

An Innovative Approach to Race Track Simulations for Vehicle Thermal Management

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ABSTRACT

Within the pre-development phase of a vehicle validation process, the role of computational simulation is becoming increasingly prominent in efforts to ensure thermal safety. This gain in popularity has resulted from the cost and time advantages that simulation has compared to experimental testing. Additionally many of these early concepts cannot be validated through experimental means due to the lack of hardware, and must be evaluated via numerical methods.

The Race Track Simulation (RTS) can be considered as the final frontier for vehicle thermal management techniques, and to date no coherent method has been published which provides an efficient means of numerically modeling the temperature behavior of components without the dependency on statistical experimental data.

The following investigation will explore an innovative methodology which utilizes a conventional method of simulation whilst integrating multiple *3-Dimensional* CFD solutions which are interpolated to match a derived moving average profile. New meshing techniques in combination with the integrated use of a *1-Dimensional* transient exhaust prediction tool facilitate higher turn-around times for dynamic vehicle conditions.

The experimental data consisted of a test vehicle conducting several laps through the Nuerburg-ring whilst acquiring temperature data on a wide range of underbody components.

Excluding the warm-up phase, a single lap simulation was conducted to evaluate the proposed methodology. A fair correlation was achieved between the simulation results and experimental data considering the time advantages of the methodology. Areas of discrepancy can be accounted for by the proposed 1-way coupling scheme and overcompensation of the component temperatures within CFD models.

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INTRODUCTION

Extending from steady state cases allows engineers to investigate the "real" on road conditions that are typically associated with transient characteristics. The ability to predict time dependent thermal characteristics of vehicle environments leads to improved product development (with rapid modification) and an inherent reduction in experimental cost. Additionally many of the critical thermal cases experimentally validated are coupled to non-equilibrium boundary condition, resulting either in an over-prediction

through steady state *3-Dimensional* modeling or an inaccurate prediction through *1-Dimensional* modeling.

As the vehicle becomes more complex with the integration of thermal management systems, through monitoring, controlling and changing the performance of the engine or cooling systems to further improve the fuel efficiency, it is evident that transient phenomena must be incorporated within production simulations in order to accurately represent the heat fluctuation throughout the vehicle. Hence there is a large industrial need for the

development of effective methodologies that can accommodate time-dependent conditions.

In order for these methodologies to be integrated as a standard processes they must accommodate the high demands of industry. These requirements include:

1a. Equal or faster turn-around times compared with current steady state simulation processes.

If not, then;

1b. The invested resources (manpower, software licenses & hardware) must equate to a significantly larger gain in accuracy within a maximum turn-around period of 1 week.

2. Transferability to alternative transient cases, alternative vehicle types and power systems.

3. Process stability. To have an accurate stable process is more important than having a higher accuracy process that rarely works.

4. Ability to automate the process once it has proved its accuracy.

If this is achieved, ultimately the dependency of experimental validation becomes less critical as accepted CFD methods are integrated into the overall development process.

The following investigation will aim at resolving one of the most highly dynamic transient cases, the race track simulation (RTS).

CURRENT STATE OF THE ART

The current body of knowledge is relatively extensive with regards to vehicle thermal management (VTM) under steady-state or moderate transient conditions (Hill Climb & Thermal Soak) ([1], [2], [3], [4], [5]).

Pryor [2], investigated a means of achieving an under hood thermal soak analysis for a truck. This method utilized a coupling methodology between steady-state CFD simulations and a transient thermal model. CFD solutions were 2-way coupled for a given time point. Between the defined coupling points an interpolation was conducted by the thermal software. The results from the thermal soak investigation correlated very well with experimental data.

The methods described particularly by Reister & Bauer [1] have opted to increase the realism of their numerical models by introducing a solid-fluid coupling ("all in one") scheme, unlike conventional methods ([2]) which use shell elements and coupling between the CFD and thermal models. In order to incorporate the heat sources a full 3-Dimensional exhaust simulation is additionally performed. This method is clearly the future of CFD for automotive applications however it inherently increases the amount of overall-processing time required due to modeling each component with individual thicknesses, thermal properties and contact interfaces to neighboring parts. An added complexity is the requirement of coupling between a fluid model and the corresponding solid model within the same CFD code to

resolve time-step differences between thermal and fluid phenomena. This process carries a dependency on increased software licences and significantly higher amounts of parallelization (with cluster hardware).

Through the analysis of the requirements for the "all in one" method, it can be suggested that a discrepancy exist between the invested resources and the gain in efficient yet accurate thermodynamic solutions. Additionally the current available resources in hardware for standard processes do not allow a comfortable transition to this methodology.

Adopting a similar methodology to the conventional steady state processes described in literature ([2], [3], [4], [5]) an immediate solution for RTS is examined. Additionally the exhaust system is modeled with techniques previously published [6] in order to further increase the efficiency of the overall process.

The final goal of the investigation is to provide a methodology that not only proves that extreme dynamic conditions can be simplified but also that these conditions can be modeled in an effective and efficient manner. The following paper provides the first progress on achieving these goals.

VEHICLE THERMAL BEHAVIOUR

In order to establish a simplified methodology accommodating the industrial requirements of "efficiency with accuracy", an open investigation of race track experimental temperature data was examined. Through analysis of several experiments on alternative tracks the following research findings were achieved:

1. Underbody components under dynamic conditions tend to fluctuate in an oscillating manner with small amplitudes.

2. The temperature behavior of components within these conditions can be indirectly related to their equivalent thermal capacities.

3. Thermally vulnerable components (with lower thermal capacities) are more sensitive to rapid fluctuation.

4. Alternatively, thermally less responsive components (with large thermal capacities) tend to resist rapid temperature change:

The experimental analysis focused on the lap periods of vehicles after the component temperatures stabilized. The warm-up phase and corresponding thermal soak phase is not included in this particular investigation, however will be presented in future publications.

Figure 1 provides an example of the vehicle speed profile during a single full lap run (approximately 10 min). The maximum speed difference can be seen as a variation of approximately 175 km/h. High speed variations are a result of the Nuenburg-ring track profile. However, when examining component temperatures of the exhaust system (Figure 2, 3, 4) the temperature profile resembles a relatively constant tendency in comparison to the vehicle boundary conditions.

The maximum temperature delta experienced on the manifold was 80K with a corresponding 50K on the CAT and 20K on the end acoustic silencer.

Another important factor for the analysis of experimental data is the rate at which sensors accumulate temperature information. The sampling rate of the experiment was approximately 0.5 seconds, allowing for a reasonable resolution of transient profiles.

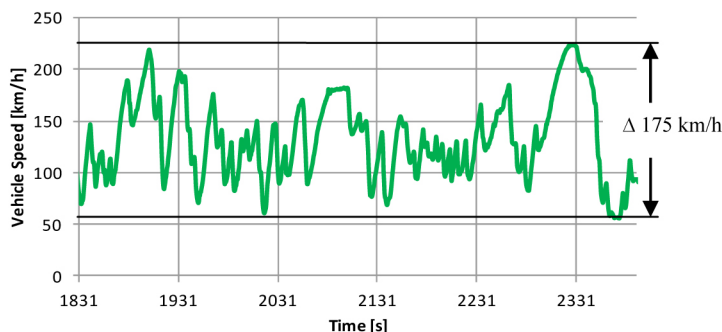


Figure 1. Velocity Profile during Single Lap - Nuerburg-ring

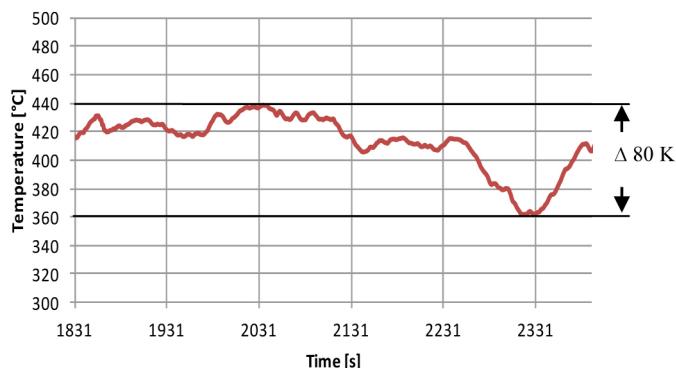


Figure 2. Manifold Temperature behavior during Single Lap - Nuerburg-ring

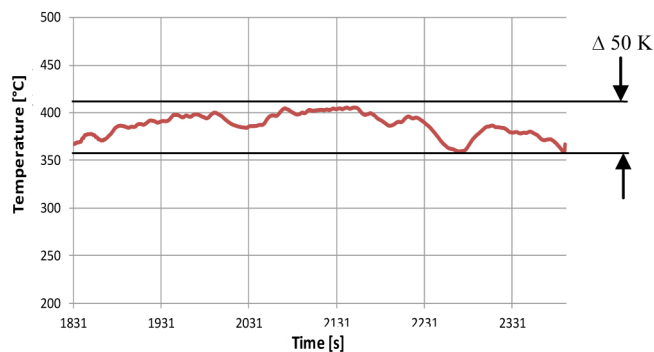


Figure 3. CAT Temperature behavior during Single Lap - Nuerburg-ring

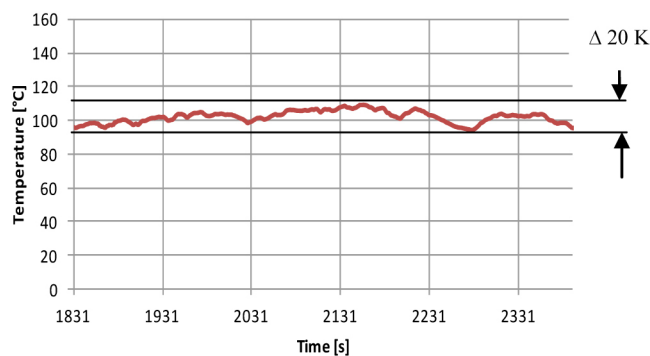


Figure 4. End Acoustic Silencer Temperature behavior during Single Lap - Nuerburg-ring

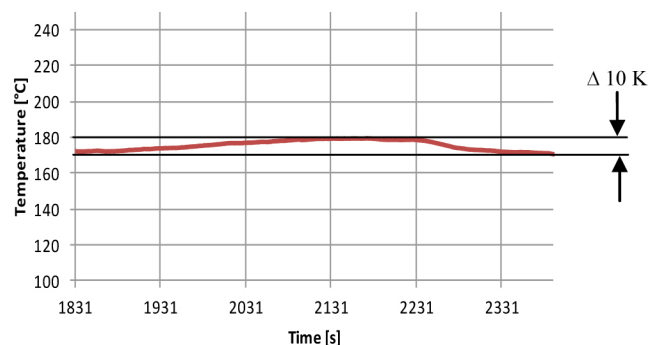


Figure 5. Heat Shield for CAT Temperature behavior during Single Lap - Nuerburg-ring

It can be seen that the temperature volatility reduces along the exhaust system towards the cold end. Additionally surrounding components such as a heat shield (Figure 5) experience even less thermal fluctuation with a temperature change of 10K. Moving away from the heat sources this temperature variation over time becomes increasingly stabilized. Hence careful attention must be paid to close proximity heat source components such as the exhaust system and heat shields during the material delegation and assigning corresponding thermal capacities.

MOVING AVERAGE SCHEMES

A running average (or moving average) has been commonly attributed tool for statistical analysis of a variety of applications, ranging from GPS signal processing [7], stock analysis [8] and forecasting sales [9]. The goal of a moving average is to dampen high frequency inputs or data fluctuations to describe the average profile of a series consisting of time dependent data.

As previously discussed, a direct relationship cannot be established between the input boundary conditions (vehicle speed, exhaust mass flow rate, etc) and the corresponding temperature behavior of underbody components. However by averaging the boundary conditions of the vehicle it is envisioned that the general component temperature tendencies may be achieved. This is due to the heat transfer

time scales being significantly larger within components compared to fluid flow field time scales [5]. Hence it is evident that a statistical moving average scheme can yield dramatic computational benefits if implemented properly.

The following benefits can be obtained by implementing a running average through the boundary conditions:

1. Potential to derive a simplified profile which reproduces the race track component temperature behaviors.
2. Reduction of high frequency changes, therefore larger time steps can be pursued for transient calculations.
3. Possibility to couple steady state CFD solutions and interpolate between points. Hence a further acceleration of computational turn-around times may be achieved.

The following disadvantages can be obtained by implementing a running average through the boundary conditions:

1. Incorrect profile based on incorrect sample size. Too large and the profile becomes an average value, to small and profile resembles the high frequency changes of the vehicle conditions.
2. Lag effects due to sampling past data. These effects can be reduced with a forward/backward scheme.

The most commonly utilized moving average schemes are a simple moving average or a weighted moving average.

Simple Moving Average

A simple moving average (SMA) is the most commonly utilised statistical schemes for damping highly volatile time dependent data [10].

$$SMA = \frac{v_n + v_{n-1} + \dots + v_2 + v_1}{\Sigma n}$$

Eqn. 1

Where v_n denotes the vehicle velocity and a given integer n . The total value of vehicle speed is then divided by the summation of sampling points Σn .

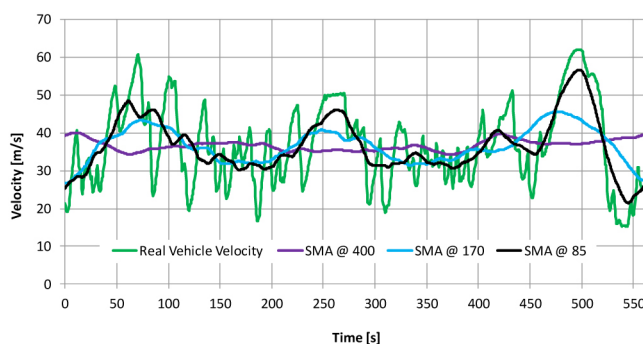


Figure 6. SMA for various sample ranges.

Figure 6, clearly demonstrates the potential for alternative profiles and consequent alternative temperature behavior by varying the sample range. SMA of 85 demonstrates a better representation than a SMA of 400 points. A compromise of both can be seen with SMA of 170 points.

A critical thermal consideration is achieving higher peaks (with higher convection) whilst stabilizing lower speeds without altering the sample range. An approach to achieve this is to introduce a power relation into the SMA, favoring the higher vehicle speeds (Eqn. 2 & 3)

$$SMA_{quad} = \sqrt{\frac{v_n^2 + v_{n-1}^2 + \dots + v_2^2 + v_1^2}{\Sigma n^2}}$$

Eqn. 2

$$SMA_{cubic} = \sqrt[3]{\frac{v_n^3 + v_{n-1}^3 + \dots + v_2^3 + v_1^3}{\Sigma n^3}}$$

Eqn. 3

Unfortunately as seen in Figure 7, reaching higher peaks were not improved by utilizing this methodology. All power based SMA's converged at the same peak point, whilst following an enhanced profile between peaks based on the power raised integer.

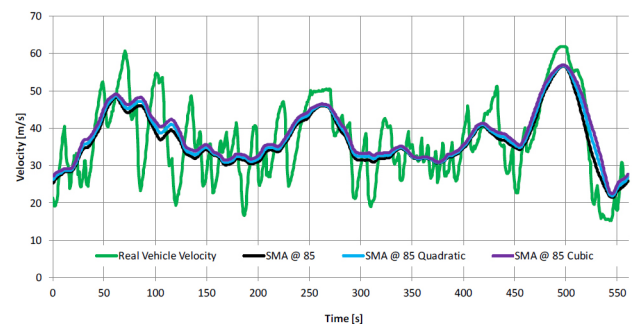


Figure 7. SMA @ 85 for alternative power combinations.

Weighted Moving Average

In order to implement higher peaks without introducing smaller sample ranges a weighted moving average (WMA) was introduced (Eqn. 4).

$$WMA = \frac{nv_m + (n-1)v_{m-1} + \dots + 2v_{m-n+2} + v_{m-n+1}}{n + (n-1) + \dots + 2 + 1}$$

Eqn. 4

Through a linearly regressed weighting scheme, bias inherent within a SMA can be compensated to improve overall running tendencies [7].

This moving average scheme can be weighted based on time or vehicle velocity. Figure 8 describes the difference between sample range of 170 weighting on time and SMA 170. It can be seen that the WMA increases the profile tendency to reach higher peaks whilst remaining relatively constant between peaks. This correlation favors the last/next