DIESEL FUEL REFORMULATION IMPACTS

ON

SYNTHETIC CRUDE OIL DEMAND †

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Abstract - The Oak Ridge National Laboratory Refinery Yield Model has been used to study the impacts of specifications for reformulated diesel fuel (RFD) produced in petroleum refineries of the U.S. Midwest in summer of year 2010. The study shows that synthetic crude oil economics can be less attractive, with a decrease in demand, when there is an RFD requirement.

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INTRODUCTION

The Oak Ridge National Laboratory Refinery Yield Model (ORNL-RYM) has been used to study the refining cost, investment, operational, and crude oil impacts of specifications for reformulated diesel fuel (RFD). Table 1 shows No. 2 on-road diesel fuel regulations and timing for several regulatory authorities and for the World Wide Fuel Charter. Given that the diesel fuel requirements for California and Texas could be largely satisfied by alternative performance-based specifications, the most challenging requirements for on-road diesel fuel are those specifications recommended by the European Union and the World-wide Fuel Charter, particularly specifications for cetane number and total aromatics. Global vehicle and engine manufacturing associations support the World-wide Fuel Charter on the basis that "Consistent fuel quality world-wide is necessary to market high-quality automotive products matching world-wide customer performance and environmental needs." ORNL-RYM has been used to estimate refining impacts with an investment pathway that assumes early notice of RFD quality requirements. With this early notice, refinery capital investment would not yet be made to satisfy the ultra low sulfur diesel (ULSD) fuel sulfur requirement of year 2006, giving greater flexibility for investment planning.

THE ORNL REFINERY YIELD MODEL

ORNL-RYM

ORNL-RYM is a linear program representing over 75 refining processes which can be used to produce up to 50 different products from more than 180 crude oils. An investment module provides for the addition of processing capacity [5,6,7,8]. ORNL-RYM was updated for this study to include the most recent process configuration and revamp cost information for distillate desulfurization units; representations of advanced desulfurization technologies that selectively remove sulfur, with low hydrogen consumption; and representation of the most recent catalyst developments [9,10].

ORNL-RYM tracks gravity, cetane index, aromatics, sulfur, flash point, pour point, viscosity, hydrogen content, heat of combustion, distillation temperatures, and pollutant emissions for diesel fuel blendstocks and products [11, 12]. Properties for other distillates and for gasolines are handled in a similar fashion. ORNL-RYM incorporates gasoline blending to satisfy formula and emissions standards mandated by the Clean Air Act Amendments of 1990 [13]. ORNL-RYM also represents requirements of the toxics anti-backsliding rulemaking of 2001 [14].

Overoptimization can occur as a result of the ORNL-RYM use of a modeling concept in which refinery streams with identical distillation cut points are kept separate through different refining processes. Ratio constraints on refinery streams can be used to avoid unrealistic separation of streams with identical distillation cut points. With ratio constraints, the proportions of streams entering a process are constrained to equal the proportions of those streams produced at a source process. This study makes use of ratio constraints in gasoline production, based on calibration results. Ratio constraints are also used for distillate deep desulfurization and dearomatization processes. It is important to recognize that refineries within a region can vary widely in technical capability, and that refineries are subject to temporal variations in complex operations. A refining outcome (*e.g.*, investment cost) can span a range, and this range has uncertainty.

PREMISES

Policy Issues

The examination of the refinery impacts of an RFD requirement raises a wide range of policy issues. In establishing specific premises for this study, we must make assumptions about the resolution of a number of currently unresolved issues. One should not interpret these premises as official views as to the appropriate resolution of the underlying policy issues, but only as one possible set of reasonable assumptions for the analysis. Some of the key premises that are policy-related in an important way include the following:

- We are examining a *national on-road diesel fuel reformulation requirement* because there is significant interest, among various parties, in changing diesel fuel quality (beyond sulfur reductions) for lower in-use emissions, to enable new vehicle emission control systems, or to improve vehicle operating characteristics. Understanding how the specific nature of such a requirement interacts with other fuel quality requirements, refinery operations, or emerging crude oil options is important to policy formulation.

- The *interaction of such an RFD requirement with the existing 2006 ULSD requirement* will be significant in terms of investment strategics that refiners might pursue. While we have assumed a 2010 start date for an RFD requirement, it could happen sooner or later than that, and refiners might - or might not - invest for ULSD in 2006 with the forward knowledge of an RFD requirement. By assuming that refiners invest once for both programs (effectively) in 2006, this analysis examines only one end of the range of possibilities.

- *Changes to off-road diesel fuel quality* are quite likely in the time frame of this analysis, but the specifics are not known. ULSD (at 15 parts per million [ppm] maximum sulfur) may become the needed fuel for some portion of the off-road diesel fuel market while some low sulfur diesel fuel (at 500 ppm maximum sulfur) may remain in the diesel fuel pool due to the phase-in of the ULSD requirement. For this analysis, a volume of diesel equal to off-road volume is assumed to be at 500 ppm and the rest at 15 ppm (*i.e.*, ULSD), but the actual end use markets for the two sulfur levels may be more mixed than that. The critical implied assumption is that all high sulfur (greater than 500 ppm) diesel fuel disappears from the refinery slate by 2010.

- *Changes to gasoline requirements* are likely in the time frame relevant to this analysis. We have premised the requirements contained in recently proposed legislation (U.S. Senate Bill S.517, subsequently amended into U.S. House of Representatives Bill H.R.4) as a plausible set of new requirements. Despite the significant changes in that legislation *(e.g.*, ban of methyl tertiary butyl ether [MTBE], elimination of the reformulated gasoline [RFG] oxygenate requirement and mandated ethanol use), the actual impact on refinery operations for the purposes of our analysis is relatively small because of pre-existing ethanol use and the almost total absence of ether use in our U.S. Midwest study region, and the limited interactions between gasoline quality and diesel fuel reformulation.

- Finally, we examine the interaction between *greater use of Canadian synthetic crude oils* and these tighter diesel fuel quality specifications, with the implicit assumption that there will be a significant growth in the volume of that synthetic crude oil production and that our study region is a natural market for that crude oil. The need for effective integration of refinery changes in the U.S. (driven by changing product quality requirements) and expanded synthetic crude oil production in Canada is the rationale for this paper.

Study Period and Geographic Area

The study period is summer of year 2010. The study area is U.S. Petroleum Administration for Defense District II (PADD II), a 15 state area in the U.S. Midwest with 27 operable refineries, annually producing 22 percent of all gasoline and 25 percent of all on-road diesel fuel produced in the U.S. Compared with other regions, PADD II has relatively high production of on-road diesel fuel and high imports of Canadian crude oil.

Of the 27 PADD II refineries, 13 have distillate hydrotreating, and we assume that these refineries are currently producers of low sulfur diesel fuel. Different studies have focused on a range of possibilities for refinery participation in on-road diesel fuel production for 2006-2007. Baker & O'Brien [15] believe that only current low sulfur diesel fuel producers are likely to continue in the ULSD market. On the other hand, MathPro [16] concludes that some refineries that do not now produce low sulfur diesel fuel may have incentives to produce ULSD. For our more distant outlook of year 2010 (with a 24 percent increase in on-road diesel fuel production, compared to year 2000), we assume that ULSD/RFD production can be spread among all refineries in PADD II.

Refinery Raw Materials and Products

Refinery inputs of crude oil and raw materials and refinery summer production rates are based on U.S. Department of Energy (DOE) data, extrapolated to year 2010 [17,18]. Raw material and crude oil costs and revenues, expressed in year 2000 U.S. dollars, are also based on DOE data [18,19].

Distillate Quality

On-road diesel fuel has sulfur, cetane number, aromatics content and emissions specifications (nominal and actual) as shown in Table 2. The actual specifications for cetane number and aromatics content are based on refiner guidance that the lowest reasonable blending margins should be based on the reproducibility of tests that determine property values. Reproducibility is the variability of the average values obtained by several test operators while measuring the same item. We assume a 3.8 number margin for our cetane number specifications, based roughly on the reproducibility of ASTM D613. For aromatics, the reproducibility of ASTM D1319 is 2.5 vol percent when total aromatics content is approximately 15 vol percent. We have no basis for assumptions for additional margins that may be needed for pipeline degradation of product quality.

Off-road diesel fuels (including No. 2 home heating oil) have maximum allowable sulfur contents of 500 ppm nominal, which is modeled as 350 ppm maximum actual. Otherwise, specifications for diesel fuels, distillates and products other than gasoline are based on industry surveys [2]. On-road diesel equivalent miles-per-gallon (mpg) are held constant across cases.

Gasoline Quality

Gasoline properties are consistent with requirements of the U.S. Clean Air Act of 1990 and with key provisions of proposed U.S. Senate Bill S.517 which, among other initiatives: specifies the Renewable Fuels Standard requirement (4.3 billion gallons for the U.S. in year 2010); prohibits the use of MTBE, not later than four years after the date of enactment; eliminates the oxygen content requirement for RFG; maintains Toxic Air Pollutant emission reductions for RFG at 1999-2000 baseline levels; and consolidates the Volatile Organic Compound (VOC) emissions specification for all RFGs to the more stringent requirement for southern RFG. Furthermore, RFG and CG satisfy the toxics anti-backsliding rulemaking of 2001[14], and all gasolines contain no more than 30 ppm sulfur, on average. For ethanol-containing gasolines, ethanol usage patterns are based on Downstream Alternatives, Inc [20]. Gasoline equivalent mpg are held constant across cases.

Refinery Capacity and Investment

Refinery capacity is based on in-place capacity and construction as reported in DOE and industry publications [2, 21-25]. Process capacity investment requires a nominal 15 percent after-tax discounted cash flow rate of return on investment (ROI), and the actual investment cost assumes a 10 percent after-tax discounted cash flow ROI. For existing capacity, typical investment costs are used for up to 20 percent expansion in capacity. For capacity greater than the defined expansion limit, investment is subject to economies of scale, according to the "six-tenths factor" relationship:

$$\text{Cost}_{\text{New}} = (\text{Capacity}_{\text{New}}/\text{Capacity}_{\text{Typical Size}})^{n} * \text{Cost}_{\text{Typical Size}}, \text{ with n between 0.6 and 0.7}$$

IMPACTS OF REFORMULATION ON PADD II REFINERIES

Base Case

In the Base Case, on-road diesel fuel must satisfy current (year 2002) requirements for sulfur content (500 ppm maximum) and cetane number (40 minimum), and there is no aromatics specification. The Base Case is not representative of current quality requirements for off-road diesel fuels, which have premised sulfur specifications of 500 ppm maximum. By using this off-road sulfur specification in all cases, we have intentionally removed a variable from the study. Key results for the Base Case and all other cases are summarized in Tables 3 through 7.

ULSD Case

In the ULSD Case, on-road diesel fuel must satisfy future requirements for sulfur content (15 ppm maximum) and cetane number (40 minimum), but there are no requirements for reformulation to satisfy more stringent cetane and aromatics specifications. We premise limited market penetration of advanced technologies that selectively remove sulfur, with low hydrogen consumption. Given the Baker & O'Brien [15] projection that thirty-eight percent of current low sulfur diesel producers will engage in revamps of distillate hydrotreating units, we allow revamping in up to five refineries. For the remaining 22 refineries, we arbitrarily assume that up to three refineries (*i.e.*, almost 15 percent technology penetration) can invest in advanced desulfurization technologies.

Five existing distillate desulfurization units are revamped into two-stage units in the ULSD Case(Table 6). Investment in advanced technologies lowers the cost of ULSD production. Relative to the Base Case, the cost increase for ULSD is 5.2 cents per gallon (cpg), as shown in Table 7. Sensitivity runs show a ULSD cost increase of 7.9 cpg via two-stage deep hydrotreating, with no investment allowed in advanced technologies; and a cost increase of 3.7 cpg with no constraints on investment in advanced technologies.

ULSD product quality is dramatically different for different desulfurization technologies. Table 4 shows that ULSD produced with advanced technologies has substantially lower cetane quality, higher aromatics content, and poorer emissions quality. While the advanced technologies are attractive for sulfur reduction, these technologies have little impact on those properties (*i.e.,* cetane quality and aromatics content) which define "reformulation" in this study.

For new two-stage installations, all of the second-stage capacity is for units with deep desulfurization, with 35 percent dearomatization. With 20 percent dearomatization in the first-stage, dearomatization across the two stages explains a large part of the on-road diesel aromatics reduction (to 16.4 vol percent) relative to the Base Case. There is also a shift of aromatics into the off-road diesel pool, relative to the Base Case. In the ULSD Case, the off-road diesel pool has an aromatics content of 30.4 vol percent, compared with 24.2 vol percent in the Base Case. A comparison of off-road diesel blendstocks for the two cases (Table 5) shows a decline in straight-run blendstocks (higher sulfur content, lower aromatics content) and an increase in hydrotreated light-cycle oil (lower sulfur content, higher aromatics content) in the ULSD Case.

RFD Case

In the RFD Case, ULSD is reformulated to satisfy more stringent cetane and aromatics specifications. Due to the high cetane number specification for RFD, distillate upgrading is via two-stage deep hydroprocessing (Table 6). There is no investment in advanced technologies that selectively remove. Five existing distillate desulfurization units are revamped into two-stage units. For new two-stage installations, 14 percent of second-stage capacity is for units with 70 percent dearomatization capability. Lesser dearomatization occurs in the first- and second-stage distillate desulfurization units: 20 percent and 35 percent dearomatization, respectively.

Cetane improver is important in satisfying the on-road diesel cetane number specification. Table 3 shows that the cetane improver treat rate is 0.122 vol percent. This rate is substantially higher than current regional averages. For example, a recent industry survey shows that the cetane improver treat rate for high quality diesel fuel was 0.027 vol percent [2].

Table 7 shows that the average cost increase for RFD is 9.0 cpg. The major component of this cost increase is capital charges. Cetane improver (in the raw material category of Table 7) contributes 1.2 cpg to the cost increase.

Tighter on-road specifications cause an increase in aromatics in the off-road diesel pool in the RFD Case. The off-road diesel pool has an aromatics content of 29.3 vol percent, compared with 24.2 vol percent in the Base Case. A comparison of off-road diesel blendstocks for the two cases (Table 5) shows a decline in straight-run blendstocks (higher sulfur content, lower aromatics content) and an increase in hydrotreated light-cycle oil (lower sulfur content, higher aromatics content) in the RFD Case compared to the Base Case. RFD has much-improved emissions characteristics, relative to the commercial reference fuel. NOx emissions are reduced by 8.3 percent, and PM emissions are reduced by 19.8 percent (Table 3).

IMPACT OF DIESEL FUEL REFORMULATION ON DEMAND FOR CANADIAN SYNTHETIC CRUDE OIL

ORNL-RYM parametric analysis features have been used to examine the impacts of RFD on the PADD II refinery demand for Canadian synthetic crude oil. As the production of synthetic crude oil increases, with economic displacement of conventional crude oils, oilsands operators and refiners will face technical challenges with improved quality requirements for diesel fuel, jet fuel, and heavy gas oil for fluid catalytic cracking feed [28,29]. The cetane quality, aromatics content, and emissions specifications for RFD in our case studies would increase these challenges. Tables 8 and 9 show fractions and selected properties for the PADD II crude oil used in the case studies; for a Canadian synthetic crude oil; and for an ORNL-RYM approximation of that Canadian synthetic crude oil. For the distillate fraction (Table 9), the synthetic crude oil and its approximation have substantially lower cetane indices, and higher aromatics contents, compared to the PADD II crude oil. However, with much lower sulfur levels, the value of synthetic crude oil should increase in the production of low sulfur products.

The parametric analysis illustrates impacts of changes in diesel product quality requirements, given the premised synthetic crude oil quality and the PADD II refinery configurations. These cases do not address the issues of (1) modifying the quality of synthetic crude oil to meet the requirements of crude purchasers; (2) modifying refinery hardware to accommodate higher levels of synthetic crude oil use; or (3) impacts on product properties (*e.g*., jet fuel and diesel lubricity) other than those specified in the case studies.

Figure 1 shows PADD II refinery demand comparisons for Canadian synthetic crude oil at various differentials in its price relative to the price of West Texas Intermediate (WTI) crude. At the actual price differential of -$0.27 per barrel in years 2000 and 2001 [31], the Figure 1 demand for synthetic crude oil for production of low sulfur diesel in the Base Case is 122 MBD, or about 2.8 percent of the total PADD II crude run. This synthetic crude oil percentage is nearly the same as the current actual 2.6 percent [32]. With production of low sulfur diesel, the demand for synthetic crude oil is 0.3 percent of the total PADD II crude run at a price premium to WTI of $2.00 per barrel, and 8.5 percent of the total PADD II crude run at a price discount $2.00 per barrel. There is a sizeable increase in synthetic crude oil demand when the maximum sulfur specification for on-road diesel falls from 500 ppm (Base Case) to 15 ppm (ULSD Case). This demand increase is expected, given the low sulfur levels of synthetic crude oil.

Figure 1 also shows that diesel fuel reformulation substantially reduces the demand for synthetic crude oil at recent prices (*i.e*., in the price differential neighborhood of -$0.27 per barrel in years 2000 and 2001), compared with demand under ULSD production. The demand effect increases as price differentials drop below $0.50 per barrel.

Figure 1 shows that diesel fuel reformulation can reverse the synthetic crude oil demand increase that resulted from the transition from low sulfur diesel to ULSD.

The relationship between desulfurization capacity and synthetic crude oil demand is illustrated in Figure 2. As expected prices for synthetic crude oil fall, the expected demand for that crude increases, and investment in first- and second stage deep desulfurization capacity declines. Due to the higher aromatics content of synthetic crude oil, investment in second stage deep desulfurization/dearomatization capacity increases as the expected demand for synthetic crude oil increases.

CONCLUSIONS

The diesel fuel reformulation study observations of Table 10 suggest the following:

- Diesel fuel reformulation costs are be substantial.
- Diesel fuel reformulation has considerable emissions reduction benefits.
- While advanced desulfurization technologies reduce the cost of ULSD, these technologies, with relatively small impact on cetane and aromatics quality, may not be chosen for RFD production. Advanced desulfurization technologies are on a suboptimal pathway for RFD production. These technologies could contribute to increased costs of a delayed notice compared to an early notice investment pathway to RFD.
- It follows that refining costs are likely to be lower with early notice of product quality requirements for RFD. With early notice of RFD requirements, refinery capital investment has not yet been made to satisfy the ULSD requirement of year 2006, and there is greater flexibility for investment planning.

- There is a sizeable increase in synthetic crude oil demand as ULSD displaces low sulfur diesel fuel, but this demand increase would be reversed by a requirement for diesel fuel reformulation.

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FIGURE CAPTIONS

Figure 1.Synthetic Crude Oil Demand Comparisons
(PADD II Summer 2010)

Figure 2. Hydroprocessing Capacity Is Related to
Synthetic Crude Oil Demand Outlook
(PADD II Summer 2010)

Table 1. On-road No. 2 diesel fuel regulations and timing [1,2,3,]

	United States				European Union (EU)		World-wide Fuel Charter Category 4[a]
	U.S. EPA		California/ Texas[b]	California[b]			
Timing	1994	2006	2006	1996 actual	2000	2005	
Gravity, API° min			33	36.5	36	36	37
Sulfur, ppm max	500	15	15	140	350	10[c]	5-10
Cetane index, min	40	40					52
Cetane number, min	40	40	48	53.8	51	54-58	55
Aromatics, max:							
Total			10 vol%	18.2 vol%			15 vol%
Polynuclear			1.4 wt%	2.8 vol%	11 wt%	1-6 wt%	2 vol%
Distillation, °F max							
T90	640	640	610	623			608
T95					680	644-680	644

[a]Markets with further advanced requirements for emission control, to enable sophisticated aftertreatment technologies for reduction of emissions of nitrogen oxides and particulate matter.
[b]Highway diesel fuel may satisfy different performance-based specifications if approved by the California Air Resources Board for a Diesel Fuel Alternative Formulation. 1996 actuals for California show the significant differences in properties due to the alternative performance-based specifications.
[C]All three EU legislative bodies (Council, Commission and Parliament) have agreed to the 10 ppm sulfur level and the start date, with only a few minor details to be worked out before a final decision later this year and publication early next year. The final end date for full implementation will be either 2008 or 2009 [4].

Table 2. Diesel fuel reformulation case studies for summer 2010[a]

Case	Investment	Sulfur ppm, max	Cetane number, min	Aromatics vol%, max
Base Case	Sunk @Base Case	500[b] (350[c])	40	NA
ULSD Case		15[b] (8[c])	40	NA
RFD Case		15[b] (8[c])	55[b] (58.8[c])	15[b] (12.5[c])

[a]Off-road diesel fuels have maximum allowable sulfur contents of 500 ppm nominal, which are modeled as 350 ppm maximum actual.
[b]Nominal specification value.
[c]Actual specification value, including refining blending margins, used in ORNL-RYM.

Table 3. Properties of on-road diesel fuel in PADD II summer 2010

Property	Base Case	ULSD Case	RFD Case
Volume, thousand barrels per day	844	860	864
Specific gravity	0.8450	0.8334	0.8291
Sulfur, ppm	350	8	8
Cetane Index	48.5	52.4	53.5
Cetane Number, clear	44.9	50.4	51.5
Cetane Improver, vol%	.000	.000	.122
Cetane Improver, number increase	0.0	0.0	7.3
Cetane Number, total	44.9	50.4	58.8
Aromatics, vol%	26.8	16.4	12.5
Viscosity, centistokes	2.65	2.80	2.76
ASTM Initial Boiling Point (IBP)[a]	377	376	375
T10[b]	436	435	434
T30[b]	463	463	463
T50[b]	499	493	492
T70[b]	549	540	539
T90[b]	589	591	591
Final Boiling Point (FBP)[a]	633	635	635
Nitrogen oxides emissions change, %[c]	-0.7	-5.9	-8.3
Particulate matter emissions change, %[c]	-2.4	-15.7	-19.8

[a]IBP and FBP are Fahrenheit temperatures based on survey reports of differences relative to T10 and T90 [26].
[b]Txx is Fahrenheit temperature at which xx vol% of sample is evaporated in ASTM distillation test.
[c]Relative to commercial fuel, with adjustment for future fleet change [27].

Table 4. Properties of on-road diesel fuels, by desulfurization technology, in PADD II summer 2010

Property	ULSD Case: Desulfurization technology	
	2-stage	Advanced
Volume, thousand barrels per day	772	88
Specific gravity	0.8312	0.8535
Sulfur, ppm	8	8
Cetane Index	52.9	44.9
Cetane Number, clear	50.9	42.9
Cetane Improver, vol%	0.000	0.000
Cetane Improver, number increase	0.0	0.0
Cetane Number, total	50.9	42.9
Aromatics, vol%	14.9	29.7
Viscosity, centistokes	2.80	2.76
ASTM Initial Boiling Point (IBP)[a]	376	373
T10[b]	435	432
T30[b]	463	466
T50[b]	492	495
T70[b]	539	547
T90[b]	591	590
Final Boiling Point (FBP)[a]	635	634
Nitrogen oxides emissions change, %[c]	-6.4	-1.4
Particulate matter emissions change, %[c]	-16.7	-2.3

[a]IBP and FBP are Fahrenheit temperatures based on survey reports of differences relative to T10 and T90 [26].
[b]Txx is Fahrenheit temperature at which xx vol% of sample is evaporated in ASTM distillation test.
[c]Relative to commercial fuel, with adjustment for future fleet change [27].

Table 5. Blendstocks of diesel fuels in PADD II summer 2010 (Percent)

Blendstock category[a]	Base Case				
	On-road	Rail-road	Other Off-road	Heating Oil	Pool
STRAIGHT-RUN:					
Kerosene (325-500)				14.3	0.3
Distillate (500-650)	5.9	9.7	6.0	44.0	6.8
NON-CRACKED, HYDROTREATED:					
Kerosene (325-500)	39.7	14.3	32.6	39.4	37.9
Distillate (500-650)	29.4	25.7	36.8	2.4	30.2
CRACKED, HYDROTREATED:					
Light Cycle Oil	24.9	30.0	23.7		24.2
HYDROCRACKED:					
Distillate (295-525)	0.1	20.4	0.9		0.6
CETANE IMPROVER					

[a]True boiling point ranges (°F) are indicated with blendstock category name.

Table 5 (Continued). Blendstocks of diesel fuels in PADD II summer 2010 (Percent)

Blendstock category[a]	ULSD Case					
	On-road from 2-stage	On-road from advanced DeS	Rail-road	Other Off-road	Heating Oil	Pool
STRAIGHT-RUN:						
Kerosene (325-500)						
Distillate (500-650)						
NON-CRACKED, HYDROTREATED:						
Kerosene (325-500)	43.7	1.4	22.1	31.6	32.7	37.5
Distillate (500-650)	39.9	62.3	31.7	37.6	37.3	41.0
CRACKED, HYDROTREATED:						
Light Cycle Oil	16.4	30.0	30.0	30.0	30.0	20.6
HYDROCRACKED:						
Distillate (295-525)		6.4	16.1	0.8		0.9
CETANE IMPROVER						

[a]True boiling point ranges (°F) are indicated with blendstock category name.

Table 5 (Continued). Blendstocks of diesel fuels in PADD II summer 2010 (Percent)

Blendstock category[a]	RFD Case				
	On-road from 2-stage	Rail-road	Other Off-road	Heating Oil	Pool
STRAIGHT-RUN:					
Kerosene (325-500)					
Distillate (500-650)					
NON-CRACKED, HYDROTREATED:					
Kerosene (325-500)	45.7	14.3	25.4	34.4	41.0
Distillate (500-650)	39.4	35.4	40.0	35.6	39.4
CRACKED, HYDROTREATED:					
Light Cycle Oil	14.7	30.0	30.0	30.0	18.2
HYDROCRACKED:					
Distillate (295-525)		20.4	4.6		1.2
CETANE IMPROVER	0.12				0.09

[a]True boiling point ranges (^{o}F) are indicated with blendstock category name.

Table 6. Process capacity expansions and additions in PADD II summer 2010
(Thousand barrels per stream day, unless otherwise noted)

Process	ULSD Case	RFD Case
Crude distillation	2	64
Vacuum distillation	3	38
Delayed coking		18
Gas oil hydrocracking		71
Distillate deep hydrodesulfurization, 1st stage unit HD1	536	529
Distillate deep hydrodesulfurization, 2nd stage unit HS2	535	496
Distillate deep hydrodesulfurization and dearomatization, 2nd stage unit HD2		78
Revamp of distillate desulfurization to HD1 + HS2	211	211
Conversion of HS2 to HD2		
Advanced distillate desulfurization technology	90	
Naphtha splitter		30
Hydrogen plant, fuel oil equivalent basis	13	21
Sulfur plant, tons per day		0.5

Table 7. Components of refinery cost changes in PADD II summer 2010 (cents per gallon of RFD)

	Base Case	ULSD Case	RFD Case
Raw material costs and product revenue changes	0.0	-1.4	-0.3
Processing costs	0.0	0.9	0.9
Capital charges	0.0	4.6	6.8
Fixed operating costs	0.0	1.1	1.6
Total cost change (10 percent ROI)	0.0	5.2	9.0

Table 8. Comparison of crude oils in RFD study

Fraction	Volume percents		
	PADD II Crude 34.0° API 1.27% sulfur	Synthetic crude oil [30] 31.4° API 0.15% sulfur	ORNL-RYM approximation of synthetic crude oil 37.3° API 0.12% sulfur
C1/C3	0.37	0.06	0.06
IC4	0.31	0.31	0.31
NC4	1.11	1.89	1.89
68-175°F	5.63	6.94	6.94
175-250°F	6.73	4.69	12.91
250-325°F	7.13	4.82	
325-375°F	5.05	3.40	
375-500°F	10.55	13.88	38.99
500-550°F	4.21	7.93	
550-650°F	10.85	17.18	
650-690°F	4.64	7.17	7.17
690-800°F	11.25	16.21	16.21
800-1050°F+	32.16	15.51	15.51

Table 9. Comparison of aggregated distillate fraction properties in crude oils of RFD study
Fraction: 375-650°F

Fraction	PADD II Crude	Synthetic crude oil [30]	ORNL-RYM approximation of synthetic crude oil
Gravity, °API	36.8	29.5	31.8
Cetane index	50.4	38.3	42.5
Aromatics, vol percent	26.6	34.6	34.1
Sulfur, wt percent	0.586	0.0391	0.0391

Table 10. Diesel fuel reformulation study findings

Case	On-road diesel upgrading pathway	Cost increase[a]	Nitrogen oxides emissions change[b]	Particulate matter emissions change[b]	Comment
Base Case	•Low sulfur •Investment as required	0.0	-0.7	-2.4	
ULSD Case	•Ultra low sulfur •Some newer technologies	5.2	-5.9	-15.7	Investment in advanced desulfurization technology results in lower costs. Sensitivity runs show cost increase of 7.9 cpg via 2-stage deep hydroprocessing, with no investment allowed in advanced desulfurization; and cost increase of 3.7 cpg with no constraints on investment in advanced desulfurization.
RFD Case	•RFD •Early notice of requirements	9.0	-8.3	-19.8	Due to high cetane specification, distillate upgrading is via 2-stage deep hydroprocessing, not advanced desulfurization technologies that selectively remove sulfur without cetane improvement.
Synthetic Crude Oil Demand Analysis	There is a sizeable increase in synthetic crude oil demand when the maximum sulfur specification for on-road diesel falls from 500 ppm to 15 ppm, but this demand increase would be reversed by diesel fuel reformulation.				

[a]Cost increase, in cpg, relative to the Base Case.
[b]Percent change relative to commercial fuel, with adjustment for future fleet change

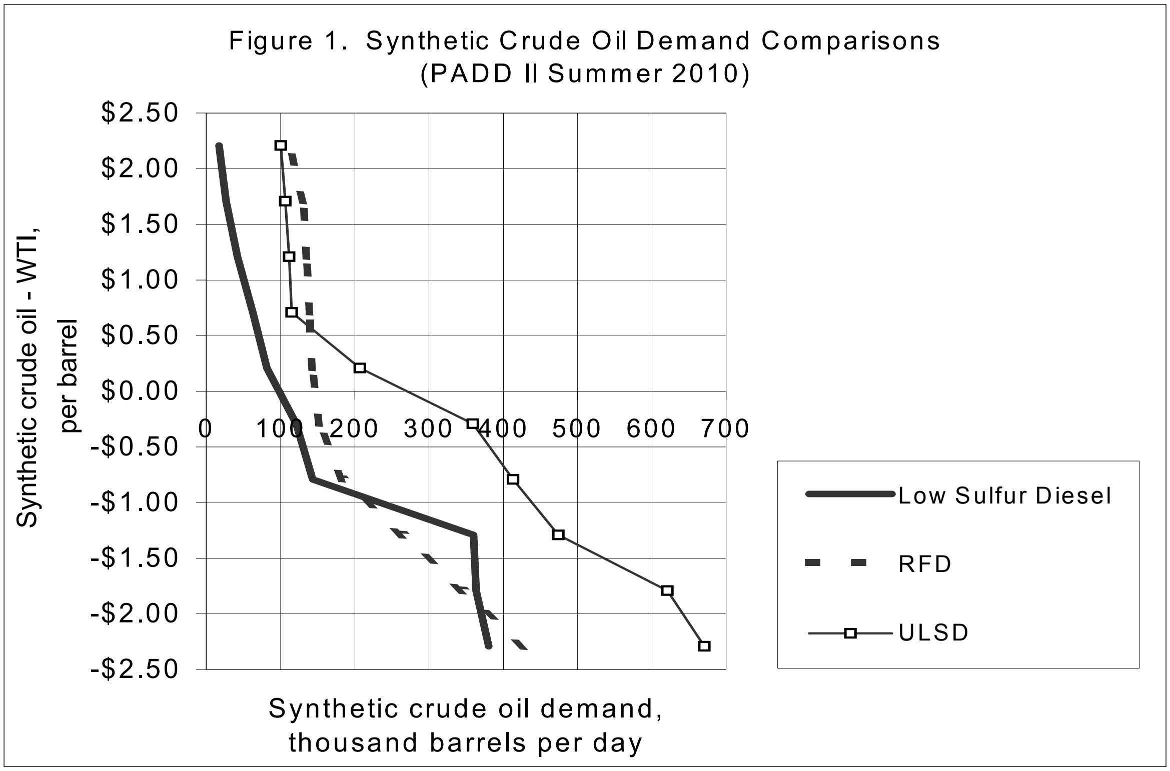

Figure 1. Synthetic Crude Oil Demand Comparisons
(PADD II Summer 2010)
$2.50
$2.00
$1.50
$1.00
$0.50
$0.00
-$0.50
-$1.00
-$1.50
-$2.00
-$2.50
0
100
200
300
400
500
600
700
Synthetic crude oil - WTI, per barrel
Synthetic crude oil demand, thousand barrels per day
Low Sulfur Diesel
RFD
ULSD

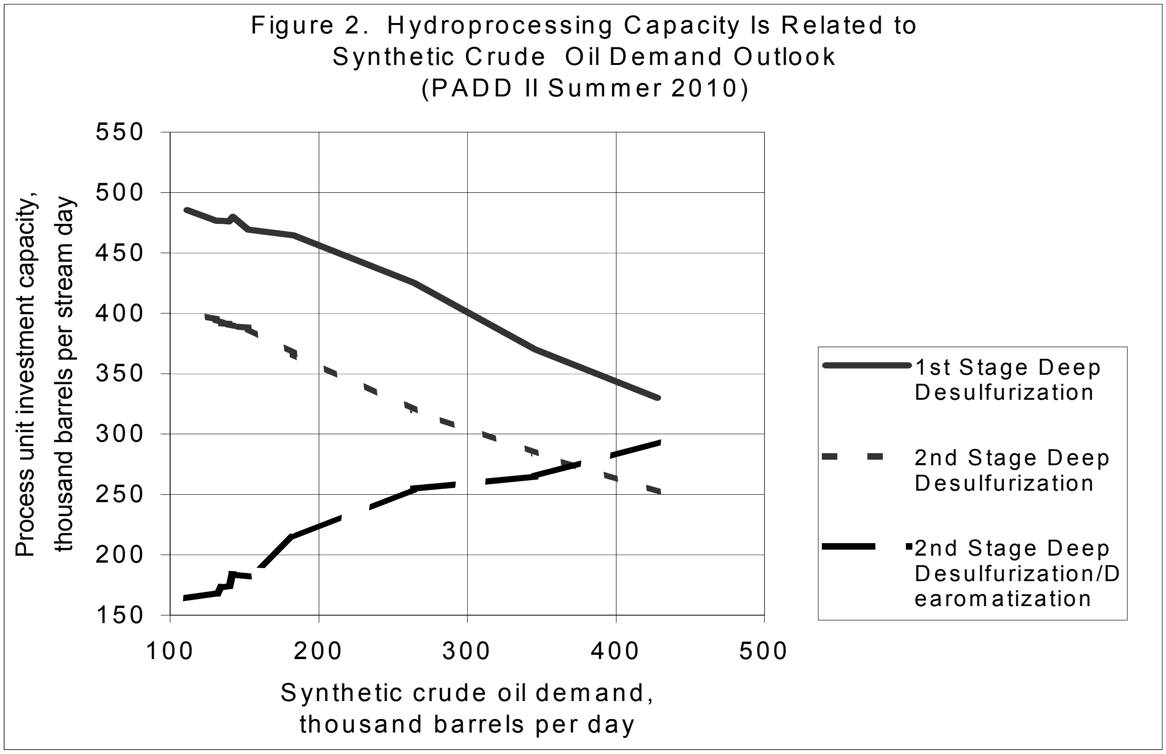
Figure 2. Hydroprocessing Capacity Is Related to
Synthetic Crude Oil Demand Outlook
(PADD II Summer 2010)
Process unit investment capacity, thousand barrels per stream day
550
500
450
400
350
300
250
200
150
100
200
300
400
500
Synthetic crude oil demand, thousand barrels per day
1st Stage Deep Desulfurization
2nd Stage Deep Desulfurization
2nd Stage Deep Desulfurization/Dearomatization