SAE TECHNICAL PAPER SERIES

2004-01-1561

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Reprinted From: Reliability and Robust Design in Automotive Engineering (SP-1844)

ISBN 0 7680 1424-7

9 780768 014242

SAE International™

2004 SAE World Congress
Detroit, Michigan
March 8-11, 2004

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ISBN 0-7680-1319-4

Printed in USA

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ABSTRACT

The link between manufacturing process and product performance is studied in order to construct analytical, quantifiable criteria for the introduction of new engine technologies and processes. Cost associated with a new process must be balanced against increases in engine performance and thus demand for the particular vehicle. In this work, the effect of the Abrasive Flow Machining (AFM) technique on surface roughness is characterized through measurements of specimens, and a predictive engine simulation is used to quantify performance gains due to the new surface finish. Subsequently, economic cost-benefit analysis is used to evaluate manufacturing decisions based on their impact on firm's profitability. A demonstration study examines the use of AFM for finishing the inner surfaces of intake manifolds for two engines, one installed in a compact car and the other in an SUV.

INTRODUCTION

Consumer demand for increased engine performance and government regulatory pressure for increased fuel efficiency and decreased emissions require automotive manufacturers to continuously improve their product lines. Product advancements are often realized through technology updates, rather than major redesigns. These include new manufacturing processes that can improve engine performance attributes. Determining the absolute improvements of performance attributes is not sufficient for making a decision whether to introduce the new process. Rather, knowing the trade-off between the cost of the new process and the realizable profit stemming from improved performance enables a proper enterprise-level decision. Such economic cost-benefit analysis depends critically on the ability to characterize the effect of machining process on product properties, and to predict the effect of property modification on product performance. Predictive simulation tools can be used to quantify the tradeoffs without extensive and costly experimentation. In this article, we demonstrate a methodology for evaluating manufacturing decisions based on their impact on firm's profitability and we use it to study the impact of the Abrasive Fluid Machining (AFM) technology for finishing the inner surfaces of intake manifolds.

AFM process employs a viscoelastic medium impregnated with grit to smooth inner surfaces of metal parts [1]. It is very effective in reducing the roughness of cast-iron or cast-aluminum components, such as inner surfaces of engine manifolds. Smoothing of intake manifold inner surfaces translates into lower flow losses, increased flow and thus better filling of cylinders. Increased trapped mass of fresh charge translates directly into higher engine torque or power. A secondary beneficial effect is the potential to reduce cylinder-to-cylinder variations, thus allowing more precise engine management. Even though there is a clear potential for tangible gains from the engineering and product performance point of view, assessing whether the new process is beneficial to the firm requires considering manufacturing and financial aspects too.

We start with the assumption that choosing such a manufacturing process and increasing product performance in turn impacts product demand. Firm's profitability is then used as a criterion that will aid the decision-maker to make his/her choice. Figure 1 shows a flowchart depicting different analyses used in this paper. The design method, which translates the engineering trade-off(s) to a microeconomics or/and financial optimization problem, has been developed [7], [10], [11].

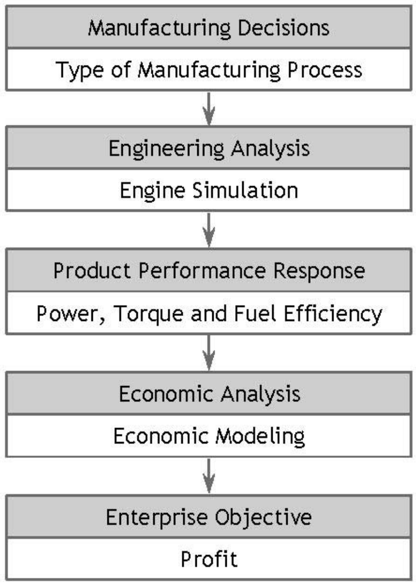

Figure 1: Decision making process spanning the manufacturing, product design and financial domains

The paper is organized as follows. First, we introduce the product (intake manifold) and the manufacturing process. Surface quality of the baseline cast aluminum manifold, as well as the product finished with AFM process, is determined next, followed by the description of an engine system simulation capable of predicting engine volumetric efficiency and performance. Then, we determine the sensitivity of the simulation to variations of surface roughness. Subsequently, the link between product performance and product demand is defined analytically. Finally, a synthesis model that spans the manufacturing, product design and financial domains is constructed and presented. The approach is applied to two characteristic cases, a high volume/low profit margin compact car and a lower volume/high profit margin SUV.

PRODUCT AND MANUFACTURING PROCESS DESCRIPTION

The engine used in this study is a V6 2.5L Spark-Ignition (SI) engine with twenty four valves, twelve of which are intake valves. The air intake manifold directs the flow of air from the throttle body to the intake valves. The intake manifold selected for this study is made of aluminum alloy. As shown in Figure 2, air flows into the manifold through a single large orifice, and is then divided into twelve “runners" that lead to the intake valves [2]. The runner length is designed for utilization of wave-action for increased filling of cylinders with fresh charge. There are two sets of runners, shorter and longer. Longer runners are tuned for maximum effects at low speeds and they are connected to primary intake ports. Shorter runners provide maximum effect at high speeds and they are connected to secondary ports that include butterfly valves that open only after engine speed has reached a predetermined threshold. Given a runner length, friction flow losses are an important factor. Even though the benefit of wave action outweighs flow losses in long runners, the manifold internal surfaces can significantly affect the overall trade-off and hence need to be considered in the design process.

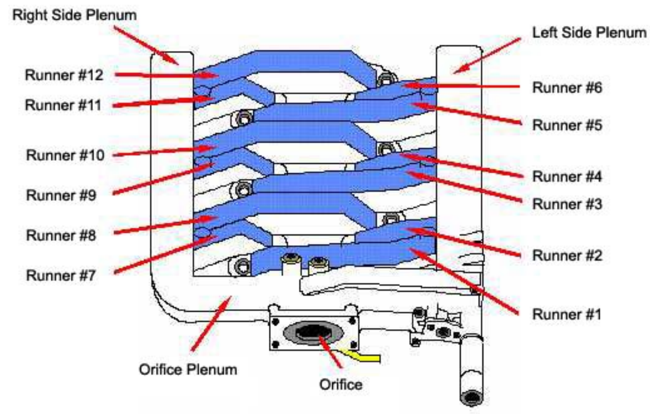

Figure 2: Intake manifold layout

Aluminum is chosen for its low weight and flexibility in manufacturing. Complex geometry of internal passages of the manifold dictates manufacturing by sand casting. Sand casting leaves rough surfaces with irregular structures that increase flow losses and generate turbulence. Innovative processes, such as Abrasive Fluid Machining, can improve runner internal surfaces, reducing the roughness of internal passages, as seen in Figure 3. Improved finish leads to better performance through reduced flow losses and improved engine volumetric efficiency, i.e. better filling of engine cylinders with fresh charge. An additional benefit is reduced variability between cylinders and thus more accurate engine calibration. The proposed trade-off analysis will quantify potential benefits and address application of AFM technology to different categories of vehicles and scales of production.

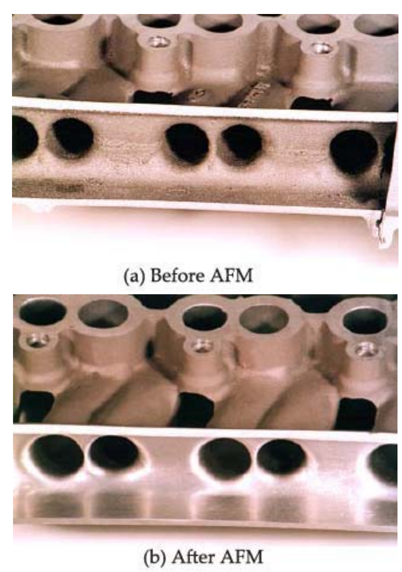

Figure 3: Appearance of manifold interior passages

SURFACE MEASUREMENT AND CHARACTERIZATION

Two versions of aluminum manifolds are examined in this study: a standard manifold with inner surfaces unfinished after sand casting, and a high-performance version with inner surfaces finished using the AFM process. A surface finish parameter, the ten-point total height of profile R_t, is used to characterize the inner surface of the manifold.

Table 1: Impact of AFM on surface roughness (μm)

Measurement Location	Before AFM	After AFM
Runner 1	73.26	16.62
Runner 2	55.72	20.40
Runner 3	61.27	38.03
Runner 4	81.55	11.43
Runner 5	85.36	9.03
Runner 6	68.36	4.87
Runner 7	62.93	26.24
Runner 8	61.43	18.74
Runner 9	56.31	14.84
Runner 10	61.93	16.72
Runner 11	83.84	17.58
Runner 12	88.11	3.86
Orifice	71.61	10.15
Orifice Plenum	74.18	4.72
Left Side Plenum	75.79	8.62
Right Side Plenum	62.41	5.77

Table 1 shows measured average surface roughness R_t at different locations in the manifold before and after applying AFM process. Measurements demonstrate high variation of R_t within the manifold, both before and after finishing. AFM process reduces casting roughness by an order of magnitude. The average reduction in roughness after AFM with the respect to R_t is 80% and overall variability is reduced by more than 70% assuming that all variables have normal distribution (Table 2).

Careful visual inspection of a cut-up manifold reveals much larger surface roughness in the inaccessible locations, such as corners and bends, compared to flat parts. Figure 4 shows another type of locally increased roughness associated with the mold insert dividing plane, and this will subsequently be taken into account when specifying the overall surface quality for the product performance simulation.

Figure 4: Local variation of roughness due to the casting mold dividing plane

PRODUCT PERFORMANCE SIMULATION

The nature of the problem at hand requires an engine simulation that has a particularly good ability to predict the effects of manifold flow on filling of cylinders and subsequent production of brake power. The V6 engine considered here has a typical tuned manifold where runner lengths are designed to take the maximum advantage of wave action in the intake system. Hence, a combination of 1-D gas dynamics model and the thermodynamic in-cylinder cycle simulation is deemed necessary. The GT-Power simulation [12] provides such an integrated tool and is selected for this work. After the simulation has been configured with the particular engine geometry, the adjustable constants were calibrated and the predictions were subsequently validated against data obtained on the experimental set-up at the University of Michigan W. E. Lay Automotive Laboratory.

The cycle simulation includes predictive sub-models for pertinent engine phenomena, such as two-zone SI combustion, convective heat transfer and emissions of NO and CO. The gas dynamics model in GT-Power involves simultaneous solution of the continuity, energy and momentum equations. The latter accounts for the effect of the surface characteristics on flow through the friction coefficient C_f. Hence, the critical link between the surface quality and the manifold flow/engine performance is established through the expression correlating the friction coefficient C_f in the pipe and the roughness h,

$$C_f = \frac{0.25}{\left(2\log_{10}\left(\frac{1}{2}\frac{D}{h}\right)+1.74\right)^2}, \qquad (1)$$

where D is pipe diameter. The simulation requires as input the information about the inner surface quality in the form of so called “sand roughness”. Thus, developing the methodology for the conversion of the measured surface roughness into the sand roughness values is a critical step in accomplishing the main goal of the study.

In order to represent roughness levels of the pipe inner surface for generic experiments, sand particles having a uniform diameter are glued on the inside of the smooth pipe. This is illustrated with a schematic given in Figure 5. If the roughness height of this surface is measured, the value would be significantly smaller that the sand diameter. Hence, the sand roughness can be conceptually defined as the sum of the glue film thickness and the measured roughness height.

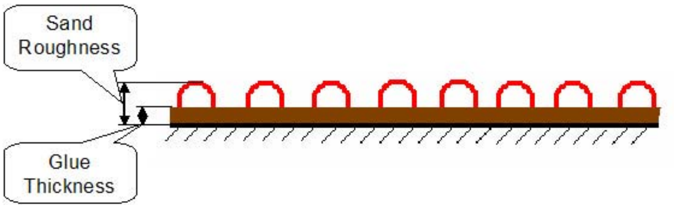

Figure 5: Defining the sand roughness

Based on this physical representation of sand roughness, the following expression linking sand roughness to measured roughness of the manifold surface is proposed,

$$h = (R_t + \sigma) F + R_g \quad (2)$$

where h is the sand surface roughness, R_t is the measured ten-point total profile height, σ is the standard deviation of R_t, F is an adjustment factor taking into account the effects of local variations at corners and the casting dividing plane, and R_g is the glue film thickness approximated by average R_t.

MANUFACTURING PROCESS EFFECT ON PRODUCT PERFORMANCE

An initial sensitivity study is performed on the effect of the AFM process to engine performance. Design of experiments is used to assess variation of power, torque and fuel economy caused by variation of surface roughness in the runners, plenums and orifice of the manifold with and without AFM. Engine performance is predicted using the engine system simulation described in the previous section.

Given the configuration of the manifold (Figure 2), considering just one roughness variable per part would lead to a total of eighteen variables. To avoid computational burden, the sensitivity study is performed with three input variables: roughness of all runners, roughness of plenums and roughness of the orifice. Measured surface roughness values were converted to sand roughness using the Eq. (2). A 95% confidence interval was used for the lower bound and upper bound of each variable. Latin Hypercube sampling was used to generate a 20-point sample.

The results of the sensitivity study before and after AFM are shown in Tables 2 and 3, respectively. Smallest and largest values for each input or output are presented in bold. Means and standard deviations are estimated using *normfit* in the Matlab Statistics Toolbox, under the assumption that the data have normal distribution. The surface roughness for all surfaces after AFM has been reduced significantly. The runner surface roughness dominates performance because it is the average of 12 sets of data. For the following studies, surface roughness at each manifold location is equally weighted under the assumption that no part dominates the engine performance. Table 4 shows performance enhancements gained by applying AFM technology. Both power and torque have been improved by about two percent while BSFC improvements were negligible; hence the focus of the subsequent analysis is on power. While the percent improvement is not large, it is important to note that the initial stage of research was limited to assessing effects of finishing manifold surfaces only. Extension of this work to the finishing of ports in the cylinder head and the throttle body would be desirable, as it is estimated that AFM application would triple or quadruple the percent improvement.

Table 2: Performance predictions before AFM

Runner S.R.*	Plenum S.R.	Orifice S.R.	Power	Torque	BSFC
μm	μm	μm	*hp*	*ft-lb*	*lb/hph*
158.94	249.72	205.67	**163.15**	**137.09**	**0.491**
168.52	**216.22**	242.25	163.07	137.02	0.491
178.11	238.55	300.78	162.92	136.89	0.491
187.70	260.89	**322.73**	162.78	136.78	0.491
197.28	246.00	212.98	162.74	136.74	0.491
206.87	279.50	271.52	162.60	136.63	0.492
216.46	219.94	264.20	162.58	136.61	0.492
226.04	268.33	315.41	162.42	136.48	0.492
235.63	253.44	234.93	162.37	136.44	0.492
245.22	231.11	198.35	162.33	136.40	0.492
254.81	275.78	249.57	162.17	136.27	0.492
264.39	272.06	308.10	162.08	136.19	0.492
273.98	257.17	278.83	162.03	136.14	0.492
283.57	223.66	191.03	162.02	136.14	0.492
293.15	234.83	293.47	161.90	136.04	0.492
302.74	242.28	227.62	161.84	135.99	0.492
312.33	264.61	256.88	161.73	135.89	0.492
321.91	**286.95**	220.30	161.64	135.82	0.492
331.50	227.39	286.15	161.61	135.80	0.492
341.09	283.23	**183.72**	**161.52**	**135.72**	**0.492**
Mean μ					
250.01	251.58	253.22	162.28	136.35	0.492
Standard deviation σ					
56.72	22.02	43.29	0.50	0.42	~0

* S.R. is surface roughness.

Table 3: Performance predictions after AFM

Runner S.R.	Plenum S.R.	Orifice S.R.	Power	Torque	BSFC
μm	μm	μm	*hp*	*ft-lb*	*lb/hph*
15.58	40.95	36.63	**166.47**	**139.88**	**0.490**
18.52	**24.90**	37.66	166.38	139.8	0.490
21.46	31.14	33.52	166.25	139.69	0.490
24.41	38.27	44.91	166.11	139.58	0.490
27.35	36.49	**27.31**	166.03	139.51	0.490
30.29	37.38	34.56	165.91	139.41	0.490
33.23	25.79	31.45	165.83	139.34	0.490
36.17	33.81	32.48	165.74	139.27	0.490
39.12	32.03	39.74	165.63	139.18	0.490
42.06	**41.84**	41.81	165.52	139.08	0.490
45.00	27.57	**46.99**	165.47	139.04	0.490
47.94	40.06	35.59	165.38	138.96	0.490
50.89	29.36	43.88	165.32	138.92	0.490
53.83	35.60	30.41	165.25	138.85	0.490
56.77	34.70	45.95	165.17	138.78	0.491
59.71	26.68	42.84	165.12	138.74	0.491
62.65	32.92	38.70	165.04	138.68	0.491
65.60	28.46	28.34	165.01	138.65	0.491
68.54	30.25	40.77	164.93	138.59	0.491
71.48	39.16	29.38	**164.86**	**138.53**	**0.491**
Mean μ					
43.53	33.37	37.15	165.57	139.12	0.490
Standard deviation σ					
17.41	5.28	6.13	0.50	0.42	~0

* S.R. is surface roughness.

Table 4: Improvement by applying AFM

	μ	σ
Runners Surface Roughness (μm)	82.6%	69.4%
Plenums Surface Roughness (μm)	86.7%	76%
Orifice Surface Roughness (μm)	85.3%	85.8%
Power (*hp*)	2.03%	0.014%
Torque (*ft-lb*)	2.03%	0%
BSFC (*lb/hph*)	0.29%	0%

ECONOMIC MODELING

According to standard microeconomic theory [3], improvement in product quality yields an increase in product demand q. Hazelrigg [4] observed that engineering decisions x affect product performance attributes α, which in turn affect the demand of the product q, as shown in Figure 6. In our case, the surface roughness decision x for the intake manifold of engine M influences horsepower α, a product characteristic observed by the consumer, and hence it would affect product demand q. The demand is also affected by price P.

Figure 6: The link between product design decisions x and product demand q [4]

Assuming a linear relationship we have

$$q = \theta - \lambda_P P + \lambda_\alpha \alpha, \tag{3}$$

where λ_α describes the sensitivity of the demand q to the change in attributes α, λ_p is the consumer price elasticity, and θ is a constant [9].

To focus on performance influence, we assume the firm will keep the price constant, i.e., the consumer price elasticity λ_p is set equal to zero,

$$q = \theta + \lambda_\alpha \alpha. \tag{4}$$

Based on Eq. (4) the actual elasticity E of demand [9], is given by

$$E = \frac{\%\Delta q}{\%\Delta \alpha}. \tag{5}$$

Assuming demographics, macroeconomic conditions, and consumer tastes do not change enough to necessitate a new market segment definition, the following economic models and analyses take the Chevrolet Cavalier as the example of high-volume/low-profit-margin compact car segment, and the Cadillac Seville as the example of lower volume, higher profit margin sport utility vehicle segment, respectively.

The earlier sensitivity study horsepower (HP) over vehicle weight (w) as the relevant system attribute. Then the elasticity of demand is defined as

$$E_{\frac{HP}{w}} = \frac{\%\Delta q}{\%\Delta \frac{HP}{w}}. \tag{6}$$

Berry, *et. al.* [5] used twenty-year automobile market observation data and estimated elasticity of demand for Chevrolet Cavalier to be 0.42. This implies that a 10% increase in horsepower to vehicle weight ratio will boost demand by 4.2%. In the same study [5] the Cadillac Seville horsepower to weight elasticity of demand was found to be 0.09. This assumes that the luxury segment customer preference with respect to acceleration is close to that of the SUV customer. There is also an assumption that consumer preference with respect to acceleration has not changed since the elasticity was measured.

The application of AFM will improve HP ratings from the current level $HP_{current}$ to HP_{future}. This translates to a shift in the demand from $q_{current}$ to q_{future}. Therefore the percentage changes are

$$\%\Delta q = \frac{q_{future} - q_{current}}{q_{current}} = \frac{\Delta q}{q_{current}},$$
$$\%\Delta \tfrac{HP}{w} = \frac{\frac{HP_{future}}{w} - \frac{HP_{current}}{w}}{\frac{HP_{current}}{w}} = \frac{\Delta HP}{HP_{current}}, \quad (7)$$

given that the manifold finishing does not affect vehicle weight.

From Eq. (6) and (7) the percentage change in quantity is modeled as

$$\%\Delta q = \left(E_{\frac{HP}{w}}\right)\left(\%\Delta \tfrac{HP}{w}\right) = E_{\frac{HP}{w}} \frac{\Delta HP}{HP_{current}}. \quad (8)$$

A change in quantity translates to a change in revenue R

$$\Delta R = (P)(\Delta q) = (P)(\%\Delta q)\, q_{current}. \quad (9)$$

Substituting $\%\Delta q$ from Eq. (8) we have

$$\Delta R = (P)\left(E_{\frac{HP}{w}} \frac{\Delta HP}{HP_{current}}\right) q_{current}. \quad (10)$$

Eq. (10) quantifies the effect of HP improvement on the firm's revenue. We assume that other vehicle characteristics observed by consumers will remain unchanged.

The average total cost of the AFM process C_{AFM} is estimated at \$5 per horsepower gained per car [1],

$$C_{AFM} = \$5(\Delta HP). \quad (11)$$

We assume that the firm is operating at its minimum efficient scale. That is, additional production will not increase its production cost per unit. Therefore the change in total cost C from increased production is:

$$\Delta C = (ATC + C_{AFM})(\Delta q) + (C_{AFM})(q_{current}), \quad (12)$$

where ATC is the existing average total cost prior to applying the AFM process. ATC does not include the investment cost that the manufacturer is required to install an AFM manufacturing system in-house. We assume AFM process will be applied by a supplier, see [6], [7].

Eqs. (10), (12) model benefits and costs by applying AFM. Although benefits are materialized through increase in quantity sold $(\%\Delta q)\, q_{current}$, the firm will bear the cost for all vehicles sold $(1 + \%\Delta q)\, q_{current}$ but not just the additional ones.

Having modeled revenue and cost, we can calculate profit

$$\begin{aligned}
\Delta Profit &= \Delta R - \Delta C \\
&= (P)(\Delta q) - (ATC + C_{AFM})(\Delta q) - (C_{AFM})(q_{current}) \\
&= (P - ATC - C_{AFM})\left(E_{\frac{HP}{w}} \frac{\Delta HP}{HP_{current}}\right)(q_{current}) - (C_{AFM})(q_{current}),
\end{aligned} \quad (13)$$

which will be used as the criterion for decision making.

ENTERPRISE DECISION MAKING

The decision-maker will ultimately choose surface roughness based on firm's profitability. Using incremental analysis we modeled the increase in profit due to an increase in product performance observed by the consumer. The decision model is then formulated as follows:

$$\begin{aligned}
\text{maximize:} \quad & \Delta\text{Profit} \\
\text{with respect to:} \quad & \text{surface roughness} \\
\text{subject to:} \quad & \text{horsepower, torque and} \\
& \text{fuel economy constraints.}
\end{aligned} \quad (14)$$

Under the assumption that no part dominates the engine performance, the surface roughness at each manifold location is equally weighted. Therefore, the decision variable represents the average sand surface roughness for all runners, orifice and plenums.

We set the upper and lower bound values for power, torque, BSFC, and surface roughness using the previous sensitivity study. The surface roughness lower bound is very close to zero, while the upper bound is the minimum value obtained using sand casting, namely, 1.00μm and 125.3μm, respectively. The bounds imply the characteristics of the manufacturing processes, i.e., if the optimal value of roughness ends up being close to the upper bound the surface finish may be realized by sand casting.

The mathematical programming statement of Eq. (14) is

$$\begin{aligned} \max \quad & \Delta\text{Profit} \\ \text{w.r.t.} \quad & R_t \\ \text{s.t.} \quad & HP_{future} \geq HP_{current} \\ & fe_{future} \geq fe_{current} \\ & Torque_{future} \geq Torque_{current} \\ & 0 \leq R_t \leq 125.3\mu m, \end{aligned} \tag{15}$$

where $HP_{current}$, $fe_{current}$ and $Torque_{current}$ are the current product's performance values of horsepower, fuel efficiency and torque, respectively. The corresponding baseline values are: 163.5*hp*, 0.492*lb/hp-h* and 137.3*ft-lb*. Horsepower, fuel economy and torque are computed using the engine simulation described earlier.

Eq. (15) is solved for the two extremes in an automotive manufacturer's fleet: compact car and sport utility vehicle. Profit margins per unit (PMU) namely, selling price per unit minus average total cost per unit, are presented in Table 5. The elasticities of specific horsepower (hp over w) discussed in the previous section are presented as well. We assume the decision is made on January, 2001. Current demands for compact car and sport utility vehicle are 40879 and 34389, respectively.

Table 5: Customer demand for vehicle acceleration and profit margins per unit for two vehicle segments

	Compact Car	SUV
PMU	~ 0	$7250
$E_{\frac{HP}{w}}$	0.42	0.09

The DIvided RECTangles (DIRECT) optimization algorithm [8] is used to solve Eq. (15). DIRECT can solve mixed-integer nonlinear programming problems and locate global minima efficiently without derivative information, when the number of variables is small, as in this case. DIRECT starts at the center of the user-supplied design space, divides it in rectangles and evaluates the objective function at the center points of these rectangles. Based on the objective function value and the characteristic dimension associated with each rectangle, DIRECT selects which rectangles to further divide until it reaches the specified number of function evaluations. This ensures that the entire space is searched in sufficient granularity in order to explore more promising areas in more detail.

RESULTS AND DISCUSSION

The results for each segment and for each performance level are presented in Table 6.

Table 6: Solution of Eq. (15) for compact car and sport utility vehicle segments

	Compact Car	SUV
Profit (*$*)	-204,647	313,551
Roughness (*μm*)	125.21	6.96
Power (*hp*)	163.98	167.04
Torque (*ft-lb*)	137.8	140.3
BSFC (*lb/hp-h*)	0.4897	0.4882

The decision model suggests application of the AFM process only in the SUV segment as opposed to both. This is the interpretation of the results recommending 90% surface roughness reduction for the SUV engine manifold and a negligible reduction for the compact car manifold. This result is no surprise. Although demand for acceleration is higher for compact cars the current profit margin level does not motivate the firm to innovate. In case of the SUV segment, the firm will offset the increased average total cost with higher profits.

This result can also be explained by analyzing the objective function.

$$\begin{aligned} &\Delta Profit \\ &= \Delta R - \Delta C \\ &= (P)(\Delta q) - (ATC + C_{AFM})(\Delta q) \\ &\qquad - (C_{AFM})(q_{current}) \\ &= \left[(PMU)\left(\frac{E_{\frac{HP}{w}}}{HP_{current}} \right) - 5 \right] (\Delta HP)(q_{current}) \\ &\qquad - \left[5 \left(\frac{E_{\frac{HP}{w}}}{HP_{current}} \right) \right] (\Delta HP)^2 (q_{current}) \end{aligned} \tag{16}$$

From Table 4, there is about 2% horsepower improvement by AFM, which means *ΔHP* is approximately four or five horsepower. When the profit margin is low, for the compact car case, $(\Delta HP)^2$ dominantly influences the objective function. Maximum profit requires the smallest horsepower improvement, *ΔHP*, which results in less surface quality improvement. In the case of SUV with a high profit margin, the change of (PMU)(*ΔHP*) is much larger than $5(\Delta HP)^2$. Thus, the former term drives the surface roughness to the lower bound in order to obtain a larger horsepower improvement.

In Table 6 we see also that profit for the compact car is negative. Looking at Eq. (16) more closely we can see that the profit will be negative even without the added cost of AFM. This is a result of the modeling assumptions made here and would merit further investigation. However, it is not a surprising result based on common understanding that being profitable solely in the compact car segment is very difficult for manufacturers. When a product portfolio is expanded to include SUV's, the profit scenario can change due to high profit associated with SUV production and the effect of CAFÉ regulations [13].

CONCLUSION

Product advancements are often realized through technology updates and manufacturing process improvements. A decision-making method has been presented that weighs the cost of process improvements against the benefits of the resulting performance increase. The methodology was demonstrated through the case study evaluating the application of Abrasive Fluid Machining for finishing inner surfaces of the engine intake manifold.

The methodology relied on a high-fidelity engine simulation for establishing a relationship between the AFM process and performance attributes. The economic analysis estimated the effect of increased performance on demand and firm's revenue. Accounting for the cost of applying the AFM process led to the expression for profit. The latter allowed formulating the decision model, i.e., a design optimization problem.

The decision model was applied and solved for engines used in two vehicle segments, a "zero" profit margin compact car and a high profit margin sport utility vehicle. The results suggest application of AFM only to the SUV segment, thus illustrating a strong link between process improvements, elasticity of demand with respect to engine power and level of profitability.

ACKNOWLEDGMENTS

This work has been partially supported by the US Army TACOM through the Automotive Research Center at the University of Michigan and the Dual Use Science and Technology Program, and by General Motors Corporation. This support is gratefully acknowledged. The authors would like also to thank Michael Kokkolaras for directing and coordinating the system design team.

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