

Turbocharger Turbine Inlet Isentropic Pressure Observer Model

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ABSTRACT

Exhaust pressures (P3) are hard parameters to measure and can be readily estimated, the cost of the sensors and the temperature in the exhaust system makes the implementation of an exhaust pressure sensor in a vehicle control system a costly endeavor. The contention with measured P3 is the accuracy required for proper engine and vehicle control can sometimes exceed the accuracy specification of market available sensors and existing models. A turbine inlet exhaust pressure observer model based on isentropic expansion and heat transfer across a turbocharger turbine was developed and investigated in this paper. The model uses 4 main components; an open loop P3 orifice flow model, a model of isentropic expansion across the turbine, a turbine and pipe heat transfer models and an integrator with the deviation in the downstream turbine outlet parameter. There were two methods analyzed; one a closed loop observer based on turbine outlet pressure and another using a closed loop observer based on turbine outlet temperature. The models were developed and validated using data from two different engines that are representative of the end points of the range of diesel engine sizes and outputs, one sold in the European market and the other in North America.

CITATION: Fulton, B., Petrovic, S., Van Nieuwstadt, M., Dixon, J. et al., "Turbocharger Turbine Inlet Isentropic Pressure Observer Model," *SAE Int. J. Engines* 8(4):2015, doi:10.4271/2015-01-1617.

INTRODUCTION

For automotive companies to remain competitive, vehicles with improved performance and fuel economy able to meet increased requirements on emissions and OBD legislation have been driving the development of more advanced and complex engine and aftertreatment systems. It is becoming increasingly important, that as the complexity of powertrain systems increase, the complexity of the control system for that vehicle needs to advance to keep pace. Part of that advancement is the development of model based engine controls to improve response and control of the physical behavior of the vehicle, engine and aftertreatment system.

An important input parameter for engine and vehicle control systems is turbine inlet exhaust manifold gas pressure (P3), this pressure is important for EGR control, turbocharger control, engine protection, engine brake control, OBD monitors and turbocharger protection features that directly affect the performance of the vehicle. The

exhaust environment in diesel engines is a very harsh environment and design actions to implement a P3 sensor into that system increase the cost of that sensor significantly. That environment also decreases the durability and reliability of the sensor. Ideally from a cost and reliability stand point removal/replacement of the P3 sensor is an attractive alternative. Most P3 modeling efforts found in the literature are orifice flow based models that use open loop estimates based on VGT position for a representation of the orifice size and a combination of air and fuel flow to produce a total exhaust flow. [2][3][4][5][6] Other models can use conservation of work or energy to predict P3 by comparing the compressor and turbine work calculations. The major challenge of modelling the P3 pressure is achieving the accuracy required by each of the vehicle functions requiring that input. The P3 open loop model used as the baseline model for comparisons purposes and input into the Observer model is a regression model based on the physical properties of orifice flow. The model is a mature model calibrated over multiple vehicle samples and operating modes.

Each of the control requirements drive accuracy metrics for any P3 inputs needed for the application. Current levels of these requirements are near or at the accuracy limits of both sensors and models. P3 sensors are pressure sensors that generally have accuracy ranges of $\pm 1.5\%$ of the full sensor range, depending upon the range of the sensor, these values can be very small and any models used in the control system need to achieve similar levels of accuracy.

The method covered in this paper was developed as an observer type model that uses an open loop estimate corrected by applying a factor determined from an output variable defined in the system. This type of model has been used successfully to improve the performance of an open loop exhaust manifold temperature model. [1] The predicted post turbine pressure or temperature is compared to the same measured downstream parameter. The difference between predicted and measured signals is multiplied by a gain factor based on the isentropic relationship to obtain a P3 correction, and the correction is added to the existing P3 modeled value. The goal of the project was to develop an exhaust manifold pressure model that uses the Observer process while maintaining limited complexity and calibration effort, with accuracy levels suitable for proper function of current engine control and vehicle diagnostic systems.

During the course of the development and verification of the P3 Observer, it was determined that the ability to correct P3 as a function of the turbine outlet temperature (T4) was also possible. A T4 based P3 Observer was developed and analyzed with and in comparison to the P4 based P3 Observer.

OBSERVER PHYSICAL REPRESENTATION

The physical representation of the modeled system shown in Figure 1 is a good visual representation and reference of the components of the system and associated boundary conditions required for the Observer model. The system components important for this Observer model are the intake manifold, the exhaust manifold, the combustion system (combustion chamber and fuel injector), the exhaust manifold, the turbocharger turbine and the down pipe at the outlet of the turbine. A primary assumption of this model is that the system has either the turbine outlet pressure sensor or modeled value and a turbine outlet temperature sensor (T4) required for OBD monitoring of the exhaust aftertreatment system of the vehicle.

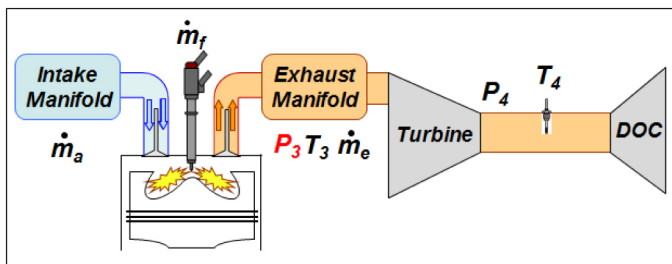


Figure 1. Physical Representation of the components important for the P3 Observer model

CLOSED - LOOP OBSERVER ALGORITHM

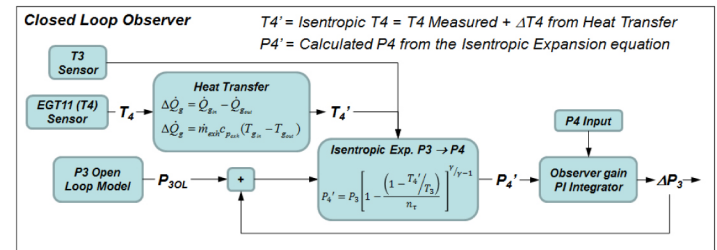


Figure 2. Closed - Loop P4 based P3 Observer Model

The closed loop observer algorithm is made up of 4 distinct components shown in Figure 2; an open loop P3 model that feeds into the equation for isentropic expansion across a turbine to determine isentropic P4, that isentropic expansion calculation uses an isentropic T4' estimate calculated from a measured T4 that is fed into a heat loss algorithm. The difference between the measured and estimated P4 values is then fed into a Proportional - Integral (PI) integrator that determines a correction value (DP3) that is applied to the open loop estimate to produce the Observer model output P3 estimate.

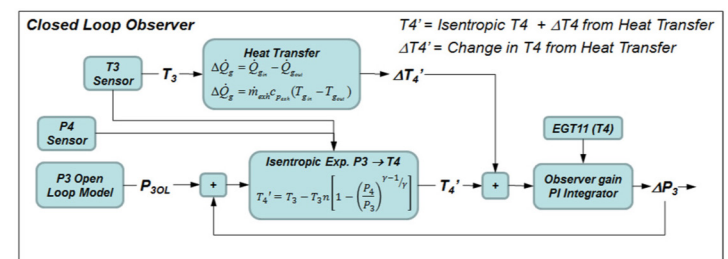


Figure 3. Closed - Loop T4 based P3 Observer Model

The closed loop observer algorithm in Figure 3 is also a P3 exhaust pressure model made up of the same 4 components shown in Figure 2; but are arranged differently to determine a T4 estimated output to observe from. These parts include an open loop model that feeds into the equation for isentropic expansion across a turbine to determine isentropic T4', that isentropic T4' is added to the estimated exhaust temperature drop ($\Delta T4$) from turbine heat loss calculated from a measured T3 that is fed into a heat transfer feature. The difference between the measured and estimated T4 values is then fed into a Proportional - Integral (PI) integrator that determines a correction value ($\Delta P3$) that is applied to the open loop estimate to produce the Observer model output P3 estimate.

OPEN LOOP MODEL - The P3 Open Loop model input can be one of many alternatives; these include simple two dimensional maps based on turbocharger position and exhaust flow to regression orifice flow fits from vehicle and dynamometer data to more complex work/energy balance models based on a comparison of the compressor and turbine. These models are usually of the form of either a pressure delta added or multiplier applied to the measured turbine outlet pressure at a steady state condition and filtered as a function of exhaust mass flow (fuel and air) shown in Equation 1. The accuracy of the open loop model is important to the error metric of the observer. The observer takes time to integrate to the measured P4 or T4 value, until then the open loop model is relied upon for fast response and the inaccuracy of the P3 observer model will increase or decrease with and open loop

model error feeding the observer. The open loop model used in this analysis was a cubic regression model based on orifice flow using the VGT position as a representation of the cross-sectional flow area and corrected exhaust flow. Orifice flow is physically represented as a squared function, but the cubic function was chosen because of the cubic response characteristics of P3 sensors used in automotive applications at the sensor measurement limits.

$$P_3 = P_4 + \Delta P(\dot{m}_e, VPS, T_3)$$

Equation 1: Open loop regression definition

During development and calibration of the open loop model used in this analysis, it was determined that use of the exhaust temperature input as a lumped assumption representative of the actual gas temperature was the most effective at reducing error. During development and validation of the Open Loop model, testing determined that the modelled pressure was directly dependent upon gas temperature and not metal or sensor temperature. This was best achieved by using T3 modeled input into the Open loop model representative of exhaust gas temperature, i.e. instant gas temperature by setting the model time constants to 0. If a sensed, or flange or representative metal temperature is used the model becomes inaccurate during transient operation due to the T3 input response differences from the gas temperature.

One advantage of the Observer type of inference method is that any existing mature open loop P3 models already present in the control system can be fed into the Observer model.

ISENTROPIC EXPANSION: For the P3 Observer that uses P4, the observer is based on the equation for isentropic expansion [7] across a turbine with turbine efficiency (η_t) as a function of corrected measurement or estimate of Turbine Shaft Speed (TSS), modeled or measured Vane Position (VPS) and a measured or estimated turbine inlet and outlet temperatures as shown in Equation 2. The P3 open loop estimate is input into the isentropic expansion equation along with the T3 measurement and an isentropic T4 value that calculates a P4 output that feeds into the observer portion of the model.

$$P_4' = P_3 * \left[1 - \frac{(1 - T_4/T_3)}{\eta_t} \right]^{\gamma/\gamma-1}$$

Where:

$$\eta_t = f\left(TSS/\sqrt{T_3}, P_4/P_3, VPS\right)$$

$$TSS = f\left(P_4/P_3, \dot{m}_e\right)$$

Equation 2: The isentropic equation for the P3 Observer based on P4

To change the P3 Observer to use T4, the isentropic expansion equation [7] was modified to calculate an isentropic turbine outlet temperature (T4') output as shown in Equation 3 below; it also uses

turbine efficiency as a function of corrected TSS, VPS position, but changes the turbine temperature ratio to an expansion ratio output that feeds into the heat transfer portion of the model

$$T_4' = T_3 - T_3 \eta_t \left(1 - (P_4/P_3)^{\gamma/\gamma-1} \right)$$

Where:

$$\eta_t = f\left(TSS/\sqrt{T_3}, P_4/P_3, VPS\right)$$

$$TSS = f\left(P_4/P_3, \dot{m}_e\right)$$

Equation 3: The isentropic equation for the P3 Observer based on T4

Turbine efficiency can be regressed from the same data set as the turbocharger speed signal. There are shared parameters in each regression, but they are regressed separately as the model intention is to be able to work with either a turbine speed sensor or a turbo speed regression in-lieu of a sensor. The turbine efficiency and turbocharger speed signal estimations used in the examples provided in this paper are based on data generated on a gas stand (see Figure 4) for one program and data generated on a dynamometer for another. This allows multiple methods of data for regression models and doesn't rely on one method of providing that data.

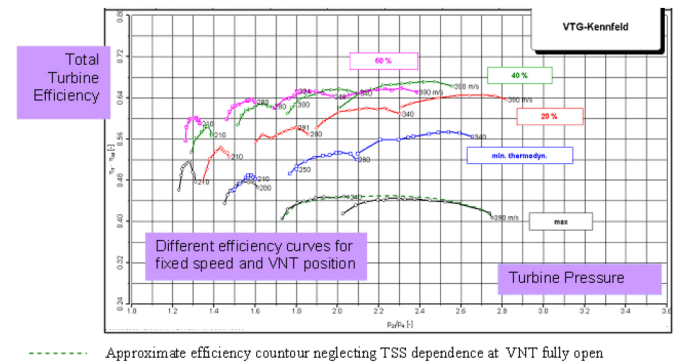


Figure 4. Turbine map example generated from gas stand data

HEAT TRANSFER: The heat loss model across the turbine uses heat transfer from the exhaust gas→wall and wall→ambient (underhood) as shown in Equation 4 and Figure 5. The model is based on the principle of heat transfer for a typical pipe model [1], and is applied across the turbine stage of the turbocharger. The heat transfer model is the same basic model for each of the Observers, but differs in how and when it is applied in each Observer.

$$\Delta \dot{Q}_g = \dot{Q}_{in} - \dot{Q}_{out}$$

$$\Delta \dot{Q}_g = \dot{m}_{exh} c_{p_{exh}} (T_{g_{in}} - T_{g_{out}})$$

$$\Delta \dot{Q}_g = \dot{Q}_1 - \dot{Q}_2$$

$$\dot{Q}_1 = h_1 A_1 (T_g - T_w) = \dot{Q}_2 = h_2 A_2 (T_w - T_{amb})$$

Equation 4: Pipe model heat transfer governing equations

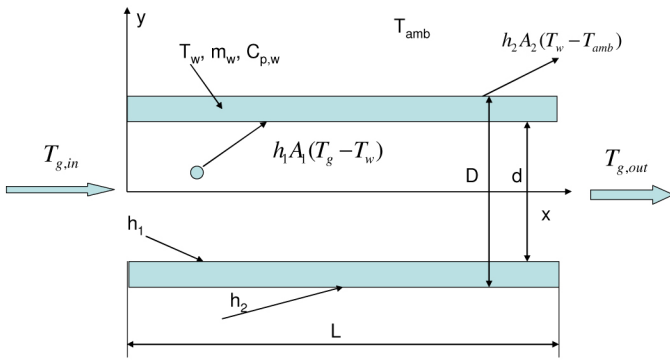


Figure 5. Pipe model heat transfer representation with governing equations

Referring to the P4 based Observer in Figure 2, the heat transfer model determines the change in temperature across the turbine housing and adds that temperature change to the measured T4 to determine an isentropic T4' estimate to be used in the isentropic equation.

Referring to the T4 based Observer in Figure 3; the heat transfer model determines the change in temperature across the turbine from the housing heat loss in parallel with the isentropic feature of the Observer determining a modeled isentropic T4' value. The delta change in the exhaust gas temperature from the turbine heat loss is added to the isentropic T4' temperature estimate to determine a real T4 value.

OBSERVER INTEGRATOR: The Observer Integrator in each model is used to compare a modeled P4 or T4 to a measured P4 or T4 value. The deviation generated from that comparison is modified with a gain derived from the isentropic expansion equation to come up with a P3 observer adjustment that is applied to the Open Loop P3 model input in the isentropic expansion block. The derivation in the following equations is for a P3 Observer based on P4

Full Differential:

$$P_3 = P_4 / \left[1 - \frac{(1 - T_4/T_3)}{n_\tau} \right]^{\gamma/\gamma-1}$$

Gain and Sensitivities:

$$\frac{\partial P_3}{\partial P_4} = 1 / \left[1 - \frac{(1 - T_4/T_3)}{n_\tau} \right]^{\gamma/\gamma-1}$$

Observer Gain:

$$dP_3 = P_{3k} - P_{3k-1}, dP_4 = P_{4k} - P_{4k-1}, K = \frac{\partial P_3}{\partial P_4}$$

$$P_{3k} = P_{3k-1} + K(P_{4k} - P_{4k-1})$$

Equation 5: The Full Differential, Gain and Sensitivity, and Observer gain equations for the P3 Observer based on P4

The observer adjustment to the P3 open loop estimate correction calculated above corrects the existing P3 open loop estimate using a PI integrator explained in the equations below:

$$\dot{x} = K(P_{4meas} - P_{4obs})$$

$$P_{3obs} = P_{3OL} + k_p * \dot{x} + k_I * x$$

Equation 6: The P3 Observer based on P4 PI integrator equations

The derivation in the following equations is for a P3 Observer based on T4 with the same Full Differential used in the equations above, but taking the derivative with respect to T4:

Gain and Sensitivities:

$$K = \frac{\partial P_3}{\partial T_4} = \frac{-\gamma P_4}{(\gamma - 1) T_3 n_\tau} * \left[1 - \frac{(1 - T_4/T_3)}{n_\tau} \right]^{(1-2\gamma/\gamma-1)}$$

Observer Gain:

$$dP_3 = P_{3k} - P_{3k-1}, dT_4 = T_{4k} - T_{4k-1}, K = \frac{\partial P_3}{\partial T_4}$$

$$P_{3k} = P_{3k-1} + K(T_{4k} - T_{4k-1})$$

Equation 7: The Gain and Sensitivity, and Observer gain equations for the P3 Observer based on T4

The observer adjustment to the P3 open loop estimate correction calculated above corrects the existing P3 open loop estimate using a PI integrator in the equations below:

$$\dot{x} = K(T_{4meas} - T_{4obs})$$

$$P_{3obs} = P_{3OL} + k_p * \dot{x} + k_I * x$$

Equation 8: The P3 Observer based on T4 PI integrator Equations

Application of the observer correction to P3 is done with a PI controller using gains as a function of mass air flow and fuel flow.

Test Vehicles

The Superduty 6.7L V8 diesel has two versions of the engine; a 'chassis certified' version generally applied to pick-up trucks less than 14000lb Gross Vehicle Weight Rating (GVWR), and a Heavy-duty dyno certified version used in 14000 lb. GVWR and heavier pick-up and chassis cab trucks. These trucks are equipped with a full after treatment exhaust systems that include a DOC / DPF / SCR with the order of the DPF and SCR system switched between the chassis and dyno cert versions of the vehicle.

The 2008.25MY Kuga 2.0L I4 diesel is a NEDC EUR Stage IV emissionised vehicle equipped with a DOC / DPF / LNT aftertreatment system.

Table 1. 2011MY 6.7L Engine Properties

Properties	Description	Units
Engine Type	4-Stroke	-
Engine Configuration	V-8	-
Displacement	6.7	L
Bore	99	mm
Stroke	108	mm
Combustion System	Compression ignition	-
Turbocharger	Honeywell GT-32 VNT	-
Fuel System	Bosch CRI 3.2 – 2000 bar	-
Compression Ratio	16.2:1	-
Valve Configuration	2 – Intake / 2 – Exhaust	-
Rated Power Chassis	400 @ 2800 rpm	hp
Peak Torque Chassis	850 @ 1800 rpm	ft-lb
Rated Power Dyno	300 @ 2800 rpm	hp
Peak Torque Dyno	650 @ 1800 rpm	ft-lb

Table 2. 2008.25MY Kuga 2.0L engine properties

Properties	Description	Units
Engine Type	4-Stroke	-
Engine Configuration	I4	-
Displacement	1.99742	L
Bore	85	mm
Stroke	88	mm
Combustion System	Compression ignition	-
Turbocharger	Borg-Warner	-
Fuel System	Delphi HPCR - 1800 (bar)	-
Compression Ratio	16.7:1	-
Valve Configuration	2 – Intake / 2 – Exhaust	-
Rated Power	136 @ 4000 rpm	hp
Peak Torque	320 @ 2000 rpm	Nm

Multiple test cycles were used for verification of the models that include dynamometer and vehicle test cycles and various drive cycles that attempt to cover a complete operating profile.

Results and Analysis

This section will cover the results and analysis of individual components of the model and the model itself; it will also include comparisons between the 2 separate models and the open loop model.

OPEN LOOP MODEL: The P3 open loop model, used as the input to the Observer output is shown in [Figures 6 and 7](#) compared to the sensed P3 value. This is representative of typical performance from this type of orifice flow based pressure model.

The response of the model is characteristic of the P3 Open Loop model and evident in [Figure 6](#) is the open loop response being close to the measured signal. The inherent accuracy of this type of model will present a very difficult task for the Closed Loop Observer to overcome.

P3 Modelled vs. Sensed Altitude Cold Start Drive

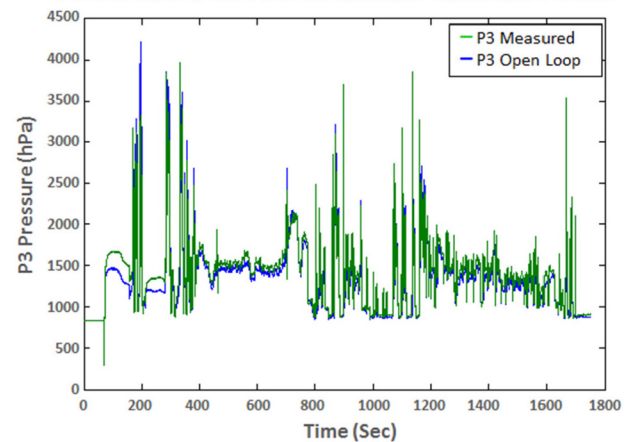


Figure 6. P3 Open Loop model vs. sensed pressure for an Altitude Cold Start drive 6.7l V8.

P3 Open Loop Model vs. Sensed Values

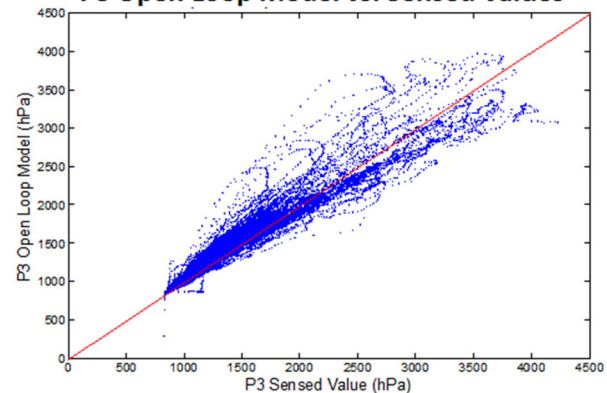


Figure 7. The measured vs. sensed P3 Open Loop values for the Altitude Cold Start drive 6.7l V8.

TURBINE EFFICIENCY: The literature review produced an overview of different methods for turbine efficiency regressions on Fixed Geometry Turbines. The published turbine efficiency regressions are dependent upon the basic isentropic equation with the addition of the VPS for the Variable Geometry Turbine application.

$$\eta_{\tau} = f\left(\frac{TSS}{\sqrt{T_3}}, \frac{P_4}{P_3}, VPS\right)$$

Equation 9: Turbine efficiency relationship

The turbocharger efficiency was regressed using generic gas stand data supplied by the turbocharger component supplier or measured engine dynamometer data. The inputs for the efficiency estimate can be a function of sensor inputs or other modeled inputs. In the case of the observer model analyzed in this paper, all the inputs can be modeled or sensor based. The output variable error was analyzed between both measured and estimated inputs into each feature and plotted.