functions. The problem then reduces to a finite-dimensional optimization problem that involves only a few parameters. To ease the computational details, the basis functions are selected as linear B-splines defined by the following expressions:

$$\varphi_0(\Delta;\sigma) = \begin{cases} 1 - |\sigma|/\Delta & |\sigma| \le \Delta \\ 0 & \text{otherwise} \end{cases}$$

$$\varphi_k(\Delta;\sigma) = \varphi_0(\Delta; \sigma - k\Delta),$$

where k is an integer. We also let an integer n be such that $1 = n \cdot \Delta$ with $\Delta > 0$. Then u is parameterized using the B-splines weighted by the unknown coefficients α_i that are precisely the values $u(\Delta \cdot i)$

$$u(\sigma) = \sum_{i=0}^{n} \alpha_i \varphi_i(\Delta;\sigma), \ \ 0 \le \sigma \le 1.$$

We thus have reduced the problem to a finite dimensional optimization problem where we optimize the (n+1) parameters $\alpha_i, \ i = 0, \cdots, n.$. By direct substitution of the parameterization for u the constraints take the form

- maximum power limit:

$$|\alpha_i| \le u_{max}, \ i = 0, \cdots, n.$$

- total energy consumption being less than zero:

$$\sum_{i=0}^{n} \alpha_i \le 0,$$

- final engine speed is equal to the desired:

$$g(u,T) = 0.$$

The constraint $g(u,T)=0$ is the most difficult to handle and we rely on evaluating g based on simulation of the scaled time model over the time interval $0 \le \sigma \le 1$.

The numerical optimization was performed using function *constr.m* of the Matlab 5.2 optimization toolbox which is based on a Sequential Quadratic Programming (SQP) algorithm for constrained optimization. To handle large values of n we relied on explicit gradient computation through the backward integration of the adjoint equations. For large n, explicit gradient calculation that takes advantage of the sequential nature of system dynamics is more efficient than the use of a center-difference formula-like approximation (see [3]). We found that the explicit gradient computation was essential to handle numerically large values of n in Matlab. The linearized equations of the diesel engine and vehicle dynamics required to formulate the adjoint equations have been derived symbolically from the nonlinear model equations with an automatic differentiator that we developed. The automatic differentiator is based on Matlab Symbolic Toolbox, that takes as an input the S-function of the model and generates a ready-to-simulate S-function of the adjoint system. The results of the numerical optimization of the TPAS and engine trajectories are reported in the following sections.

NUMERICAL OPTIMIZATION RESULTS

We apply the optimization procedure to two scenarios of acceleration requests. The first scenario reflects the "launch performance" requirements associated with acceleration from idle in the first gear. The second scenario reflects "highway passing" performance associated with acceleration in the third gear. These optimal trajectories are compared to the case of the *conventional* vehicle trajectories. The word "conventional" in this work refers to the case when the same system is simulated with TPAS disabled, i.e. when $u(t) = P_{em}(t) = 0$.

In the first scenario we consider the vehicle acceleration from neutral idle conditions ($N_e^0 = 800$ rpm) and we initialize accordingly the model states and inputs to fully balance the frictional losses in the engine. Based on preliminary information about an experimental TPAS device, we selected the maximal power limit equal to $u_{max} = 1.5$ kW, and the desired final velocity equal to 40 km/hr. The operation of the TPAS was optimized for the first gear acceleration and under the constraint of less or equal to zero total energy expenditure by the TPAS.

We selected 23 knots ($n = 23$) in the parameterization of u with linear B-splines. The optimization (initialized with different sets of initial values for $\alpha_i, i = 0, \cdots, n$, and T) converged to trajectories shown in Figures 2-3. The circles superimposed on the $u(t) = P_{em}(t)$ trajectory indicate the values of $\alpha_i, i = 0, \cdots, n$. The results are also summarized in Table 1, where total energy spent refers to the total chemical energy of fuel since the supplemental energy by the TPAS is zero.

The optimized operation of the TPAS achieves approximately 15.1 percent improvement in acceleration time and results in 2.1 percent less fuel consumption as compared to the conventional vehicle (i.e. with the TPAS turned off). As we can see in Figure 2 and 3, the TPAS supplies the energy to the turbocharger shaft during the beginning of the acceleration. At higher engine speeds and loads the TPAS absorbs some of the kinetic energy from the turbocharger, essentially, acting as a wastegate. All energy spent by the TPAS is regenerated during the same acceleration event so that the energy storage depletion is avoided. Since the TPAS reduces the pumping losses at the beginning of the acceleration (i.e. at low engine speeds) where the diesel engine efficiency is low, the total fuel consumption is improved.

It is interesting to investigate if and how the optimal trajectory changes during an acceleration scenario in the third gear, where, the vehicle starts from a steady-state cruise condition at 40 km/hr and accelerates to 90 km/hr. Figures 4-5 and Table 2 summarize the results. The acceleration time of the vehicle with the TPAS is 8.44 percent better than the conventional vehicle. The fuel consumption is essentially the same for both cases. The fuel economy advantage of the TPAS is lost because the engine acceleration is confined to a medium engine speed range where only limited improvements in engine pumping efficiency can be achieved. The qualitative features of the optimized P_{em} trajectory are the same as for the case of acceleration in the first gear.

These results indicate that it is optimal to add the supplemental energy during the initial phase of the acceleration and regenerate the energy in the final phase of the acceleration when the engine efficiency is higher. In the following section we investigate if this pattern of energy addition/regeneration persists if the supplemental power device is located at a different point in the powertrain such as in the parallel hybrid vehicle.

	Acceleration Time (sec)	Fuel Spent (g)	Total Energy Spent (MJ)
TPAS Vehicle	3.27	8.55	0.363
Conv. Vehicle	3.85	8.73	0.371

Table 1. Summary of the results for the first gear acceleration.

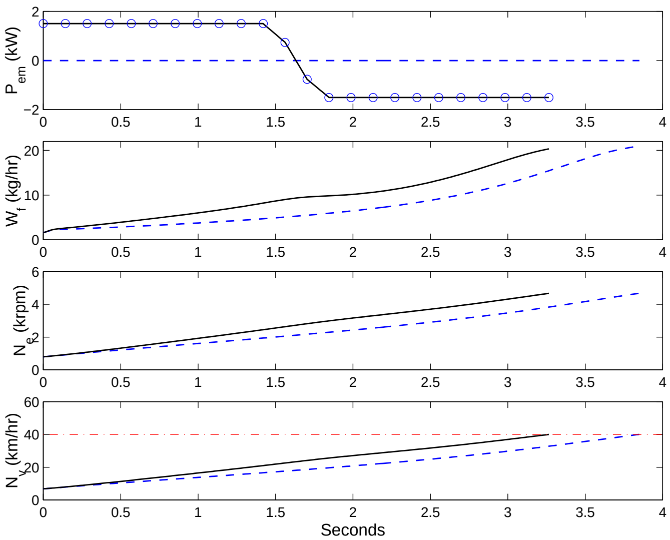

Figure 2. Comparison of TPAS (solid) and conventional vehicle (dashed) for the first gear acceleration.

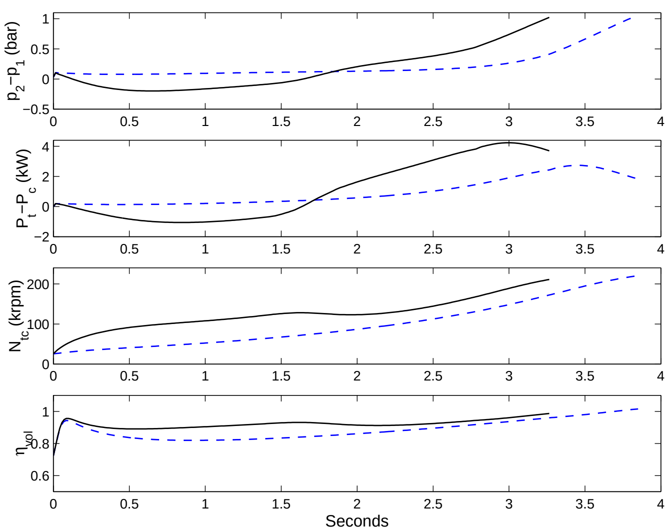

Figure 3. Comparison of TPAS (solid) and conventional vehicle (dashed) for the first gear acceleration.

	Acceleration Time (sec)	Fuel Spent (g)	Total Energy Spent (MJ)
TPAS Vehicle	12.91	30.27	1.286
Conv. Vehicle	14.10	30.31	1.288

Table 2. The acceleration time, fuel consumption and total chemical and supplemental (fuel+TPAS) energy consumption for the third gear acceleration.

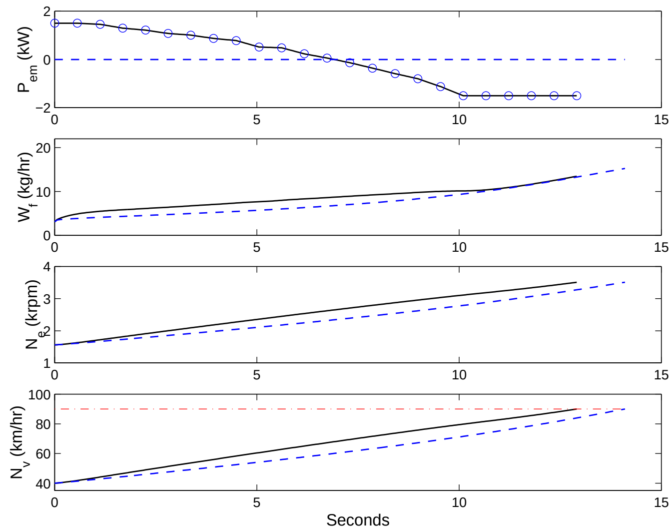

Figure 4. Comparison of TPAS (solid) and conventional vehicle (dashed) for the third gear acceleration.

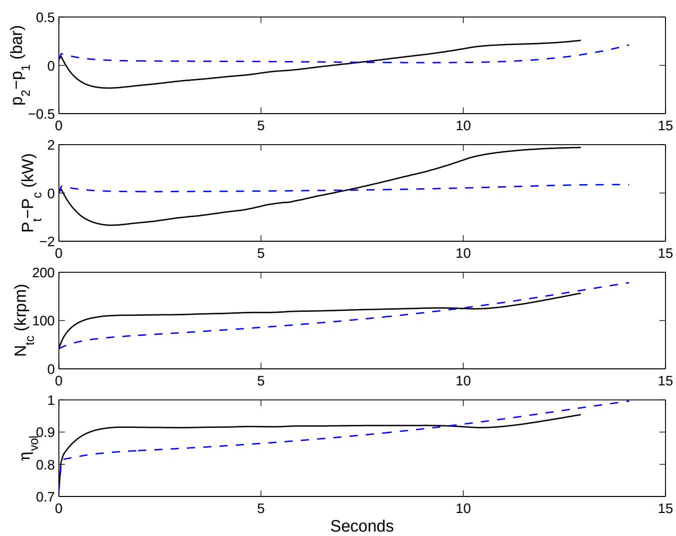

Figure 5. Comparison of TPAS (solid) and conventional vehicle (dashed) for the third gear acceleration.

COMPARISON WITH PARALLEL HYBRID

In a parallel hybrid vehicle the supplemental power (typically provided by an electric motor) supplements the engine torque to drive the vehicle. It is shown below that the optimal pattern of adding power for the parallel hybrid case is qualitatively similar to that of the TPAS. Specifically, the supplemental power should be added during the initial acceleration phase and replenished during the final acceleration phase where the engine efficiency is greater.

For the case of the parallel hybrid vehicle, we apply the same optimization methodology. We parameterize the control input $u = P_{em}$, which is now the power delivered or absorbed from the crankshaft. In this case, the power directly affects the rotational vehicle dynamics (see Figure 1(a)). We use the same number of B-splines nodes as in the TPAS trajectory optimization.

The size of the electric motor that is typically used in hybrid parallel configurations varies between 10-70 kW. We found that an electric motor with maximum power equal to 10.3 kW results in the same minimum acceleration time to 40 km/hr (with zero net electric energy consumption) for the parallel hybrid vehicle in the first gear as for the vehicle with the 1.5 kW TPAS. Hence, we selected a 10.3 kW supplemental power source for this study.

A comparison between the conventional vehicle equipped only with a heat engine and the hybrid vehicle with optimally scheduled electric power is shown in Figures 6 and 7. The fuel consumption of the parallel hybrid was 8.72 g for the 3.26 sec acceleration time. The fuel consumption in the case of the parallel hybrid is, essentially, the same as for the conventional vehicle (8.73 g). The analysis of the corresponding figures reveals that the reduction in pumping losses that occurs for the vehicle with TPAS at low speed/low load operating conditions of the engine is responsible for the slightly improved fuel economy.

INCORPORATING ADDITIONAL INFORMATION

In this section we illustrate with several case studies how additional information and constraints can be added to the optimization. Several of these case studies also illustrate how the dynamic optimization techniques can be used to guide the component selection.

EFFECT OF CHANGING ROTATIONAL INERTIA

The addition of the TPAS may lead to a different rotating inertia value of the turbocharger assembly. Since the inertia value affects the minimum time for the vehicle acceleration, we have repeated the optimization for the different values of the turbocharger inertia scale factor. The turbocharger inertia scale factor is the ratio of the inertia to its nominal value. Thus the inertia scale factor was 1 in all the previous studies and we now consider the situation when this factor is different from 1. The optimization was done for the acceleration from idle to 40 km/hr in the first gear and, as before, the maximum TPAS power was constrained in magnitude to 1.5 kW. It can be seen from Figure 8 that the inertia has to increase at least 2.5 times as compared with the conventional vehicle before the benefits of the TPAS in terms of turbo-lag reduction disappear.

EFFECT OF TPAS EFFICIENCIES

The above developments assumed an ideal situation with no motor losses. Here we illustrate how the information about losses can be taken into account. We introduce a motoring efficiency q_m and a generating efficiency q_g. The power applied to the turbocharger shaft or taken from the turbocharger shaft is P_{em}. If $P_{em} \geq 0$ then the power actually consumed from the energy storage (such as a battery) is P_{em}/q_m. If $P_{em} \leq 0$ then the power that can be put into the storage for future use is $q_g \cdot P_{em}$. In general, both of these efficiencies are functions of operating variables but here we consider a simplified situation when both of these efficiencies correspond to reasonable, average constant values. From the preliminary information about an electric TPAS we selected q_m = 0.9 and q_g = 0.7. We have optimized the time for the first gear acceleration to 40 km/hr subject to the constraint that all the energy taken by the TPAS from the energy storage is regenerated back by the end of the acceleration. The minimum acceleration time was 3.47 sec. and the fuel consumption was 8.70 g. This is 1.64 percent deterioration in fuel consumption and 6.12 percent deterioration in acceleration time as compared to the ideal case (see Table 1). The acceleration time and the fuel consumption are still better than for the case of the conventional vehicle. Figures 9-10 show the optimized trajectories. Note that for a portion of time, $P_{em} = 0$.

EFFECT OF CHANGING MAXIMUM POWER LIMIT

It is of interest to see if changing the maximum power limit has an effect on the acceleration performance. This limit was equal to 1.5 kW in all the previous cases. The net energy consumption by the TPAS is, as before, constrained to be zero. The minimum acceleration time as a function of maximum power limit for the first gear acceleration to 40 km/hr is shown in Figure 11. Increasing the maximum power limit decreases the minimum acceleration time. Increasing the maximum power limit has a beneficial effect on the fuel consumption, see Figure 12.

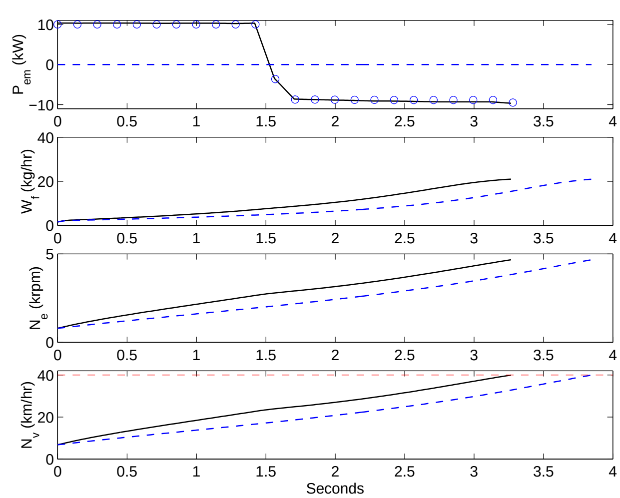

Figure 6. Comparison of the parallel hybrid vehicle (solid) and conventional vehicle (dashed) for the acceleration in the first gear.

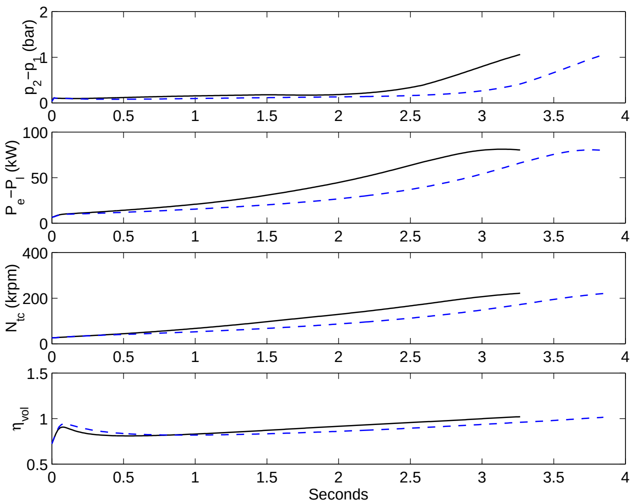

Figure 7. Comparison of the parallel hybrid vehicle (solid) and conventional vehicle (dashed) for the acceleration in the first gear.

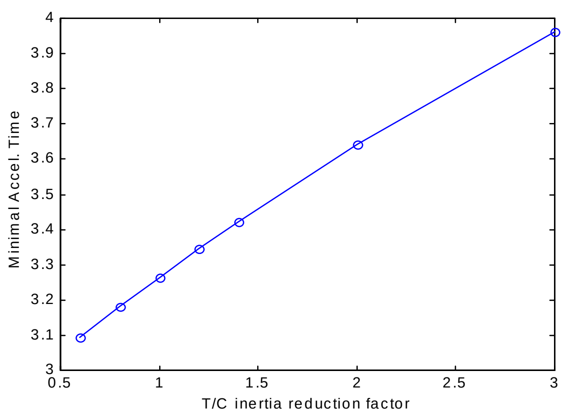

Figure 8. The minimum acceleration time as a function of the turbocharger inertia scale factor for the first gear acceleration to 40 km/hr.

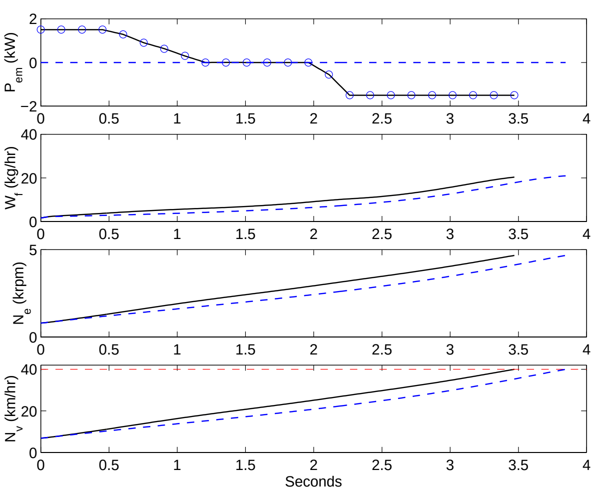

Figure 9. Comparison of TPAS (solid) and conventional (dashed) vehicle for the first gear acceleration. The effect of TPAS efficiencies is included.

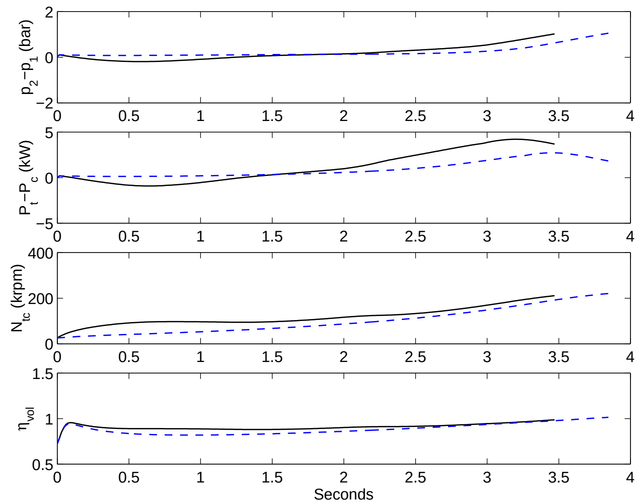

Figure 10. Comparison of TPAS (solid) and conventional (dashed) vehicle for the first gear acceleration. The effect of TPAS efficiencies is included.

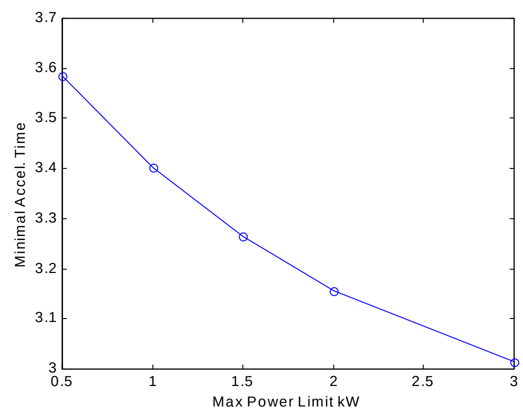

Figure 11. The minimum acceleration time as a function of the maximum power limit for the first gear acceleration to 40 km/hr.

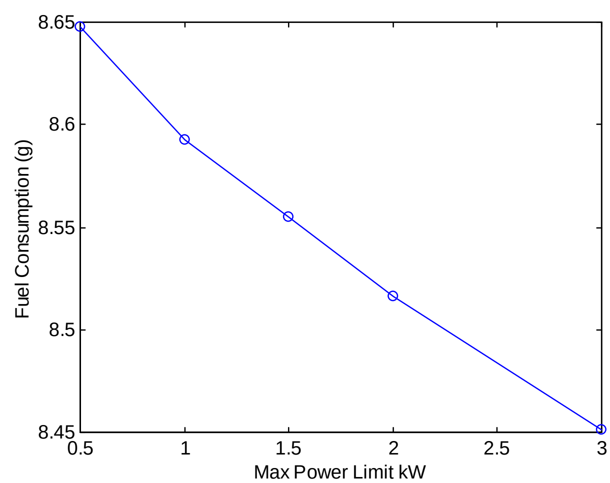

Figure 12. The fuel consumption as a function of the maximum power limit for the first gear acceleration to 40 km/hr.

EFFECT OF ADDING MAXIMUM TORQUE CONSTRAINT

Typical electric motors exhibit both power limits and torque limits. The torque limits may become active at low rotational speed while the power limits may, typically, become active at high rotational speeds. If τ_{em} denotes the torque generated or absorbed by the TPAS then the constraint takes the form

$$|\tau_{em}(t)| \le \tau_{max} .$$

Note that since the TPAS power is treated as a control input,

$$u = P_{em} ,$$

the treatment of the torque constraint amounts to enforcing a mixed pointwise-in-time state/control constraint of the form,

$$|u(t)| \le \tau_{max} \times (N_{tc}(t) \times \pi / 30) .$$

To handle this constraint, an iterative procedure is used. On the k-th step of this procedure we obtain the trajectory of the turbocharger rotational speed, $N_{tc}^{k}(t)$, corresponding to some TPAS power trajectory $u^{k}(t)$. Let t_i^k denote the i-th knot in the B-spline parametrization of $u^k(t)$ so that

$$u^k(t_i^k) = \alpha_i^k, i = 1, \cdots n.$$

Then, on the (k+1)-th step the optimization is performed over the values of $\alpha_i^{k+1}, i = 1, \cdots n$, subject to an additional constraint of the form

$$|\alpha_i^{k+1}| \le \tau_{max} \times (N_{tc}^{k}(t_i^{k+1}) \times \pi / 30), i = 1, \cdots, n.$$

As a result, we generate the TPAS power trajectory, $u^{k+1}(t)$. Then k is incremented and the procedure is repeated. As we iteratively increase k, we intuitively expect the solution to approach the optimal solution. For the application here this approach was used and has been shown to work well.

Under a 0.15 N-m maximum torque limit, in addition, to 1.5 kW maximum power limit and net energy consumption constrained to zero the results are summarized in Tables 3-4. As compared to the case of power limits only the minimum acceleration times have increased only slightly. As compared to the conventional vehicle (with no TPAS), the improvement in minimum acceleration time is approximately 13.88 percent, and the improvement in fuel consumption is approximately 2.28 percent for the first gear acceleration to 40 km/hr case. These improvements are, respectively, 8.29 percent and 0.165 percent for the case of accelerating from 40 km/hr to 90 km/hr in the third gear. The optimal trajectories for the first gear acceleration case are shown in Figures 13-15. These trajectories are qualitatively very similar to the case when only the power limits are imposed, except that the torque constraint becomes active at low rotational speeds of the turbocharger. The optimal trajectories for the third gear acceleration case are similar.

	Acceleration Time (sec)	Fuel Spent (g)	Total Energy Spent (MJ)
TPAS Vehicle	3.31	8.53	0.363
Conv. Vehicle	3.85	8.73	0.371

Table 3. Summary of the results for the first gear acceleration with the torque constraint.

	Acceleration Time (sec)	Fuel Spent (g)	Total Energy Spent (MJ)
TPAS Vehicle	12.93	30.26	1.286
Conv. Vehicle	14.10	30.31	1.288

Table 4. Summary of the results for the third gear acceleration with the torque constraint.

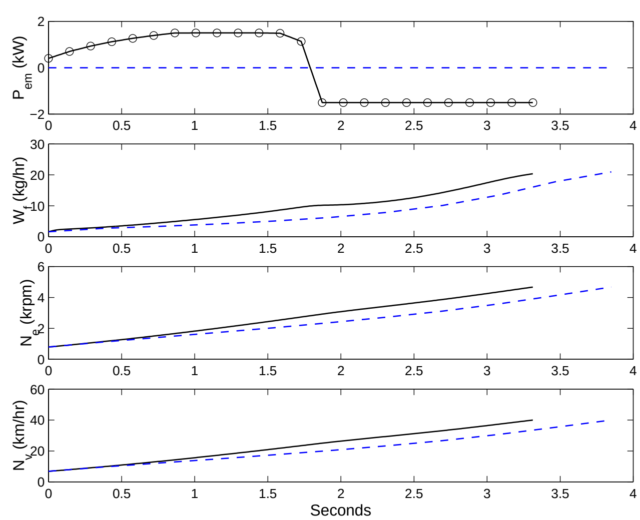

Figure 13. Comparison of TPAS (solid) and conventional vehicle (dashed) first gear acceleration with the torque constraint.

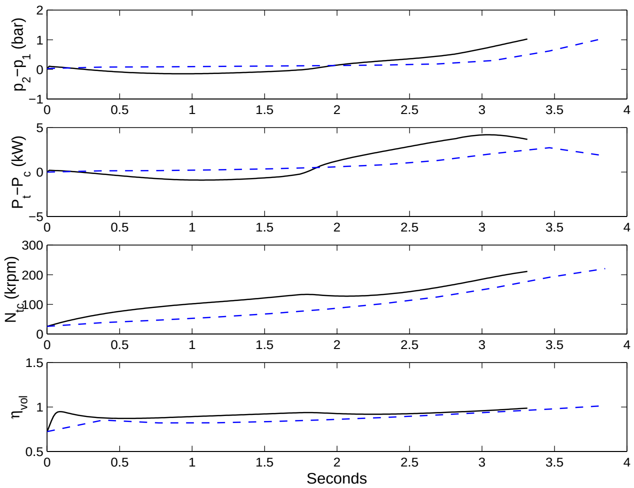

Figure 14. Comparison of TPAS (solid) and conventional vehicle (dashed) first gear acceleration with the torque constraint.

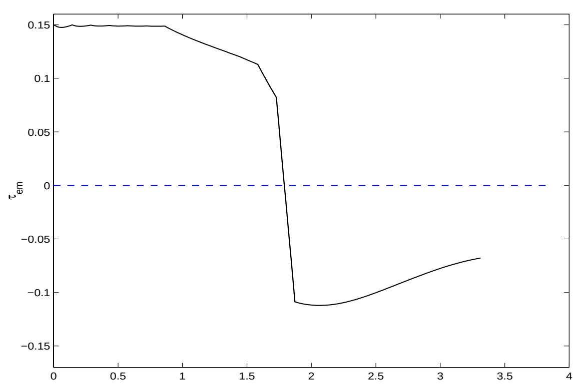

Figure 15. Comparison of the supplemental torque for the vehicle with TPAS (solid) and for the conventional vehicle (dashed) during the first gear acceleration with the supplemental torque constraint.

CONCLUSION

A preliminary assessment of the feasibility and benefits of a Turbocharger Power Assist System (TPAS) has been conducted. The results can only be used to assess trends and may not be suitable for quantitative interpretation. The major accomplishments and results are summarized here.

- We have demonstrated that sizable turbo-lag reduction can be achieved without sacrificing the smoke emission performance and with zero net energy expenditure by the TPAS over the acceleration interval. The improvement in the initial engine torque response with the TPAS is perhaps a more dramatic measure that the driver would immediately appreciate.

- Not only the acceleration performance but also the fuel consumption of the vehicle with the TPAS is equal or better than the fuel consumption of the conventional vehicle (approximated in this work as the same vehicle with TPAS turned off).

- The increase in inertia of rotating parts of turbocharger and TPAS results in the increase in the minimum acceleration time. However, for the case studied the inertia has to increase by a large number, about 2.5 times, before the benefits of TPAS in terms of acceleration time disappear.

- Increasing the TPAS maximum supplying and absorbing power levels decreases the minimum acceleration time and the fuel consumption. This conclusion is reached although the net energy consumption by the TPAS during the acceleration interval is zero, i.e. all the energy spent by the TPAS to accelerate the turbocharger is regenerated.

- The motoring/regenerating efficiencies have been shown to have a significant effect on the minimum acceleration time. Hence, an accurate model for the TPAS has to be ultimately used to assess more precisely TPAS benefits.

- It is also possible to interpret the benefits of the TPAS in terms of smoke and particulate emission reduction. Specifically, by adding a TPAS and optimally controlling its operation in an existing vehicle, lower particulate and smoke levels can be achieved with no deleterious effects on vehicle acceleration. This is possible due to operation at higher values of the air-to-fuel ratio for the vehicle equipped with the optimized TPAS.

- The utility of the optimal control techniques in assessing powertrain feasibility with respect to transient performance objectives has been demonstrated. The results are useful not only for the fundamental understanding of the supplemental power addition issues at the turbocharger shaft but also for specifying the subsystem level requirements for the TPAS and for guiding the component selection process.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

TPAS Turbocharger power assist system
EGR Exhaust gas recirculation
SQP Sequential quadratic programming