Supervisory Control for NOx Reduction of an HEV with a Mixed-Mode HCCI/CIDI Engine

Cristian Musardo, Benedetto Staccia, Shawn Midlam-Mohler, Yann Guezennec, Giorgio Rizzoni

Abstract— **Diesel HCCI (Homogenous Charge Compression Ignition) is a combustion technology showing great promise for the drastic reduction of oxides of nitrogen and particulate matter from diesel engines. Whereas conventional DI (Direct Injection) combustion burns primarily with a diffusion flame, HCCI combustion is a premixed combustion. This premixed reduction results in significantly lower NOx when compared to the DI counterpart. However, it is widely recognized that medium to high loads are not currently achievable with this combustion system. To circumvent this limitation, our implementation is a mixed-mode HCCI/DI combustion, which relies on the use of an essentially unmodified common-rail CIDI engine, coupled with a highly effective atomizer for external mixture formation. With this concept, the engine can operate in HCCI mode, HCCI/DI mixed mode, or DI mode depending on the load, and with seamless, progressive mode transition. The concept has demonstrated extremely low levels of nitrogen oxides (below $3ppm$) and smoke (FSN < 0.03) and pure HCCI operation up to an IMEP of $4.7bar$. These levels are an order of magnitude lower than for conventional diesel combustion.**

In this paper, we present a supervisory control strategy for a hybrid electric vehicle which best exploits the NO_x characteristics of such a mixed-combustion mode engine, while optimizing fuel economy and meeting driver's demand. This strategy is an extension of our Adaptive Equivalent Consumption Minimization Strategy (A-ECMS) control strategy, suitably modified to explicitly minimize NO_x emissions. The HEV configuration, coupled to this control strategy, allows to very effectively manipulate the operating points of the engine to be primarily constrained in the HCCI regime, with very low NO_x emissions. This results in dramatically reduced NO_x emissions during actual driving conditions, while retaining the high fuel economy of CIDI engines and hybrids and maintaining the performance envelop of the vehicle. In summary, the control strategy automatically exploits the relatively small region of HCCI operation to minimize NOx emissions.

I. INTRODUCTION

This paper combines two independent facets of our current research: on one hand, advances in combustion technology for compression ignition engines with our very recent progress to demonstrate the feasibility for Diesel-fueled, high compression ratio engines to function at low loads in pure HCCI mode (with negligible NO_x emissions and smoke) and smoothly transitioning to conventional CIDI mode at higher loads, and on the other hand, our recent advances in universal and self-adaptive supervisory control strategy for hybrid electric vehicles. In this paper, we will demonstrate the remarkable potential of marrying these two disparate technologies towards a low emissions and highly efficient powertrain. Previous attempts to mitigate NO_x emissions via hybridization had yielded only modest results, with comparatively similar gains in emissions to trade-off in fuel economy [1], [2].

This study builds upon a series of experiments which have led to changing very significantly the NO_x emissions on a CIDI engine under a limited range of operating conditions. Namely, these two techniques are: 1) to operate the engine in pure HCCI combustion mode at light loads, transitioning smoothly to a mixed HCCI/DI at intermediate load and delivering all the high load in pure DI (conventional) mode; and 2) to use water injection at high loads (in pure CIDI mode) to mitigate the NO_x emissions in that region of the operating map. While such a modified engine is capable of achieving some NO_x emission reduction on its own, the benefits can be maximized if the operating points of the engine can be "manipulated" by suitable hybridizing and controlling the powertrain. In order to explore this concept, a brief background on the two engine modifications and their effects is summarized in the next few paragraphs.

HCCI combustion has currently been limited to operation at light to mid loads due to its characteristically rapid heat release causing knock at mid to high loads. One method of extending the NO_x benefits of HCCI operation is through mixed-mode combustion [3]. With this technique, HCCI combustion is used to achieve part of the load, while a traditional DI injection is used to meet the remaining load. HCCI combustion is typically advanced from top dead center, thus, there is generally still time to inject and burn DI fuel in the same engine cycle. In this way, it is possible to take advantage of the low NO_x and PM combustion of the HCCI, while still meeting the torque demand of the driver.

Based on testing conducted by OSU-CAR (Ohio State University Center for Automotive Research) and FKFS (Forschungsinstitut fr Kraftfahrwesen und Fahrzeugmotoren) in Stuttgart, Germany as well as in the open literature, maps were developed for hypothetical mixed mode HCCI/DI engines, also implementing water injection at mid to high load as shown before. Three versions of this hypothetical engine were developed. In this paper, they are referred to "HCCI Low", "HCCI Medium" and "HCCI High". The first one (HCCI Low) is meant to approximate what is currently achievable with a simple modification of the existing engine and little re-programming of the engine controller. The second one (HCCI Medium) is meant

C. Musardo and B. Staccia are with Politecnico di Milano, Piazza Leonardo da Vinci 32, 20133 Milano, Italy.
S. Midlam-Mohler, Y. Guezennec and G. Rizzoni are with the Center for Automotive Research, Ohio State University, 930, Kinnear Road, Columbus, OH 43210, USA.

0-7803-9098-9/05/$25.00 ©2005 AACC

to approximate what should be achievable with further engine development work in the area of engine control, and the third one (HCCI High) is meant to represent a very optimistic view of what might be possible with significant modification to the engine controller and probably a reduction of the compression ratio from nominally 18 down to 15 or 16.

Experimental results [4] have shown that an IMEP of $4.7bar$ can be achieved on a single cylinder engine. Based on this, it was assumed that an IMEP of $4.0bar$ could be used over the speed range from idle up to $4000rpm$. From this IMEP, the frictional mean effective pressure (FMEP) for the engine was used to calculate the brake mean effective pressure (BMEP) achievable. The BMEP was then directly transferable to a torque value. The NOx emissions below this value were set to nearly zero, which is in accordance to HCCI combustion and consistent with the experimental results obtained on a single cylinder engine. For 2 bars of MEP above this pure HCCI mode, it was assumed that a mixed mode HCCI/DI operation was possible (feasibility recently demonstrated on single cylinder engine at FKFS). In this region, the NO_x was assumed to blend linearly from the near zero NO_x pure HCCI case into the conventional NO_x map of the engine. This effect is consistent with the experimental results. For the two more aggressive HCCI cases (HCCI Medium and HCCI High), the MEP limit in pure HCCI mode was set to 6 and $8bars$, respectively, while the mixed mode limit was set at a fixed $2bar$ of MEP above that threhhold. Above that MEP, the engine map is unmodified.

The resulting NO_x maps for the 3 cases are shown below in Figures 1, 2 and 3. The dotted and dashed lines represent the limits of pure HCCI and mixed HCCI/DI mode of operation. Clearly, these NO_x maps are dramatically different from the stock engine. The aim of this paper is to exploit the features of these maps with the use of such an engine through the hybridization of the powertrain.

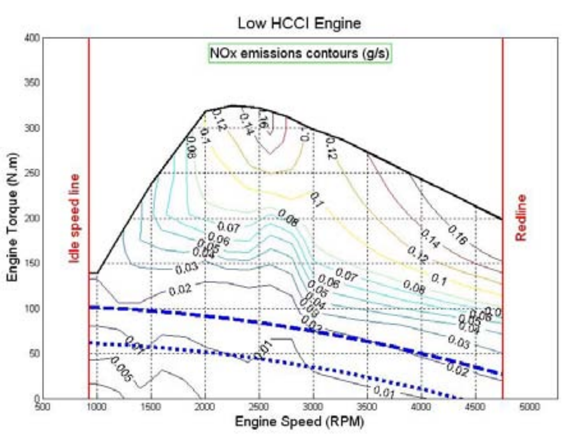

Fig. 1. - NO_x Map of Hypothetical Engine with Pure HCCI below IMEP of $4bar$ and Mixed HCCI/DI mode between IMEP of 4 and $6bar$ ("HCCI Low" Case).

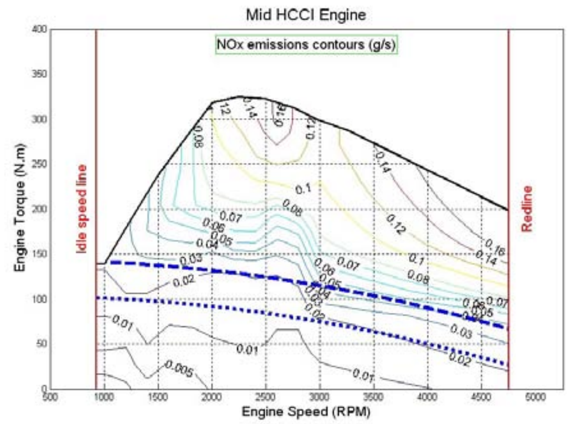

Fig. 2. - NO_x Map of Hypothetical Engine with Pure HCCI below IMEP of $6bar$ and Mixed HCCI/DI mode between IMEP of 6 and $8bar$ ("HCCI Medium" Case).

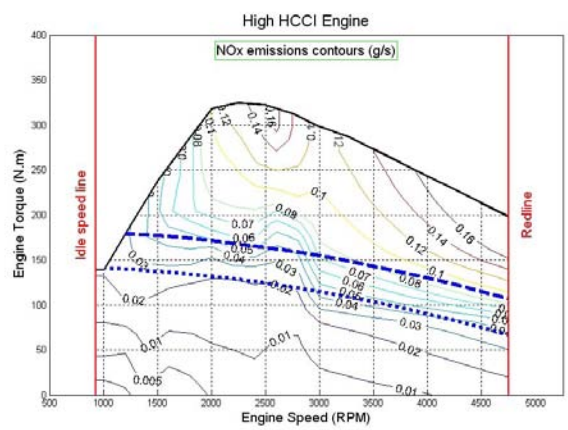

Fig. 3. - NO_x Map of Hypothetical Engine with Pure HCCI below IMEP of $4bar$ and Mixed HCCI/DI mode between IMEP of 8 and $10bar$ ("HCCI High" Case).

II. ADAPTIVE ECMS STRATEGY

The Equivalent fuel Consumption Minimization Strategy (ECMS) defines an equivalent fuel flow rate $\dot{m}_{f,equ}(t)$ so that the global fuel consumption minimization can be replaced by a local one [5], [6], [7]. The equivalent fuel consumption $\dot{m}_{f,equ}(t)$ is defined as the sum of the actual fuel consumption of the ICE $\dot{m}_{ice}(t)$ and the equivalent fuel consumption of the EM $\dot{m}_{em,equ}(t)$:

$$\dot{m}_{f,equ}(t) = \dot{m}_{ice}(t) + \dot{m}_{em,equ}(t) \tag{1}$$

The equivalent fuel consumption of the EM $\dot{m}_{em,equ}(t)$ can be calculated converting an instantaneous usage of the EM in terms of future/past fuel cost or saving. The energy provided by or to the EM is converted in equivalent fuel via the component efficiencies. Since the electrical energy in-flows and out-flows of the battery are non-local in time, the conversion efficiencies can be defined only in statistical sense.

Considering the architecture of a parallel hybrid vehicle, the analysis of the power flows through the components leads to the following expression of the equivalent fuel consumption of the EM $\dot{m}_{em,equ}(t)$:

$$\dot{m}_{equ,em}(t) = \\ = \begin{cases} \dfrac{1}{\bar{\eta}_{chg}} \dfrac{1}{\eta_{em}(P_{em}(t))\eta_{batt}(P_{em}(t))} \dfrac{P_{em}(t)}{H_{LHV}} & P_{em}(t) > 0 \\ \bar{\eta}_{dis} \cdot \eta_{em}(P_{em}(t))\eta_{batt}(P_{em}(t)) \dfrac{P_{em}(t)}{H_{LHV}} & P_{em}(t) < 0 \end{cases} \tag{2}$$

where $\bar{\eta}_{chg}$ and $\bar{\eta}_{dis}$ are the average efficiencies in all charging condition and all discharging conditions, respectively.

The two average efficiencies $\bar{\eta}_{chg}$ and $\bar{\eta}_{dis}$ are not known a priori and strongly depend on the driving schedule. Thus, they are considered as parameters of the strategy that can be tuned in order to minimize the fuel consumption while respecting the charge sustaining constraint.

A. A-ECMS STRATEGY FOR FUEL CONSUMPTION

As shown in [8], the whole driving cycle can be split into missions of appropriate length and a pair ($\bar{\eta}_{chg}$, $\bar{\eta}_{dis}$) can be associated to each mission so that the overall performance provided by the sum of these missions is comparable to the global optimum.

The Adaptive ECMS (A-ECMS) uses an adaptive algorithm to determine the pair that achieves optimal performance while satisfying the charge sustaining constraint. The main idea of the algorithm is to find the pair of average efficiencies that assures a flat *SOC* trend over the mission. The slope of the *SOC* trend over the mission can be related to the variation of the average efficiencies with respect to their optimal values through a sensitivity plane. Using an *a priori* probability density function, the algorithm finds the most probable correction to be applied to the current average efficiencies to keep the *SOC* trend flat over the mission.

B. MODIFICATION OF A-ECMS STRATEGY FOR NO_x EMISSION REDUCTION

The above A-ECMS strategy was suitably modified to formulate the "cost" function to reflect not only the fuel cost (and additional equivalent electrical fuel cost), but also a fictitious equivalent fuel cost associated with the NO_x emissions. Specifically, the NO_x emissions were taken into account adding a cost term to the instantaneous equivalent minimization. In order to make the NO_x emissions comparable to the equivalent cost, at each time t, the equivalent cost of using the EM and the mass flow rate of NO_x are normalized as follows:

$$\dot{m}_{f,equ}(t) = (1-\lambda) \cdot \hat{\dot{m}}_{EQU}(t) + \lambda \cdot \hat{\dot{m}}_{NOx}(t)$$

$$\hat{\dot{m}}_{EQU}(t) = \frac{\dot{m}_{EQU}(t)}{\max\{|\dot{m}_{EQU}(t)|\}}$$

$$\dot{m}_{EQU}(t) = \dot{m}_{ice}(t) + \dot{m}_{em,equ}(t) \tag{3}$$

$$\hat{\dot{m}}_{NOx}(t) = \frac{\dot{m}_{NOx}(t)}{\max\{\dot{m}_{NOx}(t)\}}$$

The coefficient λ weights the importance of the NO_x emissions minimization relative to the fuel consumption minimization. With $\lambda = 0$, this strategy is identical to the A-ECMS strategy described in [9]. With $\lambda = 1$, the strategy is only governed by NO_x emissions and has been found not to lead to a charge-sustaining condition, because the cost does not depend anymore on fuel consumption (actual and virtual).

C. RESULTS

Simulations using the A-ECMS energy and emission management strategy were performed for a hybrid vehicle, the OSU 2004 FutureTruck. This vehicle is build on a Ford Explorer platform and features a 2.5ℓ CIDI engine from VM Motori, a 5-speed manual transmission, a belted AC-induction electric machine and a $5.8Ah$, $310V$ nominal lead-acid battery pack. Figure 4 shows the operating points of the ICE and EM on the FUDS cycle for the HCCI Low Engine Case for two typical values of λ (0.0 and 0.5). Also shown are the fuel consumption increase and the NO_x emission reduction. When only the fuel consumption is taken into account ($\lambda = 0$), the ICE operating points are distributed in the high efficiency regions of the engine map. As soon as more weight is attributed to NO_x emissions in the minimization ($\lambda = 0.5$), many points are scattered in the lower part of the map where HCCI dramatically reduces NO_x emissions. Since the engine efficiency is poorer in that region, higher fuel consumption is observed. It is important to note that all these cases correspond to charge-sustaining cases.

III. SUMMARY OF RESULTS

Table I summarizes the results for all the cases investigated. The percentage increase or decrease for fuel and NO_x emissions are based on the results obtained with the stock engine in the same hybrid configuration. The table shows the clear trade-off between fuel economy penalty and NO_x reduction for various values of the weighting parameters λ for both the FUDS and FHDS cycle. All cases are charge sustaining, except when the formulation (with $\lambda = 1.0$) does not take fuel into consideration. For all engine categories and for both the FUDS and FHDS driving cycles, the best trade-off point between fuel consumption increase and NO_x emission decrease appear to always be around $\lambda = 0.25$ or slightly more. For these values of λ, the fuel consumption increase is small (5 or 5%) for a NO_x reduction of the order of 40 to 80%, depending on the engine used.

IV. CONCLUSIONS

The work presented in this paper clearly demonstrates the robustness and universality of the Adaptive ECMS (A-ECMS) energy management strategy presented in [8] and summarized herein. The strategy is not rule-based and effectively optimally exploits the characteristics of the powertrain components (in this case the fuel consumption and NO_x emissions maps for the engine). The same energy management strategy as used with the stock engine was blindly used to obtain the results shown here within a few hours of supplying alternate maps for the engine. Despite the simplicity of this implementation, the heuristic a posteriori evaluation of the placement of the ICE and EM operating points matches the engineering intuition for minimizing NO_x emissions and still yields solutions which are charge-sustaining and have a minimal fuel economy penalty. The paper also demonstrates the tremendous potential of engines capable of operating in HCCI mode over some fraction of their operating range in the context of hybrids. This point is clearly exemplified by the modest reduction in NO_x emissions due to the engine alone (because so many operating points do not fall in the limited range achievable in HCCI mode), but this limited range can be maximally exploited with a hybrid drivetrain, by manipulating the location of the instantaneous operating point of the engine with the use of the electric motor. The potential of this approach is extremely promising and experiments are in progress towards a vehicle-based implementation in the context of the DOE-sponsored FutureTruck (and subsequent upcoming Challenge X) vehicle competition.

REFERENCES

[1] Y. Guezennec, S. Midlam-Mohler, M. Tateno, and M. Hopka, "A 2-stage approach to diesel emission management in diesel hybrid electric vehicles," *Proc. of 2002 IFAC Meeting*, 2002.

[2] V. H. Johnson, K. B. Wipke, and D. J. Rausen, "HEV control strategy for real-time optimization of fuel economy and emissions," *SAE Future Car Congress*, 2000, SAE Technical Paper 2000-01-1543.

[3] M. Ishida, H. Ueki, and D. Sakaguchi, "Prediction of NOx reduction rate due to port water injection in a di diesel engine," *SAE International Fall Fuels and Lubricants Meeting and Exhibition*, 1997, SAE Technical Paper 972961.

[4] S. Midlam-Mohler, Y. Guezennec, G. Rizzoni, and M. B. Simon Haas, H. Berner, "Mixed-mode HCCI/DI with external mixture preparation," *FISITA 2004 World Automotive Congress*, 2004.

[5] A. Brahma, Y. G. Guezennec, G. Paganelli, G. Rizzoni, and S. Yurkovich, "A hardware -and architecture- independent supervisory control strategy for hybrid-electric drivetrains," in *$4^t h$ Stuttgart International Symposium on Motor Vehicles and Combustion Engines*, Feb. 2001.

[6] G. Paganelli, M. Tateno, A. Brahma, G. Rizzoni, and Y. Guezennec, "Control development for hybrid-electric sport utility vehicle: Strategy, implementation and field test results," in *Proc. of American Control Conference*, Arlington, VA, 2001, pp. 5064–5069.

[7] A. Brahma, Y. G. Guezennec, G. Paganelli, G. Rizzoni, and S. Yurkovich, "General supervisory control policy for the energy optimization of charge-sustaining hybrid electric vehicles," jSAE Review, Vol. 22, No. 4, pp. 511-518, 2001.

[8] C. Musardo, B. Staccia, B. Bittanti, Y. G. Guezennec, G. Paganelli, G. Rizzoni, and S. Yurkovich, "An adaptive algorithm for hybrid electric vehicles energy management," *FISITA 2004 World Automotive Congress*, 2004.

[9] D. A. Langer, N. K. Petek, and E. A. Schiferl, "Maximizing the effectiveness of water-blended fuel in reducing emissions by varying injection timing or using after-treatment device," *SAE 2001 World Congress*, 2001, SAE Technical Paper 2001-01-0513.

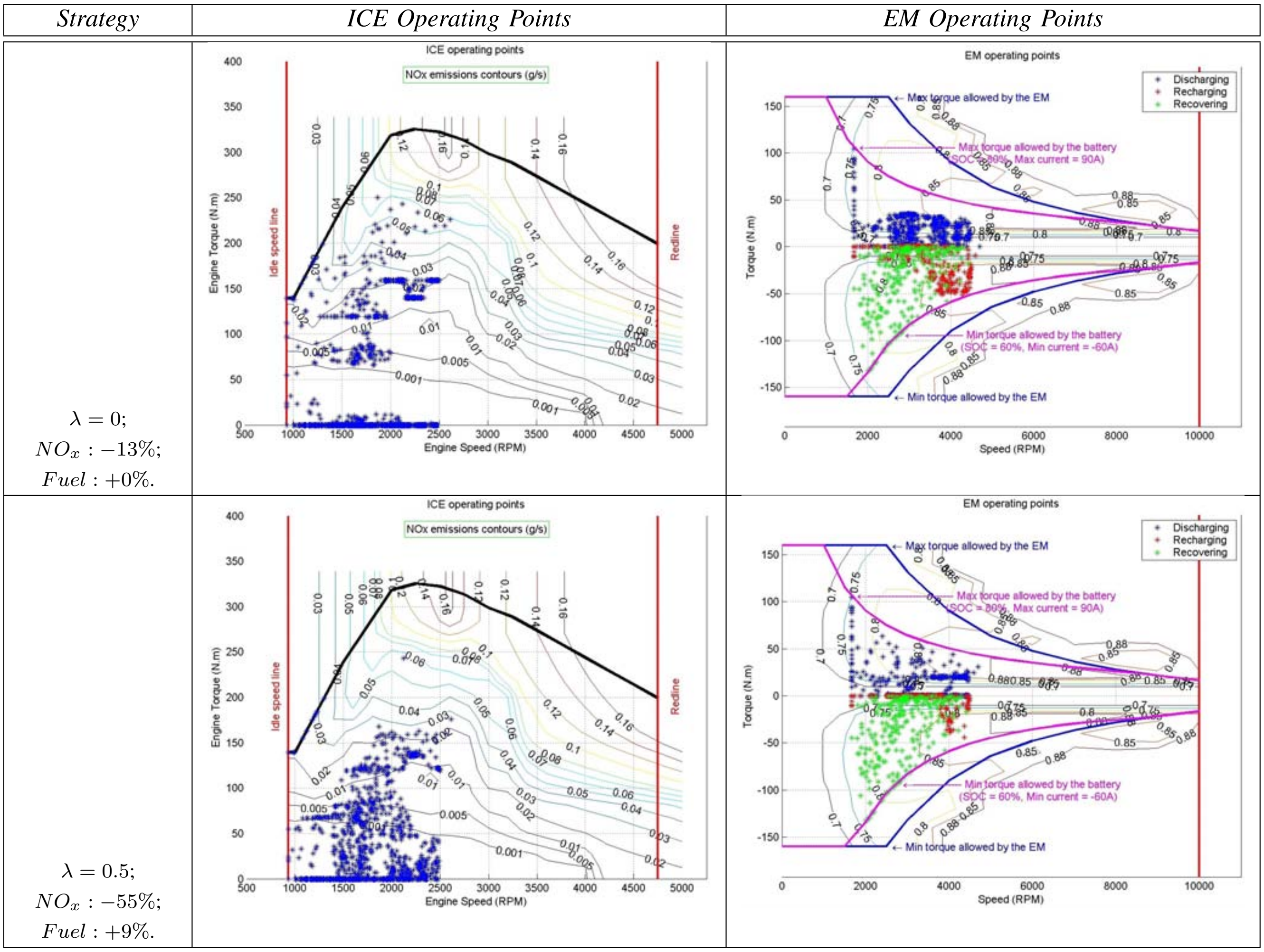

Fig. 4. Operating Points of ICE and EM for 2 Control Strategy ($\lambda = 0$ and 0.5) on FUDS Cycle for HCCI Low Engine Case.

TABLE I

SUMMARY OF FUEL USAGE AND NO_x EMISSIONS FOR ALL ENGINE CASES AND BOTH FUDS AND FHDS DRIVING CYCLES AS A FUNCTION OF THE RELATIVE WEIGHTING PARAMETER.

Engine Mod.	λ	FUDS/FHDS Mileage [MPG]	Fuel Cons. Increase [%]	NO_x Emissions $[g/mi]$	NO_x Emissions [%]
HCCI Low	0	$26.91/27.09$	$0\%/0\%$	0.97 / 1.01	$-13\%/-16\%$
	0.25	$25.62/25.60$	$+5\%/5\%$	0.67 / 0.78	$-41\%/-35\%$
	0.50	$24.37/24.51$	$+9\%/+10\%$	0.51 / 0.66	$-55\%/-46\%$
	0.75	$22.39/22.51$	$+17\%/+17\%$	0.38 / 0.41	$-66\%/-66\%$
	1.00	X / X	X / X	X / X	X /X
HCCI Medium	0	$26.91/27.09$	$0\%/0\%$	0.80 / 0.93	$-28\%/-23\%$
	0.25	$25.49/25.37$	$+5\%/6\%$	0.52 / 0.61	$-54\%/-50\%$
	0.50	$23.98/24.73$	$+11\%/+9\%$	0.30 / 0.54	$-74\%/-55\%$
	0.75	$22.57/22.61$	$+16\%/+16\%$	0.19 / 0.22	$-83\%/-82\%$
	1.00	X / X	X / X	X / X	X /X
HCCI High	0	$26.92/27.09$	$0\%/0\%$	0.50 / 0.63	$-55\%/-48\%$
	0.25	$25.69/25.54$	$+5\%/6\%$	0.20 / 0.21	$-82\%/-83\%$
	0.50	$25.20/24.93$	$+6\%/+8\%$	0.11 / 0.09	$-90\%/-92\%$
	0.75	$24.78/24.47$	$+8\%/+9\%$	0.08 / 0.07	$-93\%/-94\%$
	1.00	X / X	X / X	X / X	X /X