interim report on the european refining implications of severe reformulation of gasoline and diesel fuel

Prepared for the CONCAWE Automotive Emissions Management Group by the Special Task Force on the refining consequences of varying road fuels qualities (AE/STF-9).

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ABSTRACT

This report records the results of a study to assess the EU-12 refining industry implications of severe universal reformulation of gasoline and diesel fuel individually and together, in terms of investment and operating costs, energy consumption and carbon emissions. It concludes that the edge of the envelope within which a practical set of reformulation options might lie would require investment of up to US $40-60 billion, would increase refining own use and loss from about 8% to 11% of throughput and would increase overall CO_2 emissions by up to 55 Mt/yr.

This is an interim report and the study will go on to assess fuels packages lying within this envelope which are options needing cost/ benefit assessment under the European Auto/Oil Programme.

KEYWORDS

Arthur D. Little, automotive fuel, benzene, CO_2 emission, cost, diesel fuel, energy consumption, EU-12, fuel specification, gasoline, LP model, MTBE, oil industry, refinery, reformulation.

CONTENTS

SUMMARY

This is an interim report on the implications for the European refining industry if significant changes were to be mandated throughout the EU on some critical quality specifications of transportation fuels. The studies described herein were made in the early part of 1995, with the specific remit to estimate the increases in cost and in net consumption of primary energy resources attendant upon "reformulation" of motor gasoline and/or road diesel fuel. The results provide a technical basis for CONCAWE's contribution to the European Auto/Oil Programme for development of a cost-effective set of measures to improve air quality by controlling vehicle emissions.

Detailed analyses have been made of the type and magnitude of refining process capacity additions which would be required to meet stringent sets of specifications for gasoline and diesel in the period 2000-2010. These indicate that the probable investment cost of a six-property reformulation of gasoline would be in the range of G$20-25, including investments made outside the EU to produce the large volumes of imported oxygenated components required. Reformulation of three key properties of diesel, including cetane index at 55, would probably require G$10-13 investment, all at EU refineries. If the diesel reformulation package included cetane index at 58 instead of 55, it would cost much more, probably about G$20-35.

The cost of reformulating both fuels simultaneously has been estimated, and the results of this study indicate that the investment for simultaneous reformulation of both fuels would not be significantly higher than the sum of reformulation costs of the individual fuels. This indicates that the expected antagonisms between gasoline and diesel reformulations have been masked by some unforeseen offsetting synergistic effects. Some of the causes of this apparent synergism have been identified, but it has not so far been possible to quantify their individual contributions to the net cost of reformulation. Simultaneous reformulation would cost G$30-40, with diesel at 55 cetane, and about G$40-60 with diesel at 58 cetane index.

The investment ranges quoted above reflect scope for variability in product demand outlooks and in investment strategies which the oil industry might implement in response to a requirement for reformulation.

Reformulation costs would not be distributed evenly across the 99 EU refineries, since the type and magnitude of new process capacity required is highly dependent on the configuration of process mix in the original refinery. The study therefore estimated costs for each of the four major refinery configurations, categorized as follows:

Simple refineries, with neither cat. cracking nor hydrocracking and complex refineries, sub classified as:-

Catalytic cracking refineries, without a hydrocracker

Hydrocracking refineries, without a catalytic cracker

Refineries with both a catalytic cracker and a hydrocracker

A fundamental conclusion is that if constraints on composition of transportation fuels tended to tighten simultaneously, all refinery sites would tend to converge towards a uniform configuration, including catalytic cracking plus hydrocracking and/or some process for severe hydrogenation of distillates. The simpler refineries rely on catalytic reforming of naphtha as their major source of octane, and could not, as they stand, meet their gasoline demand at the low total aromatics specification postulated in this study Whereas the cat. cracking refineries, although having access to a greater diversity of high-octane gasoline components, would face severe problems in meeting diesel demand at high cetane, low density, ultra-low sulphur and curtailed boiling range specifications. In gasoline reformulation cases, the simple refineries would either have to invest in new catalytic cracking capacity, thereby sparing some of the existing catalytic cracking capacity in complex refineries, or go out of business, thereby necessitating the replacement of the lost hydroskimming capacity by investment in the surviving complex refineries A possible way of minimizing total industry investment, at the expense of escalating logistics costs, would be to maintain the production capability of the simple refineries by setting up component exchanges between cat. cracking and non-cat. cracking refineries. But whatever strategy (or mix of the above strategies) were to be preferred, a severe reformulation programme would undoubtedly generate serious hydrogen imbalances at many refineries, necessitating heavy and widespread investment in hydrogen generation plants.

The energy-intensive nature of the hydrogen generation process is a major factor in accounting for the significant decreases in efficiency of raw material utilization within refineries which are observed in cases of severe reformulation. Refineries' own consumption and loss, expressed as the mass percentage of total refinery input which fails to emerge as saleable product, is about 8% in the 2000 base case, but could rise to over 11% in the most severe diesel-plus-gasoline reformulation case studied.

"Well-to-wheel" carbon balances have been drawn up, taking into account refining operations, vehicle use and the synthesis from natural gas of any oxygenate imports required to supplement refinery production. In all cases studied, the imposition of more restrictive fuel specifications would generate an increase in global emissions of carbon dioxide. Assuming simultaneous reformulation of both road fuels, the increase in CO_2 emissions has been calculated as about 7 Mt/yr in 2000, with the potential to grow to about 11 Mt/yr by 2010, at 55 cetane index. In the corresponding 58 cetane case, the increase in 2010 global CO_2 emissions would be 55 Mt/yr. To put these increases in perspective, it should be noted that current best estimates of total global CO_2 emissions for 2010 range from 30 Gt/yr to 40 Gt/yr.

The work described in this report is in effect a scoping study, in that it has focused on one pre-defined package of property changes for each of the road fuels. It is planned to continue the group's work by extending the study to other selected combinations of quality changes.

1. INTRODUCTION

Adjustment or “reformulation” of transportation fuel quality is one of the measures under consideration in the EU for control of emissions from road vehicles of so-called air toxics and other volatile organic compounds (VOCs), oxides of nitrogen (NOx) , carbon monoxide (CO), and particulate matter (PM). Other potential measures in the continuing effort to improve urban air quality include vehicle technology developments, improved programmes of vehicle inspection & maintenance, traffic management schemes, and imposition of selective fiscal sanctions. All of these control measures are being evaluated under the aegis of the European Commission/ACEA/EUROPIA European Auto/Oil Programme, a major objective of which is to establish the relative cost-effectiveness of the air quality improvements achievable by implementing various combinations and permutations of the potential control options available.

Several studies on various aspects of fuel quality reformulation have been made in the recent past by organizations other than CONCAWE, the most significant of these being a study on gasoline reformulation options made by A. D. Little for the German Umweltbundesamt (UBA). CONCAWE’s Automotive Emissions Special Task Force 9 (AE/STF-9) has reviewed all of these studies and the group's comments on the ADL study are briefly summarized in the following section of this report.

To the best of STF-9's knowledge, none of the studies made to date addresses the problem of simultaneous reformulation of gasoline and diesel, although future legislation might well require this. In view of the potential for (possibly antagonistic) interactions between the processing changes required for diesel and those required for gasoline, STF-9 considered that it would be unwise to assume that the costs of simultaneous reformulation would be equal to the sum of the costs of reformulating the two fuels individually. The study therefore evaluates a set of cases representing simultaneous reformulation of gasoline and diesel, as described in more detail in **Section 3** "Scope".

The work described in this report may be considered as a scoping study, insofar as it does not set out to cover the myriad possible permutations of product quality changes, but to define the four "corners" of a quality envelope large enough to contain most of the combinations likely to come under consideration. It cannot be too strongly emphasized that the values of individual product quality specifications which define this envelope have been chosen for study purposes only. They should in no way be regarded or interpreted as forecasts, targets or proposals for future fuel quality. The scope of the product quality envelope is chosen to reflect technical possibilities, without prejudging the question of economic viability.

For each of the two study years (2000 & 2010), and for each of the two petroleum products demand outlooks considered (low growth & high growth), a set of four cases was constructed, reflecting the following four different sets of quality assumptions:-

Base - Existing and already-mandated specifications on road fuels

Gasoline - Very stringent package of specifications on benzene, aromatics, sulphur and oxygen contents, RVP and back-end distillation. All else as in base

Diesel Fuel - Very stringent package of specifications on sulphur content, cetane, and back-end distillation. All else as in base

Combined - Very stringent specifications packages as above on both gasoline and diesel

Within each of these three reformulation packages, only a single value of each product quality specification was considered in the first instance. In other words the study did not initially aim to develop curves of cost versus reformulation severity for individual properties, as the ADL/UBA study did for benzene in gasoline. However, analysis of the initial results appeared to indicate that costs for diesel reformulation might escalate rapidly at cetane indices slightly higher than the originally selected level of 55. The study was therefore eventually extended to evaluate a diesel reformulation to 58 cetane index in addition to the 55 cetane case.

2. EARLIER WORK

In early 1992, in anticipation of additional European interest being generated in gasoline composition as a result of the US activity on reformulated gasoline (RFG), CONCAWE started to extend the work done by its Automotive Emissions Special Task Force 6 (AE/STF-6) which had looked into the refining effects of reducing gasoline benzene and aromatics contents. The extension to cover lower levels of gasoline benzene and aromatics, additionally looking into oxygen, sulphur and olefins, and at lower levels of RVP was commenced by AE/STF-8 which concentrated on identifying the energy effects.

These preliminary findings helped to put CONCAWE in the position to be able to comment constructively on ADL's gasoline reformulation study. In general, the basic assumptions and methodology used by ADL are considered sound, and CONCAWE accepts in broad terms ADL’s cost results. The key comments offered by CONCAWE mainly address presentation issues, and aim to highlight and clarify some of the qualifications which must be applied in interpreting the results of such a complex study. They are:

- The ADL report does not provide any insight into the air quality deficiencies which need to be addressed. The information in the report can therefore only be used as cost input to a rigorous cost benefit or cost-effectiveness analysis.

- Investment costs are annualized using a capital charge factor. Annualizing and expressing on a cost/litre basis does not adequately demonstrate the cash requirements on the industry. It is important that the investment requirements are clearly visible.

- The mathematical procedure for establishing industry average costs does not appear to be based on a business logic that is readily understandable and acceptable.

- CONCAWE believes that ADL’s annual capital charge factor is too low at 15% to provide a healthy industry. A capital charge of 20% (at least) will be required to satisfy debt and equity holders of an average European based oil company.

- CONCAWE does not believe that the increased sales of butanes resulting from an RVP reduction can necessarily be maintained as a permanent correction mechanism. In the longer term, reinvestment is likely to occur to correct the lost production of gasolines. The annualized costs are likely to be similar to those estimated by ADL but capital investment will be required.

- The report has built up its cost profile based on a specific order of environmental priorities. The sequence is not based on known air quality problems. The cost of measures will be dependent on the sequencing. It is therefore important that Air Quality Standards are established before measures are cost estimated, compared and selected.

- There is an assumption that the industry will be able to plan before the year 2000 investment so as to take into account the new requirements for fuels reformulation thus avoiding up to $2 billion of so-called regret investment. It is unlikely that investment decisions can always be deferred or modified to such an extent.

- The reformulated fuel has not been corrected back to a constant energy basis. This underestimates the CO_2 debit by approximately 400 kt/annum or 10% of the net increase resulting from complete gasoline reformulation.

This ADL study has become a reference work to be taken into account in the European Auto/Oil Programme. The present CONCAWE study expands upon it with respect to the gasoline issues and also addresses the diesel fuel issues concurrently.

The early work also drew attention to two very important features of road fuel composition considerations, namely:

I) The composition is crucially dependent on the refinery configuration. Therefore any cost studies must consider the specific reformulation capabilities of the different types of refineries which exist in Europe today. For this reason, the four representative refinery categories to be simulated by the CONCAWE LP model were characterized in terms of their base case road fuel compositions and their existing process options for fuels products upgrading. This characterization procedure is described in detail in a following section.

ii) Nearly every existing refinery, no matter what its configuration, could relatively easily make some proportion of its road fuels to “reformulated” qualities without significant investment, by selective use of components. This can be done only if, at a given refinery, either the reformulated specification is not limiting in the base case, or the refinery has the freedom to adjust its supply/demand balance. However, the economics of the reformulating refinery do not need to take into account any consequent adjustments required elsewhere to maintain a constant industry supply/demand/quality balance. Proper quantification of these adjustments would necessitate a detailed refinery-by-refinery analysis, and it is therefore neither practical nor meaningful to use an industry-wide simulation tool to attempt to evaluate a partial reformulation scenario. The implications of this conclusion for the present study are detailed in **Section 3.2** below.

3. SCOPE

The purpose of this study is to quantify the EU refining implications of universal reformulation of gasoline and diesel fuel, individually and together, in terms of investment and operating costs, energy consumption and carbon emissions.

3.1. NATIONAL SUPPLY/DEMAND VARIATIONS ARE NOT DIRECTLY ACCESSED

Because of the very large scope of the problem, it was decided to work initially on an EU-wide basis, and to identify the implications for any specific country or sub-region at a later stage, as required. For the purposes of the study the 12-member constitution of the EU as at year end 1994 has been assumed.

No attempt has therefore been made at this stage to simulate the refining operations of individual Member States. However, a very approximate estimate of the cost breakdown by country could be obtained by allocating the calculated EU total among the 12 countries on the basis of the relative representation in each country's refining industry of the four basic refinery types or configurations which were modelled in the study.

3.2. LOCALIZED IMPLEMENTATION OF REFORMULATION IS NOT ADDRESSED

The principal tool employed to calculate the increments of new process capacity required for reformulation is an optimizing linear programme (LP) model, which simulates the EU refining industry as four "mega-refineries" and optimizes it as a single entity, within a given set of constraints. The key constraints are product quality and demand, crude and feedstock availability and type, and process plant capacity. The amount of feedstock consumed and product made within any one of the four refinery blocks may vary from case to case, provided that EU totals are as predefined in the input for the specific case. But the product quality constraints are the same for each of the four refinery blocks.

For this reason the results of this study cannot be extrapolated to infer the cost of reformulating, e.g. 10% of the gasoline consumed in the EU, or, say, the diesel fuel supplied to 3 or 4 specified cities. The theoretical approach to such a question would be to identify the segment of the refining industry which supplies the target demand area, to define the make-up by process category of that segment, and to model that segment as a separate block, with appropriate reformulated product quality specifications applied to that segment only. The LP solution for such a case would by definition select the most favourable crude slate and mix of product demand for the target segment, taking advantage of the relative lack of product quality constraints in the remaining refineries to dump "problem" crudes and product demands. Compared with the EU refining industry as a whole, the target segment would have a significantly greater degree of freedom to optimize, which would inevitably be reflected in a lower unit cost (i.e. investment or total annual cost per ton of product) than the cost of universal reformulation.

Indeed, it is quite possible that the model could find a way to reformulate on a small scale for zero apparent investment cost, by employing logistics adjustments to achieve a product quality which would require major investment if implemented on a EU scale.

3.3. STEPWISE ADJUSTMENT OF INDIVIDUAL FUEL PROPERTIES IS NOT EXPLORED

Cases for reformulation of gasoline-only, diesel-only, and both fuels simultaneously have been established to represent extreme examples of reformulation packages. The individual product qualities within these packages reflect either the most severe quality levels mooted to date by the participants in the European Auto/Oil Programme or, in some cases, the limiting levels achievable by available technology. They are not however to be regarded or interpreted in any way as proposals, targets or forecasts of future fuel quality, or as predictions of possible legislation on reformulation.

The base case and the three reformulation cases effectively define the corners or boundaries of a product quality envelope. Refinery effects have been modelled by treating these four cases as indivisible "packages"; it is not a primary purpose of the present study to break down the costs of the packages in order to allocate them to changes in individual properties. The package approach was taken in order to establish the cost and energy implications, and the range of process additions likely to be required, in the event of a severe simultaneous universal reformulation scenario. Also, as a matter of refining planning technique, it is desirable to set up a simulation within the LP model with enough processing capacity to provide feasible solutions under the most extreme set of constraints likely to be imposed during the study; this should ensure that the model will yield a set of feasible and mutually self-consistent solutions in any less severe reformulation cases to be run in the future.

It should be noted that A.D. Little as their contribution to the current DGIII-sponsored cost-effectiveness studies, are committed to providing cost curves for individual properties, and it is envisaged that the analytical data contained in this report will be incorporated, after review by ADL, into the input database for their studies.

STF-9 did not take the cost-curve approach in this first phase of their studies, for two reasons. First, it was felt necessary to scope out the hitherto unanalysed problem of simultaneous reformulation of gasoline and diesel, in view of their potentially interactive effects on refinery hydrogen balance. Secondly, it would be a practical impossibility to analyse the large number of possible combinations and sequences of fuel quality adjustments which could be envisaged.

It was nevertheless decided to extend the range of the study to re-evaluate the diesel cases at a second level of cetane index, namely 58, in addition to the originally-specified reformulation level of 55. This was done in order to explore the relationship between reformulation costs and cetane level, because initial results suggested that costs might well increase very steeply between these two levels.

3.4. BASE CASE AND REFORMULATED PRODUCT QUALITY PACKAGES

The boundaries of the quality envelope developed for study purposes are defined as follows:

Gasoline	**Base Case**	**Reformulated fuel**
RVP	70 kPa max. Assumed as representative of EU pool	10 kPa reduction Simulated by 60 kPa max spec.
Sulphur	500 ppm (m) max	100 ppm (m) max
Benzene	5% (v) max	0.5% (v) max
Aromatics	50% (v) max	25% (v) max
Oxygen	2.8% (m) max	2.0% - 2.8% (m)
Olefins	20% (v) max	20% (v) max
% D+L @ 70°C (E70)	20% - 50% (v)	20% - 50% (v)
% D+L @ 100°C (E100)	45% - 65% (v)	45% - 65% (v)
°C @ 90% D+L (T90)	N.A.	Undefined reduction simulated by exclusion of heaviest components

Diesel Fuel	**Base Case**	**Reformulated Fuel**
Cetane Index ***(surrogate for cetane number)***	46 min	55 min. AND 58 min
Sulphur	500 ppm (m) max	200 ppm (m) max
% D+L @ 250°C (E250)	50% (v) max	50% (v) max
% D+L @ 350°C (E350)	90% (v) min	95% (v) min
Density	0.82 - 0.86 kg/dm^3	0.82 - 0.86 kg/dm^3
°C @ 90% D+L (T90)	N.A.	Undefined reduction simulated by exclusion of heaviest components

In accordance with standard practice, blending tolerances in the form of "safety margins" were superimposed on several of these specifications to compensate for imprecisions of measurement and for the day-to-day variability of blend qualities which an annually-based LP model does not predict.

Cetane was treated as a special case of this rule, in that the LP model input limits on cetane index were defined as numerically equal to the nominal cetane number specifications, i.e. no safety margin as such was specified. The rationale for this decision is based on the judgement that variability around the mean quality of “real world” production blends would be of the same order of magnitude (ca. 3 points of CN) as the upgrading potential available from the addition of ignition quality improver/ additive. Credit for the upgrading potential of the additive has in effect already been included and the levels of cetane number defined above are therefore the maxima obtainable with the processing packages identified by the study

Specifications on properties not included in the above table (e.g octane, cold properties, etc.) are as defined in CONCAWE's base case supply/demand planning documentation (ref. CONCAWE 1995, CONCAWE 1994 Planning Cycle - Base Case Supply/Demand Plans, Document No. 95/02, Brussels: CONCAWE)

For all STF-9 study cases the basic results consist of statements, for each refinery type, of material balances, product qualities, plant capacities and throughputs, investment and other costs, and refining energy consumptions. Overall carbon balances were also generated.

4. BASIS FOR REFINERY SIMULATION

The starting point for this study are the “CONCAWE 1994 Planning Cycle - Base Case Refining Supply/Demand Plans”. These were prepared by the CONCAWE Refining Planning Advisory Group covering the years 2000 and 2010 for a low growth and a high growth scenario, i.e. 4 “edge” cases, and were assembled with a full knowledge of AE/STF-9’s needs. These scenarios are intended to represent reasonable boundaries to the oil supply/demand outlook, but they are not in themselves forecasts.

4.1. DEMAND SCENARIOS

Low (LO) and a high (HI) road fuel demand scenarios for the years 2000 and 2010 have been derived by CONCAWE from the ADL scenarios and their underlying DG-XVII and 1991/2 actual sources. RPAG matched a low gasoline demand outlook with low diesel demand and a high with a high in order to define the LO and HI boundary outlooks for overall oil demand, respectively. The market demands and the production call on EU refineries are as follows:

EU Market demand for transportation fuels (Mt/yr)

	1991	2000		2010	
		LO	HI	LO	HI
Gasoline	108	115	125	110	140
Diesel fuel	91	100	125	120	150

Demand call on refineries excl. refinery fuel, losses and sulphur (Mt/yr)

	1991	2000		2010	
		LO	HI	LO	HI
Gasoline	117	125	135	120	150
Diesel fuel	91	100	125	120	150
Total oil demand	499	487	558	475	582

Base cases are fully documented by CONCAWE Document No. 95/02.

4.2. SUPPLY MECHANISMS

To model the refinery changes required for reformulation of the road fuels, the general approach taken is to require the same product demand on refineries to be met as in the base case. In the case of gasoline, the demand is defined in terms of constant transportation kilometres, thus making allowance for the lower heating value effects of oxygen and aromatics (i.e. carbon hydrogen ratio) contents. The only non-investment supply demand variable allowed is the use of the marginal crude oil. This is assumed to be high sulphur Middle East quality; Arab Heavy assay data are used. Imports of methanol as co-feedstock for refinery MTBE plants, and additional imports of MTBE, are also permitted but the investment and energy effects are taken account of outside the model.

This approach ensures that all the effects of reformulation are identified in terms of facilities requirements which can be costed in investment terms.

4.3. REFINERY CONFIGURATIONS

Four refinery configuration categories have been identified into which the 99 existing EU-12 refineries, with a total crude capacity of 610 Mt/yr., can be allocated.

The numbers of refineries in each category, their total crude oil capacities and the criteria for the categorization are:-

SIMPLE (32)**	**FCC (43)**	**HCU (14)**	**FCC & HCU (10)**
93 Mt/yr	**341 Mt/yr**	**82 Mt/yr**	**94 Mt/yr**
No FCC or HCU but may have visbreaker and/or coker	Must have FCC and no HCU	Must have HCU but no FCC	Must have both FCC and HCU
May have lubes	May have lubes	May have lubes	May have lubes
May have bitumen	May have bitumen	May have bitumen	May have bitumen
	May have RDS and other conversion	May have RDS and other conversion	May have RDS and other conversion

Note: FCC = Cat. Cracker, HCU = Hydrocracker, RDS = Residue Desulphurization

** N.B. Since 12 of the 32 simple refineries are sub-categorized as having no significant capability for road fuel production, only 20 refineries are considered in the simple category for investment evaluation purposes.

4.4. GASOLINE REFORMULATION MECHANISMS

Benzene to some extent can be reduced by lowering the benzene content of the reformate used (in the model) by selecting the reformer feedstock cut option with 85 deg C initial cut point rather than 65 deg C. This routes part of the benzene precursors to light naphtha/isomerization feed. However, reformer feed fractionation measures alone cannot reduce gasoline benzene content even as far down as 1% (v). To reach 0.5% (v) requires additional processing. The selected option, which can be applied in refineries of all configurations, is reformate splitting followed by light reformate benzene saturation and once through isomerization. The isomerization step is required because the saturation of benzene to cyclohexane results in the loss of some 18 octane points which can be compensated by the octane gain by isomerization of cyclohexane and paraffins in the hydrosaturated light reformate.

RVP can be controlled at the required levels by butane exclusion. This is a deconversion step which, as with some of the other side effects of reformulation, can be made up, for instance, by some additional increments of cat. cracking.

Oxygen content can be controlled by any of a number of approved high octane oxygenates. It is assumed here that MTBE would be used. In addition to the refinery MTBE capacity installed, it is assumed that 2 Mt/yr of non-refinery MTBE is available in Europe and is used in the base case. The additional MTBE required to meet a 2% (m) min requirement is assumed to be imported from worldscale grass roots plants associated with non-European gas fields. The level of imports implied is up to 15 Mt/yr.

Aromatics content could be reduced by reducing the proportion of reformate in the gasoline. All the other gasoline components have much lower aromatics contents and some are aromatics-free. As well as additional cat naphtha and imported MTBE, additional light naphtha isomerate, alkylate and refinery MTBE, as appropriate, can figure in the low aromatics cases.

Sulphur enters gasoline only with cat. cracked gasolines. If the cat. cracked gasoline is split into light (LCG) , medium (MCG) and heavy (HCG) fractions, it is found that the sulphur distribution is very predominantly weighted into the heavier cuts. To reach as low as 100 ppm (m) in a refinery with a cat. cracker requires the sulphur to be taken out of both the medium and the heavy cuts. Hydrodesulphurization of the heavy cut inevitably causes a 3 points octane reduction. The potentially somewhat larger octane loss from hydrodesulphurizing medium cat. naphtha can be regained by cat. naphtha reforming.

Because of concerns with data accuracy and calibration, the 90% D+L temperature (T90) of the gasoline is not represented in the LP model as a numerical specification. Back end distillation is controlled by selectively excluding the heavier components from the reformulated blends. Since there are no blending destinations other than gasoline for the excluded components, the process operating modes which generate them cannot appear in the optimized LP solution for a gasoline reformulation case. Specifically, the blending rules are as indicated in the table below:

COMPONENT	NOMINAL BOILING RANGE °C	BASE CASE BLEND	GASOLINE REFORMULATION
HEAVY CAT. GASOLINE	140-180	Allowed in blend	Allowed in blend
HEAVY CAT. GASOLINE	140-221	Allowed in blend	Not allowed in blend
REFORMATE FROM NAPHTHA FEED BOILING AT:-	65-155 85-155	Allowed in blend	Allowed in blend
	65-180 85-180	Allowed in blend	Not allowed in blend

The exclusion of the reformates made from feeds with a nominal end point higher than 155°C is to allow for the distillation "tail" effect of reforming, whereby the end point of the reformate is normally 25-30°C higher than that of the feed. These measures are roughly equivalent to a reduction of gasoline T90 from the typical EU level of approximately 165 deg C to about 155 deg C.

4.5. DIESEL FUEL REFORMULATION MECHANISMS

Sulphur can be reduced below 200 ppm (m) by high pressure (above 60 bar) hydrodesulphurization (HP HDS). A side effect is an increase in dearomatization which, comparing HP with LP HDS, improves cetane number of virgin gas oils by about 1 point and cat cracked gas oils by about 4 points

Cetane index control to very high levels requires a capability to process most of the diesel fuel components in a two-stage medium-pressure (50 bar) hydrodearomatization unit (MPHDA). Such units can improve the cetane number of virgin gas oils typically from about 53 to about 60, and cat. gas oils from approximately 12-15 to 23-29 (blending values). An alternative option available is single stage high pressure (100 bar) mild hydrocracking (HPHDA) applied to cat. distillate streams only. This offers the potential to improve cetane number of cat distillates to a level about 10 points above that which can be achieved by the 2-stage technology.

Back end distillation control, as with the T90 in gasoline, is achieved by excluding the heaviest cut point components from diesel (AGO) blends. In the diesel cases, however, the process operating modes which generate the heavier components are not necessarily excluded from the LP solution, since significant quantities of the rejected components can normally be accommodated in the heating gas oil (IGO). This is an important flexibility, which permits the thermal conversion units to stay on line in a diesel reformulation case. Blending rules for diesel reformulation are summarized in the following table.

COMPONENT	NOMINAL BOILING RANGE °C	BASE CASE BLEND	DIESEL REFORMULATION
HEAVY VIRGIN GAS OIL (HGO)	350-370	Allowed in AGO & IGO blends	Not allowed in AGO blend
MEDIUM CAT. GAS OIL (MCO)	350-370	Allowed in AGO & IGO blends	Not allowed in AGO blend
VISBROKEN & COKER GAS OILS	155-370 180-370	Allowed in AGO & IGO blends	Not allowed in AGO blend
IMPORTED GAS OIL BLENDSTOCK	155-370	Allowed in AGO & IGO blends	Not allowed in AGO blend

The exclusions are roughly equivalent to a 5 points lightening of diesel fuel E320, which would raise the EU typical level from about 80% to about 85%.

4.6. PROCESS UNIT INVESTMENT COSTS

The following table summarizes the investment costs of the principal types of unit required for reformulation:-

TYPE OF UNIT	CAPACITY Mt/yr	kB/CD	COST - M$
LOW PRESSURE REFORMER	0.876	20	95
HIGH PRESSURE REFORMER	0.876	20	80
REFORMATE SPLITTER	0.650	14	5
C5/C6 ISOMERIZATION - 0/T	0.219	5.8	20
C5/C6 ISOMERIZATION - RECYCLE	0.219	5.8	35
LT. REFORMATE ISOMERIZATION + BENZENE SATURATION	0.219	5.8	40
HCCG HYDROTREATER	0.900	20	50
MCCG REFORMING (revamp of existing reformer installation)	N.A.	N.A.	20 (per location)
ALKYLATION	0.182	4.5 (alkylate)	50
MTBE - refinery scale	0.051	1.2	10
- world scale	0.500	12	350
METHANOL SYNTHESIS - world scale	0.500	13	400
HP DISTILLATE HDS	0.730	15	90
CAT DISTILLATE HP HDA (incl. hydrogen generation)	0.730	15	120
TWO-STAGE MP HDA (incl. hydrogen generation)	0.730	15	100
CAT CRACKER	1.569	30	225
HYDROCRACKER - O/T	1.300	25	150
HYDROCRACKER - RECYCLE	1.300	25	210
HYDROGEN GENERATION	0.050	N.A.	50

4.7. REFINERY INVESTMENT ALLOCATION LOGIC

The LP runs indicate the amount of existing and new processing capacity utilized within each of the four refinery categories to meet a given quality package. However, since the real-world industry cannot operate with the same high degree of inter-refinery optimization as the mathematical model, it would be an over-simplification to estimate the costs of reformulation by calculating the number of logically-sized units required to provide the new capacity defined by the LP solution.

A realistic estimation of investment must be based on a logical analysis, with the LP output as the starting point, of the likely number and size of new process units needed in any particular case. This analysis reflects the three fundamental investment strategies which the industry might adopt if confronted with a requirement for severe reformulation.

These strategies have been called:-

> “Stand alone”, in which each refinery invests in whatever combination of new or expanded process units it needs to remain viable in a reformulated case. This may well mean that the refinery would become a member of a different category. For instance, the standalone strategy would require simple refineries to build cat. cracking capacity in order to meet the reformulated gasoline specification.
>
> ”Consolidate”, wherein the simple refineries shut down and replacement crude oil hydroskimming capacity is built at the complex refinery sites as required to meet the total oil demand. This strategy is relevant only to cases in which gasoline is to be reformulated, since in diesel-only cases the simple refineries do not face the prospect of shutting down to avoid a potentially uneconomic investment in a cat. cracker.
>
> “Network” where components are assumed to be traded between refineries of different configurations with consequent freight cost debits. This reduces, but does not eliminate the capital investment requirement.

These investment strategies have been expressed as a set of logic rules. These in turn define the decision criteria for a Lotus IMPROV program which has been designed to interrogate the LP-solutions and determine the numbers and sizes of new units in each case, and thence to calculate the cost implications.

Application of the logic of either of the first two strategies tends to generate an investment programme comprising a large number of new units at or close to the minimum practical size. With the network logic, the typical size of the new units becomes larger and the number to be built is rather smaller, since the assumed availability of unlimited transportation links provides the industry with the opportunity to share the costs of a few optimally-sized units among several refineries.

These investment strategies are described in further detail in **Section 6** "Discussion".

5. RESULTS

5.1. DIESEL REFORMULATED TO 55 CETANE

5.1.1. Investment

Investments have been evaluated separately for each demand scenario and year by three different methods, representing the three industry strategy options outlined in the foregoing **Section 4.7** (**Figures 1** and **2**). Investment requirements to satisfy the demand for oxygenates are separately identified (**Figure 3**). All investments are shown as increments for reformulation relative to the base case for the given year and demand scenario.

The total investment in new process plant by European refineries as well as in external suppliers of MTBE is listed below for each of the different investment philosophies. The required investment capital varies considerably as a function of refinery type and scope of reformulation.

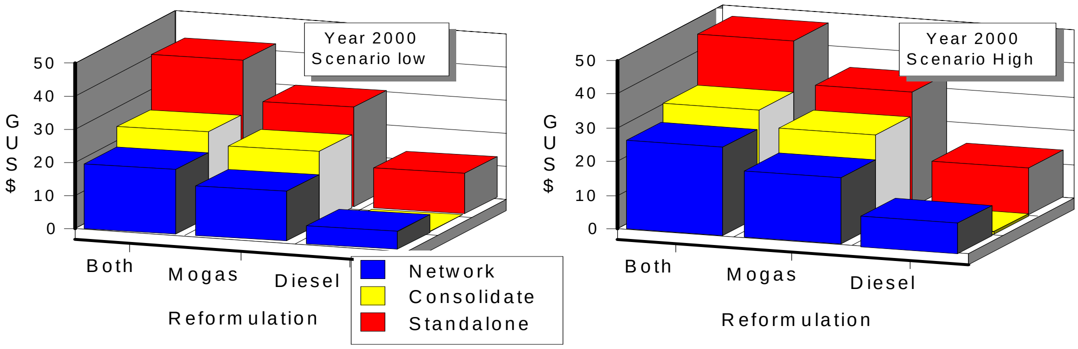


Figure 1 Investment requirements Year 2000 (55 cetane)

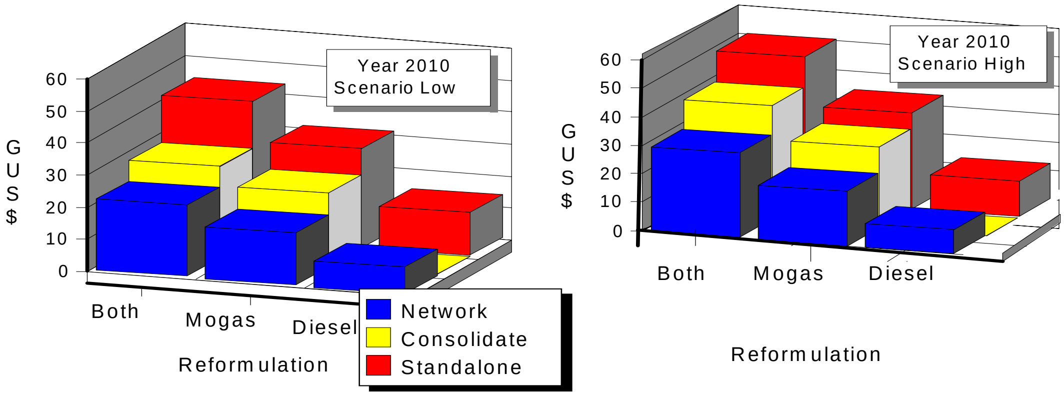


Figure 2 Investment requirements Year 2010 (55 cetane)

MTBE and associated methanol supplies are assumed to come from outside the European Union. The likely supply areas are the Middle East or other region where low cost gas is available in enough quantities to support investments in world scale MTBE facilities. All the incremental demand for MTBE is expected to be sourced from new facilities as sufficient marginal capacity will not be available in the wake of the introduction of US reformulated gasoline legislation. Significant capital investment, in the range of US $9-12 billion, will be required in any reformulation case which utilizes the maximum limiting amount of oxygen (2.8%) in the gasoline pool.

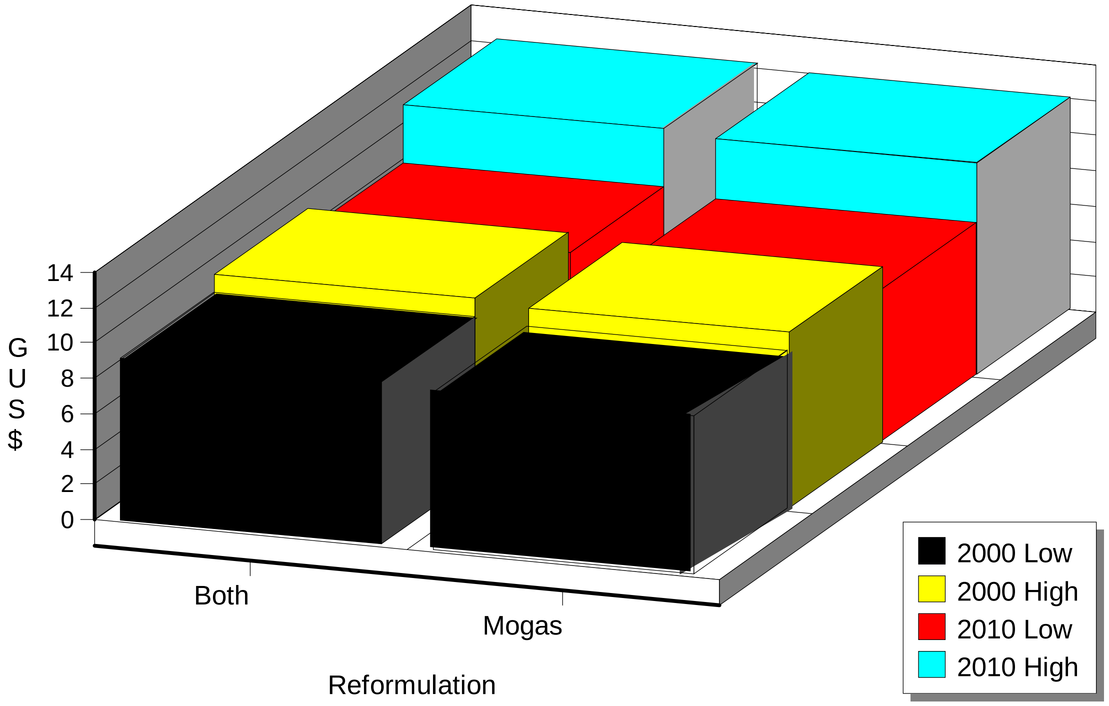


Figure 3. Investment Outside Europe (55 cetane) (MTBE and Methanol Plants)

5.1.2. Investment Summary

			2000		2010	
			Low	High	Low	High
Summary MUS$	**Internal Investments**	Both	**18,849**	**24,026**	**21,637**	**27,209**
		Mogas	**13,390**	**17,026**	**14,426**	**15,037**
		Diesel	**10,338**	**12,163**	**12,068**	**11,252**
	External Investment	Both	**9,119**	**10,213**	**8,891**	**12,148**
		Mogas	**8,908**	**9,909**	**8,621**	**11,920**
		Diesel	**0**	**627**	**1**	**(1)**
	Total	Both	**27,969**	**34,239**	**30,529**	**39,357**
		Mogas	**22,298**	**26,935**	**23,048**	**26,957**
		Diesel	**10,338**	**12,791**	**12,069**	**11,251**
Fixed costs MUS$ pa	**Total Fixed**	Both	**814**	**1,038**	**935**	**1,175**
		Mogas	**578**	**736**	**623**	**650**
		Diesel	**447**	**525**	**521**	**486**

The numbers in the preceding table are weighted average investments, based on STF-9's best judgement of the likely implementation levels of the three industry development strategy options. This judgement assigns a 25% weight to the Network strategy, 50% to Consolidate and 25% to Standalone.

However, in cases in which only diesel is to be reformulated, the weighting used is 25% Network and 75% Standalone, since the Consolidate approach has no meaning when gasoline is not reformulated.

5.1.3. Refinery own consumption and loss

The internal refinery self consumption will increase with increasing severity of reformulation. Refinery losses also increase due to expanded processing and more carbon will be rejected to atmosphere as a result of additional demand for hydrogen, which will have to be supplied by hydrogen generation plant. Reformulation of gasoline alone would lead to increases in own consumption plus loss, relative to the corresponding unreformulated base cases, in the range of 1.1 - 1.9 Mt/yr. For diesel-only reformulation the increase would be in the range 0.6 - 2.6 Mt/yr, and for a simultaneous reformulation of both fuels it would be 2.2 - 3.4 Mt/yr.

Consumption and loss data are shown as percentages of refinery intake in the following graphs.

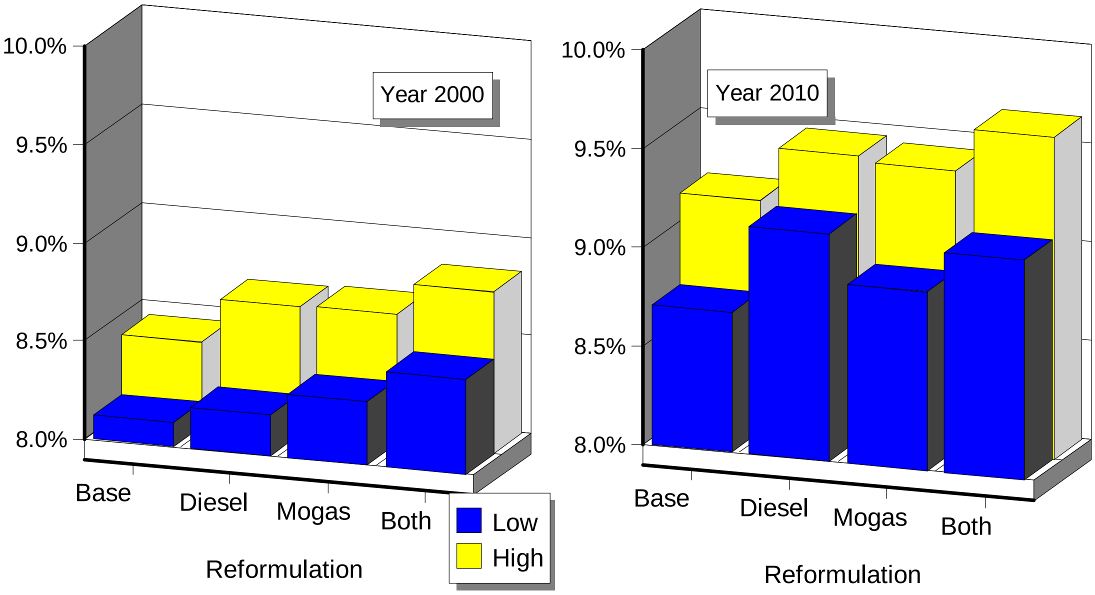


Figure 4 Refinery Own Consumption and Losses (55 cetane)

5.1.4. CO_2 Emissions

Analysis of the energy and material balances of EU refineries and external processing sources indicate that reformulation would generate increases in global emissions of CO_2 of 2.5 - 10.0 Mt/yr (diesel only), 2.9 - 6.0 Mt/yr for gasoline only, and 6.6 - 11.2 Mt/yr for simultaneous reformulation of both. To put these figures in perspective, it should be noted that total anthropogenic emissions of CO2 are currently between 25,000 and 30,000 Mt/yr., with some forecasters predicting an increase to over 40,000 Mt/yr by 2010.

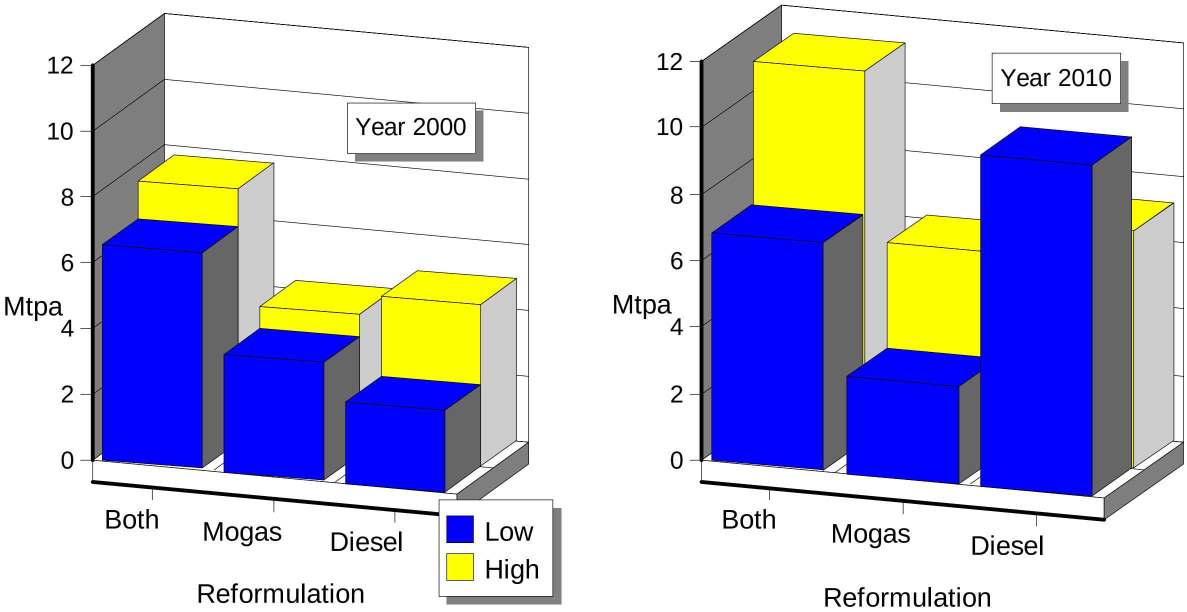


Figure 5 Increase in CO_2 Emissions (55 cetane)

5.1.5. Fixed Costs

Maintenance, operating labour and general other fixed overheads will increase due to the additional process units and the greater complexity of the plants. Maintenance cost have been estimated to be 3% per annum of the capital investment. Operating labour is estimated to 20% of the maintenance costs. General overheads are calculated as 20% of maintenance and operating labour costs. The weighted averages are estimated to range US $0.8 - 1.2 billion per year for simultaneous reformulation and US $0.5 - 0.7 for gasoline only and US $0.4 - 0.5 for diesel only reformulation. The ranges cover the different demand scenarios and years.

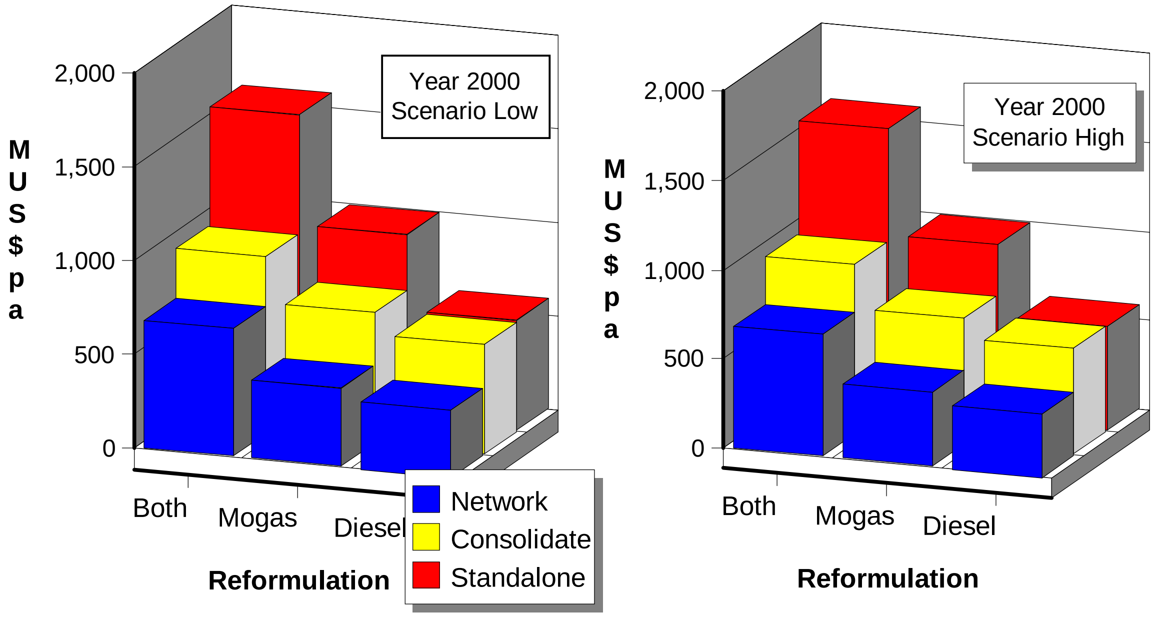
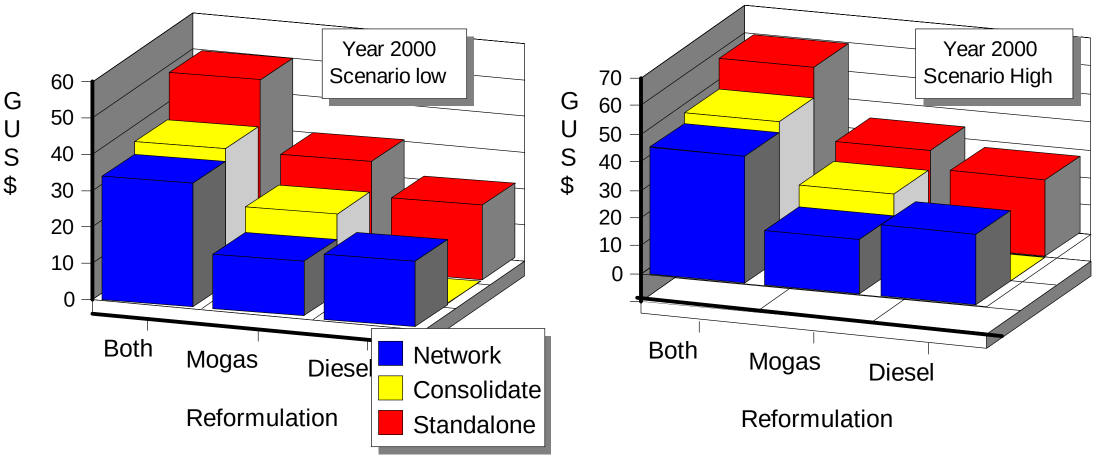


Figure 6 Increases in Fixed operating cost (55 cetane)

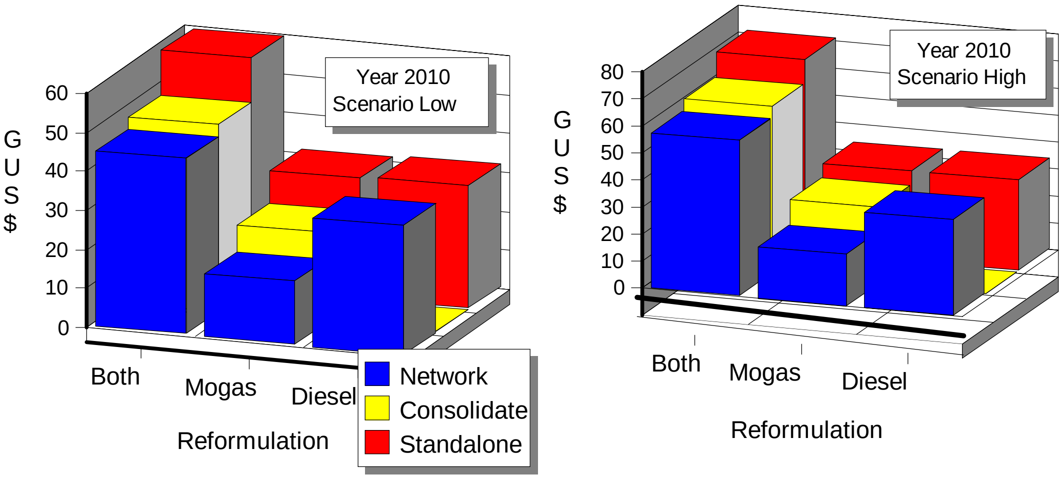
5.2. DIESEL REFORMULATED TO 58 CETANE

5.2.1. Investment

As for the 55 cetane study cases, which are summarised in **Section 5.1.1**., investments at 58 cetane have been evaluated separately for each demand scenario and year by three different methods, representing the three industry strategy options outlined in **Section 4.7** (**Figures 7** and **8**). Investment requirements to satisfy the demand for oxygenates are separately identified (**Figure 9**). All investments are shown as increments for reformulation relative to the base case for the given year and demand scenario.



Figures 7 and 8 **Investment requirements year 2000 and 2010 (58 cetane)**



As in the 55 cetane cases (see **Section 5.1**) incremental demand for MTBE is expected to be sourced from new facilities built outside the European Union. Significant capital investment, in the range of US $10 - 14 billion, will be required in any case which utilises the maximum amount (2.8%) of oxygen in gasoline.

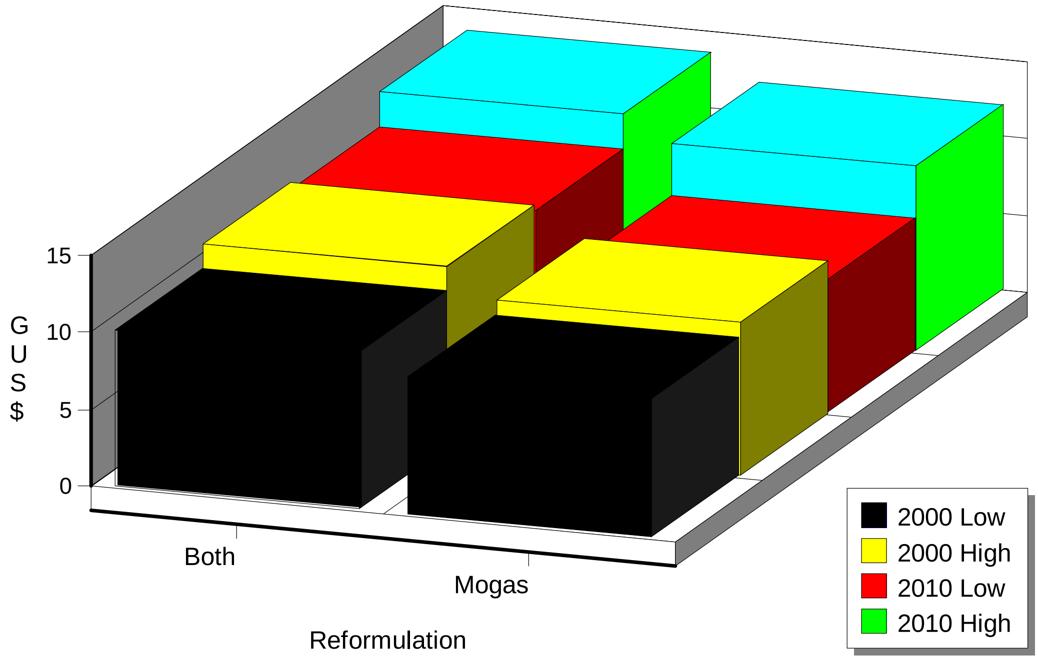


Figure 9. Investment Outside Europe (58 cetane)

5.2.2. Investment Summary

			2000		2010	
			Low	High	Low	High
nvestment ummary IUS$	**Total Internal Investments**	Both	**29,073**	**39,323**	**38,744**	**49,278**
		Mogas	**13,390**	**17,026**	**14,426**	**15,037**
		Diesel	**19,720**	**26,352**	**31,794**	**33,958**
	Total External Investment	Both	**10,158**	**11,693**	**11,250**	**13,520**
		Mogas	**8,908**	**9,909**	**8,621**	**11,920**
		Diesel	**1**	**(1)**	**0**	**(0)**
	Total	Both	**39,231**	**51,016**	**49,994**	**62,798**
		Mogas	**22,298**	**26,935**	**23,048**	**26,957**
		Diesel	**19,721**	**26,351**	**31,794**	**33,958**
ixed costs IUS$ pa	**Total Fixed**	Both	**1,256**	**1,699**	**1,674**	**2,129**
		Mogas	**578**	**736**	**623**	**650**
		Diesel	**852**	**1,138**	**1,373**	**1,467**

As for the 55 cetane cases, the numbers in the preceding table are weighted average investments. The basis for the weighting is as described in **Section 5.1.2.**

5.2.3. Refinery own consumption and loss

The internal refinery own consumption will increase with increasing severity of reformulation. Refinery losses also increase due to expanded processing and more carbon will be rejected to atmosphere as a result of additional demand for hydrogen, which will have to be supplied by hydrogen generation plant. Reformulation of gasoline alone would lead to increases in own consumption plus loss, relative to the corresponding unreformulated base cases, in the range of 1 - 2 Mt/yr. For diesel-only reformulation the increase would be in the range 8 - 12 Mt/yr and for a simultaneous reformulation of both fuels it would be 9 - 16 Mt/yr.

Consumption and loss data are shown as percentages of refinery intake in the following graphs.

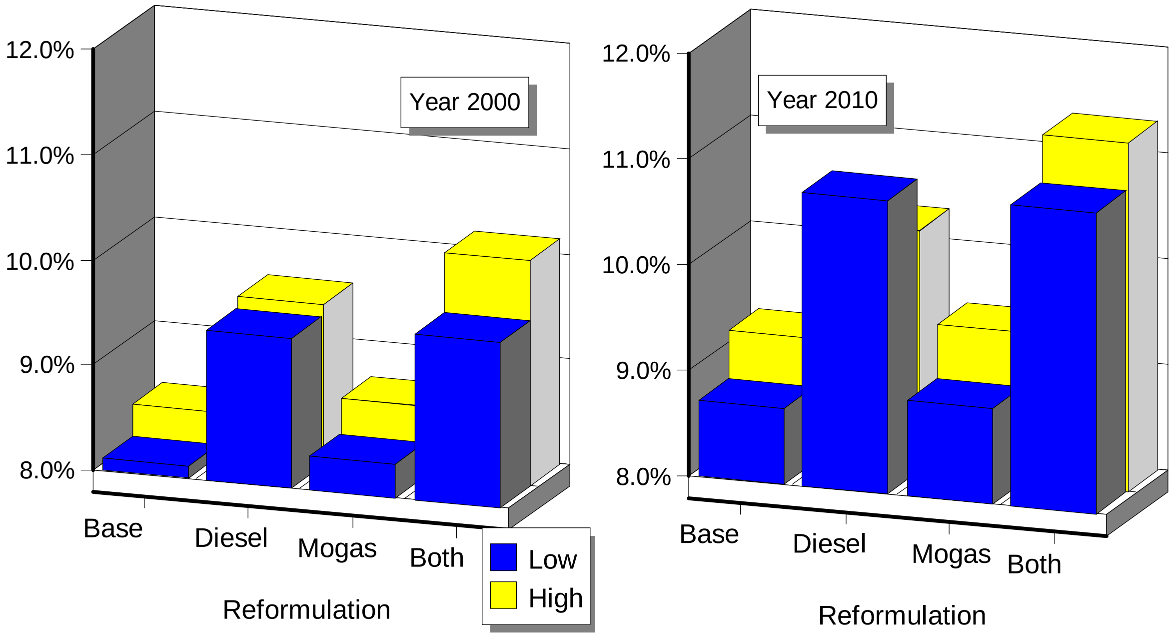


Figure 10 Refinery Own Consumption and Loss (58 cetane)

5.2.4. CO_2 Emissions

Analysis of the energy and material balances of EU refineries and external processing sources indicate that reformulation would generate increases in global emissions of CO_2 of 27 - 47 Mt/yr (diesel only), 3 - 6.0 Mt/yr for gasoline only, and 29 - 55 Mt/yr for simultaneous reformulation of both. To put these figures in perspective, it should be noted that total anthropogenic emissions of CO_2 are currently between 25,000 and 30,000 Mt/yr., with some forecasters predicting an increase to over 40,000 Mt/yr by 2010.

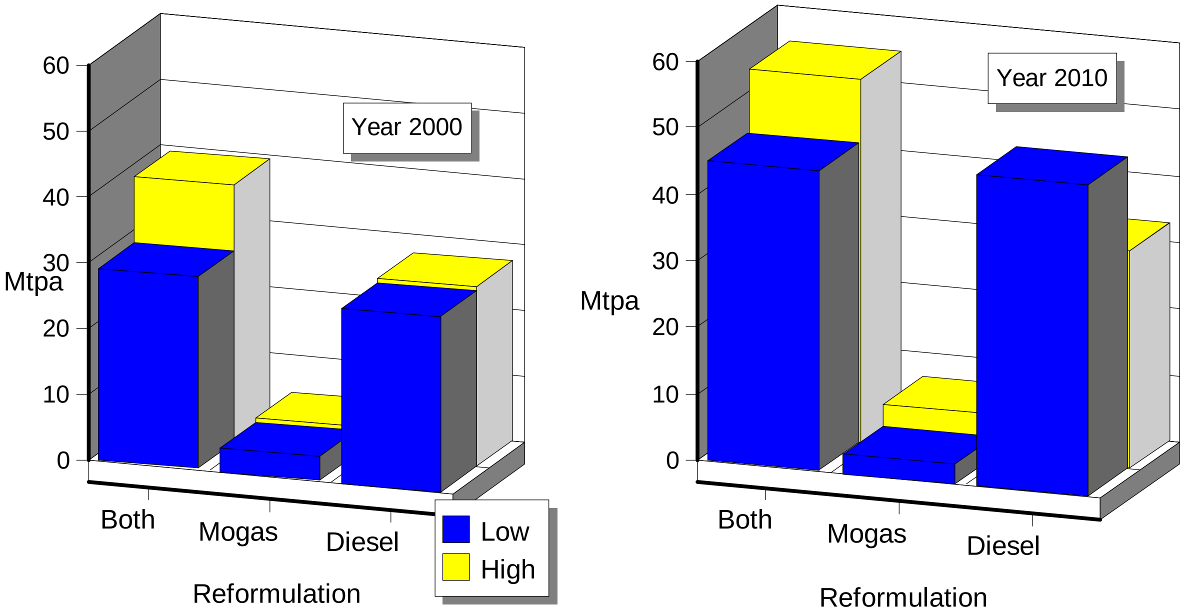


Figure 11 Increase in CO_2 Emissions (58 cetane)

5.2.5. Fixed Costs

The basis for estimation of fixed costs is as described in **Section 5.1.5.** The weighted averages are estimated to range US $1.2 - 2.1 billion per year for simultaneous reformulation and US $0.5-0.6 for gasoline only and US $0.9 - 1.5 billion for diesel only reformulation. The ranges cover the different demand scenarios and years.

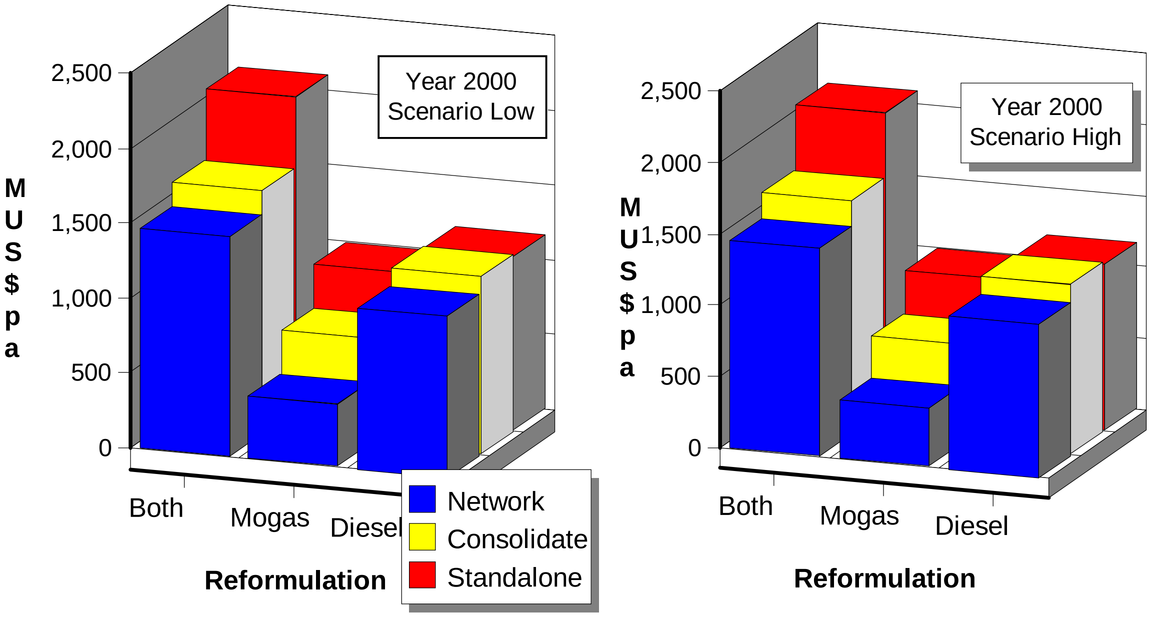


Figure 6 Increases in Fixed Operating Cost (58 cetane)

6. DISCUSSION

6.1. REFORMULATION COST IS A STRONG FUNCTION OF REFINERY CONFIGURATION

The high-octane gasoline components produced from catalytic reforming are highly aromatic in character and essentially sulphur-free, while those made in cat. crackers are not so aromatic, but more olefinic, and also contain significant levels of sulphur. The chemical composition of diesel blending components also varies widely depending on source. Straight-run components are basically paraffinic, but cat. cracked products in the diesel boiling range contain much higher proportions of ring compounds, and generally more sulphur. It follows that the measures required to reformulate these fuels with respect to aromatics content, sulphur and cetane number will reflect these differences in base composition, and for this reason the costs of a particular reformulation package differ markedly from one refinery type to another.

6.2. INTERPOLATION BETWEEN COST CURVES & PACKAGE EVALUATIONS REQUIRES CARE

As explained in **Section 3.3**, this study is designed to evaluate reformulation packages rather than to establish the shape of cost versus composition correlations. The concept of cost curves, charting the progressive increase in reformulation costs against the corresponding progressive reduction in emissions as a given individual quality constraint is tightened, is a simple one, but realisation of a set of meaningful cost curves could present some problems in practice, because in general, neither real-life refineries nor LP models have the necessary degrees of freedom to permit them to vary individually the qualities of a fuel blend. For example, attempts to simulate or manufacture an increase in diesel cetane may well produce a fuel blend for which not only cetane, but also density and boiling range differ from the base blend.

For this reason the cost of a reformulation package does not necessarily reflect the summation of the costs of the individual quality changes contained in the package. By the same token the cost of any individual quality cannot be deduced with certainty by comparing the costs of two or more different packages. In other words, reformulation costs should not be regarded as additive, given the scope for process and quality interactions, and the diversity of available quality correction mechanisms in a complex system such as a refinery. Caution must therefore be exercised in any comparison of package studies with cost curve studies.

6.3. PRODUCT QUALITY INTERACTIONS CAN INFLUENCE EMISSIONS EFFECTS

In the laboratory, the relationship between emissions of a given pollutant and any single parameter of fuel quality can be established with reasonable precision by blending up and testing a so-called orthogonal matrix of research fuel blends in which fuel quality parameters are varied one at a time, with all others held at a constant level. This procedure can be followed to eliminate the interactive contribution to emissions of quality parameters other than the one under study.

However as noted above in **Section 6.2**, each reported quality of gasoline and diesel is a complex function of fuel composition, and it is therefore virtually impossible in a refinery environment to make a change to any one parameter of fuel quality without affecting to some extent its other qualities. Furthermore, the refining adjustments required for reformulation of gasoline may well affect diesel quality, and vice versa. In evaluating the emissions impact and costs of any specific reformulation it is therefore necessary to take into account the potential contribution of such unintentional quality changes as well as those which the reformulation deliberately set out to achieve.

6.4. CONSEQUENCES OF GASOLINE REFORMULATION

6.4.1. Survival options for simple refineries - Standalone or network

The simpler refineries rely on catalytic reforming of naphtha as their major source of octane, and could not, as they stand, reformulate gasoline to the 25% max. specification on total aromatics postulated in this study. Even if they were to maximize imported MTBE content of their pool and expand isomerization capacity to process all available C5 /C_6 molecules from crude distillation, cat. reforming and visbreaking/thermal cracking, these refineries would be deficient in low-aromatics high-octane components, and would therefore be unable to make reformulated gasoline. To survive at 25% aromatics, simple refineries would need access to additional high-octane components which are manufactured only at cat. cracking refineries. This implies that each simple refinery would either have to build its own cat. cracker and substantially reduce reformer throughput, or set up a component exchange programme with a cat. cracking refinery, exporting perhaps about half of its reformate and/or reformer feed and importing replacement octane-tonnes in the form of cat. cracked naphthas and alkylates. If all simple refineries took the exchange route, refinery investment would be roughly only one third of that required to keep them all running, i.e. to follow the standalone route, but the total added logistics costs for the network strategy would probably be in the range of M$60/yr to M$90/yr.

The construction of a new cat. cracker at every one of the 20 gasoline-producing simple refineries in the EU would bring into existence some 15 Mt/yr of new FCC capacity, assuming that new units would be logically sized, at about 750-800 kt/yr on average, to match availability of cat. feed from crude. Most if not all of this new capacity would be surplus to EU requirements for boiling point conversion purposes, and would therefore spare an equivalent amount of the FCC capacity already installed in complex refineries. Upgrading simple refineries to cat. cracking status would necessitate investment not only in the cat. crackers themselves, but also in the secondary units required to process the FCC products, e.g. alkylation or MTBE plants at all locations, in distillate hydrodesulphurization at most locations, and, at 6 of the 20 sites, in new vacuum distillation capacity. An investment scenario in which ALL simple refineries would invest to survive independently appears to be rather unlikely since it is not only the highest investment option in any given year and demand outlook (see table in **Section 6.4.6** below), but would also severely erode refining margins at the existing cat. cracking sites.

The oil industry in general would therefore not find this scenario attractive. It is however, entirely conceivable that national governments of countries with a preponderance of simple refineries would wish to maintain a viable independent refining industry by upgrading at least some of their simple refineries to cat. crackers.

Surviving simple refineries, having eliminated their aromatics surplus, either by investing in cat. cracking or by exchanging components, would have to control the other quality parameters of the reformulated gasoline specification package, notably RVP, benzene, sulphur, back-end distillation and oxygen content in the same manner as the complex refineries, as discussed in the following **Section 6.4.3.**

6.4.2. Shutdown option for simple refineries - Consolidation

Any simple refinery unable to resolve its aromatics/octane imbalance by one of the methods described above would have no option but to shut down. If, in the extreme, it is assumed that all 20 of the existing gasoline-producing simple refineries were to shut down, about 87 Mt/yr of crude distillation capacity, accompanied by 15 Mt/yr, 15 Mt/yr, and 25 Mt/yr respectively of vacuum distillation, reforming, and distillate hydrodesulphurization, would be lost, together with a not insignificant proportion of the EU lubricants and bitumen capacity. Two countries of the EU would be left without a refining industry, and at least two other Member States would lose more than 18% of their existing crude capacity.

6.4.3. Implications for complex refineries if all simple refineries remain in operation- Standalone

6.4.3.1. Hydrocracking refineries without FCC

53 of the 67 complex refineries in the EU are equipped with cat. crackers, and 10 of these 53 have hydrocracking as well. However 14 of the 67 have a hydrocracker but no cat. cracker, and these 14 refineries would face the same aromatics surplus problem as the simple refineries if required to reformulate gasoline. It is assumed that all 14 of the hydrocracking refineries would remain in operation and would install cat. cracking capacity. The average logical size of these new cat. crackers, based on running all available vacuum gas oil feed surplus to hydrocracker feed requirements, would be somewhat smaller, at approximately 500 kt/yr, than the average size built at the simple refineries. Associated alkylation, MTBE, and distillate hydrodesulphurization capacity would be needed, but additional vacuum distillation capacity would not in general be required.

6.4.3.2. Cat. cracking refineries

As discussed above, a 25% vol max aromatics specification would impose an upper limit of around 20-30% on reformate content of the gasoline pool at all refineries. Once the simple and hydrocracking refineries had been modified to meet this constraint as described above, major differences in composition between the pools of the original four basic types of refinery would be reduced, and all surviving refineries would have a component pool rather similar to that of the original FCC category.

The set of process additions required to reformulate RVP + benzene + sulphur + oxygen + olefins + back-end volatility is therefore virtually common to all refineries, as follows:-

60 kPa max RVP is met by reducing butane content of the blend. Incremental cat cracking plus some form of C4 oligomerization process are required to make good the octane-to-fuel downgrading effect of RVP reduction at constant gasoline and LPG demand.

0.5% vol max benzene is met by installing at all refineries a new processing train comprising (a) reformate splitting to segregate a light benzene-rich fraction, (b) hydrogenation of the light reformate to saturate the benzene to cyclohexane and (c) isomerization of the hydrosaturated light reformate. All refineries in addition require to invest in conventional superfractionation and isomerization capacity to maximize octane upgrading of all available virgin C_5/C_6 streams.

100 ppm max. sulphur is met by installing hydrotreating capacity to achieve a 90% desulphurization of the heaviest fraction of cat. cracked naphtha, which, at 2500-3000 ppm in an untreated state, is the principal contributor of sulphur to the blend.

2.0% wt min oxygen is met by investing in plants to synthesize MTBE from purchased methanol and refinery butenes surplus to alkylation feed requirements, and importing the balance of MTBE from sources outside the EU with access to large quantities of natural gas field butanes. The investment in world-scale MTBE plants at the gas fields has been estimated separately from the EU refining industry's own internal investments.

20% max olefins would be met if all of the foregoing process additions were installed together with the new alkylation capacity which would be installed with the new cat. crackers at the former simple and hydrocracking refineries for octane balancing purposes

In the STF-9 simulation model, back-end volatility is limited by excluding from the gasoline pool all components with a nominal TBP end-point of 180 deg. C or higher.

The typical refinery, revamped for reformulation as summarized above, also requires investment in hydrogen generation capacity to make good the net deficiency caused by reduction in reformer utilization and increased demands for benzene saturation, isomerization and cat. naphtha hydrotreating operations

6.4.4. Implications for complex refineries if all simple refineries remain in operation- Network

In a strategy of maximum inter-refinery product transfer, the investment package required at the complex refineries contains most of the same types of units as in the standalone situation. The new units are however much fewer in number, and typically larger in size, since new capacity is built only as required to close the material balance of the total refining system as an optimized entity.

Thus spare capacity in one refinery category can be utilized to eliminate new investment in the same process within a different category.

6.4.5. Implications for complex refineries if all simple refineries were shutdown - Consolidation

The hydrocracking refineries build cat. crackers, as described in **Section 6.4.3.1.** above. All surviving refineries thus become cat. cracking refineries and all therefore need to invest in the kind of processing package described above in **Section 6.4.3.2.** In addition, substantial amounts of atmospheric and vacuum crude distillation, distillate hydrodesulphurization, lubricants and bitumen capacity must be built to replace that lost with the demise of the simple refineries and speciality plant.

6.4.6. Cost Comparison - Standalone vs Consolidation vs Network

The table below summarizes investment costs within EU refineries for reformulating gasoline only, under the assumption that all 20 simple refineries would, as a group, invest to survive, shut down, or survive by octane components exchange. These data have been extracted to illustrate how the total cost of gasoline reformulation in the EU varies according to the option taken by the simple refineries. External investment to manufacture MTBE for importation into the EU is excluded from the following table.

EU REFINERY INVESTMENT -G$				
Gasoline reformulation in year:	**2000**		**2010**	
Demand outlook	LOW	HIGH	LOW	HIGH
"STANDALONE" All simple refineries invest in FCC	21.0	23.9	22.2	21.4
"CONSOLIDATE" All simple refineries shut down	13.2	17.4	14.0	15.8
"NETWORK" Maximize inter-refinery product exchange	6.2	9.6	7.5	7.2
(plus annual logistics costs for "NETWORK" option)	<0.1	<0.1	<0.1	0.1

6.5. DIESEL REFORMULATION

6.5.1. Options for cat. cracking refineries - Standalone

The middle distillates or light cycle oils (LCO) produced by the catalytic cracking process are characterized by higher densities, and much lower cetane numbers, than the straight-run or hydrocracked distillates of corresponding boiling range. Consequently, cat. cracking refineries would have much greater difficulty than simple or hydrocracking refineries in making diesel at the levels of 55 and 58 cetane index which were specified for the diesel reformulation cases in this study. Conventional distillate hydrodesulphurization processes, operating at pressures up to 70 bars or so with cobalt/molybdenum catalyst, have but a small influence on cetane, typically providing an upgrading of 3-5 cetane numbers at best on most cat. cracked distillate blends.

Cat. cracking refineries without hydrocrackers would therefore have to invest, in all diesel reformulation cases studied, in a more sophisticated form of process for upgrading cetane. This study assumes the availability of two investment options for hydrodearomatization (HDA) of cat. cracked distillates, namely :-

> Medium pressure two-stage HDA, operating at 50 bar pressure and utilizing a noble metal catalyst in the second reactor, which reduces the sulphur level of unconverted LCO to less than 10 ppm, while typically raising its cetane index to a level close to 30.
>
> High pressure single-stage HDA, operating at 100 bar. This unit can boost the cetane index of LCO to over 40, while simultaneously removing more than 99.9% of the sulphur.

A third investment option, at cat. cracking refineries with vacuum gas oil available in excess of cat. cracker feed requirements, would be to build a conventional hydrocracker to run in parallel with the cat. cracker, converting surplus vacuum gas oil into low-sulphur, high-cetane distillate blending component. Of the 43 cat. cracking refineries which do not now have a hydrocracking capability, approximately one third would be large enough to provide feed for an economically-sized hydrocracker

Hydrocrackers could also be used to upgrade some of the heavier cat. cracked and virgin distillate streams, in the 350/370°C boiling range, which would otherwise have to be downgraded from diesel to fuel in order to meet the reformulated diesel specification of 95% min D+L at 350°C.

Given that hydrogen consumption in the hydrocracking and hydrodearomatization processes is between 2% and 4% by weight on unit feed, the addition of either of these processes to an existing cat. cracking refinery would almost certainly increase the demand for hydrogen treat gas to a level beyond the capability of its catalytic reformer to supply. Since opportunities to achieve economies of scale by inter-refinery transfers of hydrogen are rather rare, it would probably be necessary to install a new hydrogen generation facility at each cat. cracking refinery as part of a cetane upgrading project.

In general the desulphurization effect of any hydrocracking or/and HDA capacity which a refinery might install for cetane control would not be sufficient *per se* to meet a reformulated sulphur specification of 200 ppm on diesel. This is because less than 25% of the EU's existing distillate hydrodesulphurization (HDS) capacity is rated at high (70 bar) pressure, and the remaining low and medium pressure units can leave up to 2000-3000 ppm sulphur in the straight-run distillates from Middle East crudes, and up to 6000 ppm in thermally-cracked distillates.

Essentially all refineries would therefore need to expand, or build new, 70 bar HDS units to meet a 200 ppm sulphur specification.

6.5.2. Options for simple and hydrocracking refineries - Standalone

6.5.2.1. Diesel reformulation at 55 cetane

Unlike the "pure" cat. cracking refineries described above, the simple and hydrocracking types of refinery would not, in every case, need to build HDA units to meet a diesel specification of 55 cetane. At moderate levels of diesel demand, both these refinery categories would be able, at least in theory, to optimize their distillate blending to meet this cetane level. However, since highly-hydrodesulphurized Middle East straight-run gas oils are the only components available to them with cetane indices higher than the 55 minimum diesel specification, their ability to do so in practice would depend on the extent to which they could selectively segregate these premium components into diesel blends. If they were able by selective blending to avoid installing HDA processes, these refineries' only investment requirement for diesel reformulation (at 55 CI and moderate levels of demand) would be in high pressure distillate HDS for sulphur control at 200 ppm as discussed in **Section 6.5.1** above However, if diesel demand were to increase as projected in the high growth demand scenario, all categories of refinery would by 2010 require some of the more sophisticated HDA type of processing as well.

Assuming that gasoline reformulation were not simultaneously mandated, simple and hydrocracking refineries in general would probably be able to maintain a positive hydrogen balance through the early years of a 55 CI diesel reformulation programme by continuing to run their catalytic reformers at or near maximum capacity. Investment in new hydrogen manufacturing facilities could thereby be deferred until growth in diesel demand necessitated the installation of HDA processing. But it should be noted that a study of this type cannot examine specific refinery situations, and that this general statement might not apply at every individual plant location.

6.5.2.2. Diesel reformulation at 58 cetane

If the cetane requirement in the diesel reformulation package is increased from 55 to 58, the cost of diesel reformulation increases by a factor of 2 to 2.5. Even if the simple and hydrocracking refineries had the stream segregation flexibility described in **Section 6.5.2.1.**, their highest quality components would not be good enough to go into a 58 CI diesel blend without severe hydrogenation. In every demand scenario, all refineries have to invest heavily in MPHDA or HPHDA, since a high proportion of all available diesel components, both cracked and straight-run, require this intensity of treatment to meet a diesel specification of 58 cetane index.

6.5.3. Diesel component exchange - Network

The processing requirements for diesel reformulation, as described qualitatively in **Sections 6.5.1** and **6.5.2** above, assume that each refinery category would continue to meet an invariant demand mix, solving its own problems by investment. To the extent that cat. cracking refineries could adjust their diesel/heating gas oil/gasoline production ratios, and/or exchange LCO for virgin and hydrocracked distillate components from other refinery types, the total investment requirement for the EU could in theory be reduced, as in the case of gasoline reformulation.

In a 55 CI reformulation case, the EU investment under a 100% network strategy would be one half to two-thirds of the investment required on a standalone basis. However, in all 58 CI reformulations, adoption of a network strategy would achieve little if any savings by comparison with the standalone strategy. This is because, in the base case without investment in HDA, there are no streams available at any refinery with cetane indices above 58. There are therefore essentially no opportunities for trading off low cetane for high cetane components between refineries.

The investment analysis indicates that as cetane index specification is increased from 55 to 58, the investment cost of diesel reformulation under the network strategy increases by a factor of 3 to 4.

6.5.4. Consolidation logic is invalid in diesel-only reformulations

As noted in **Section 4.7**, the logic of the consolidation strategy is not relevant in a diesel-only reformulation case.

6.5.5. Cost comparison - Standalone vs Network (55 cetane)

The table below summarizes investment costs within EU refineries for reformulating diesel only, at the 55 CI level, under the assumption that all existing refineries would invest in facilities as described in **Sections 6.5.1** and **6.5.2** above and continue to operate, (a) without component and product exchange, or (b) with theoretical networking among refineries of different types. External investment to manufacture MTBE for importation into the EU, which is essentially negligible in a diesel reformulation case, is excluded.

EU REFINERY INVESTMENT - G$				
Diesel reformulation at 55 CI in year:	**2000**		**2010**	
Demand outlook	LOW	HIGH	LOW	HIGH
"STANDALONE" All simple refineries invest in FCC	11.9	13.4	13.3	12.3
"NETWORK" Maximize inter-refinery product exchange	5.6	8.3	8.4	8.0
(plus annual logistics costs for "NETWORK" option)	<0.1	<0.1	<0.1	0.1

6.5.6. Cost comparison - Standalone vs Network (58 cetane)

The table below summarizes investment costs within EU refineries for reformulating diesel only, at the 58 CI level, in the same format and on the same bases as the preceding table. External investment to manufacture MTBE for importation into the EU is excluded.

EU REFINERY INVESTMENT - G$				
Diesel reformulation at 58 CI in year:	**2000**		**2010**	
Demand outlook	LOW	HIGH	LOW	HIGH
"STANDALONE" All simple refineries invest in FCC	20.3	26.8	31.4	33.5
"NETWORK" Maximize inter-refinery product exchange	18.0	25.0	33.1	35.4

Added annual logistics for the 58 CI case have not been estimated, in view of the facts that the network strategy offers no investment cost advantage over the standalone case, and that the added logistics costs would be insignificantly small, given the extremely limited scope for inter-refinery component trading at a specification of 58 cetane

6.6. GASOLINE AND DIESEL REFORMULATION

6.6.1. Simple refineries invest to survive - Standalone

All 14 hydrocracking refineries, together with those simple refineries which elected for the investment option outlined in **Section 6.4.1.,** would install a cat cracker and the other elements of the gasoline reformulation investment package described in **Section 6.4.3.2**. All surviving refineries would therefore face the same kind of diesel reformulation problems as the original cat. cracking refineries, as described in **Section 6.5.1**. above, and would in general all need to invest in HDA plus hydrogen generation plus distillate HDS capacity. In addition, up to 15 of the 43 original FCC refineries could install hydrocracking.

6.6.2. Simple refineries shut down - Consolidate

The investment requirement for cat cracking at the simple refineries would be avoided, but the loss of hydroskimming capacity represented by the shutting down of 20 simple refineries would have to be made good by investment at the surviving complex refineries, as described in **Section 6.4.2.**

6.6.3. Component exchange maximized - Network

As in the gasoline reformulation situation, total processing investment could be minimized by maximizing inter-refinery exchanges of problem components. This would require the simultaneous operation of an octane component exchange network as described in **Section 6.4.4**., and a diesel component network as described in **Section 6.5.3.**

6.6.4. Cost comparison - Standalone vs Consolidation vs Network (55 cetane)

The table below summarizes investment costs within EU refineries for reformulating gasoline and diesel (at 55 CI) simultaneously, under the assumption that all 20 simple refineries would, as a group, invest to survive, shut down, or survive by inter-refinery trading of components for gasoline and diesel. External investment to manufacture MTBE for importation into the EU is excluded.

EU REFINERY INVESTMENT - G$				
Diesel reformulation at 55 CI in year:	**2000**		**2010**	
Demand outlook	LOW	HIGH	LOW	HIGH
"STANDALONE" All simple refineries invest in FCC	32.4	36.5	34.0	37.8
"CONSOLIDATE " All simple refineries shut down	16.4	21.9	19.6	26.9
"NETWORK" Maximize inter-refinery product exchange	10.3	15.9	13.3	17.3
(plus annual logistics costs for "NETWORK" option)	0.2	0.2	0.2	0.2

6.6.5. Cost comparison - Standalone vs Consolidation vs Network (58 cetane)

The table below summarizes investment costs within EU refineries for reformulating gasoline and diesel (at 58 CI) simultaneously, under the same assumptions as for the table immediately above. External investment to manufacture MTBE for importation into the EU is excluded.

EU REFINERY INVESTMENT - G$				
Diesel reformulation at 58 CI in year:	**2000**		**2010**	
Demand outlook	LOW	HIGH	LOW	HIGH
"STANDALONE" All simple refineries invest in FCC	39.4	48.2	47.8	57.1
"CONSOLIDATE " All simple refineries shut down	26.6	37.7	36.8	47.9
"NETWORK" Maximize inter-refinery product exchange	23.6	33.8	33.6	44.1
(plus annual logistics costs for "NETWORK" option)	0.2	0.2	0.2	0.2

6.6.6. Synergistic & antagonistic processing interactions

The investments for the simultaneous gasoline and diesel reformulation cases are, in general, equal to or somewhat lower than the sum of the investments calculated for separate reformulations of the two fuels in corresponding scenarios. The apparent synergy represents the net resultant of several contributory factors, the individual effects of which cannot readily be separately quantified by analysis of the LP results, given the complexity of the system being simulated. Among those which can be identified in qualitative terms, the factors promoting synergism include:

6.6.6.1. Modelling effects

The tendency of the LP model to minimize added capacity requirements, which is a consequence of its inbuilt flexibility to optimize operations of all refineries of a given type as if they were a single unit.

The implicit assumption within the LP model simulation of steady state operation on an annual basis, with no day-to-day scheduling problems or seasonal variations in product demand to be met.

These two are technical effects of the planning tool employed in the study. The undefinable degree of over-optimization which they contribute would not be achievable in a real-world industry situation, in which 99 refineries are in mutual competition under variable logistical and economic conditions

6.6.6.2. Material & energy balance effects

The import of large volumes of MTBE into the EU, as projected in all the gasoline and combined reformulation cases, would have the effect of reducing total crude runs in such cases relative to corresponding base (unreformulated) and diesel cases. Any such replacement of marginal crude by MTBE has the effect of reducing the refinery's desulphurization load, and hence its demand for hydrogen, relative to the base case. This hydrogen effect may be taken as a credit for combined reformulation versus the corresponding diesel-only reformulation. It is not, however allowed as an investment credit for gasoline-only reformulation versus a non-reformulated base case, since the study groundrules include the principle that investments made to realise the base case in any given year cannot be recouped by a subsequent decision to reformulate. (i.e. no credits may be taken for so-called "regret investment"). The application of this logic can generate a large degree of apparent synergism between gasoline and diesel reformulation cases.

6.6.6.3. Scale effects

In the "standalone" investment environment, in which all refineries survive and invest individually, some economy-of-scale effects are probably at work, to make the average $/t/yr cost of new capacity somewhat lower in the combined reformulation case than in reformulation of either fuel individually

For the reasons given above, the present study does not conclusively confirm or refute the conjecture, tentatively put forward in STF-9's earlier qualitative "early warning" study, that because of the mutual reinforcement of negative hydrogen balance effects simultaneous reformulation would have a more severe impact than the additive sum of separate gasoline and diesel reformulations.

7. RAW MATERIAL UTILIZATION IMPLICATIONS

7.1. OVERALL SUPPLY/DEMAND EFFECTS

In any given study scenario the basic crude slate and the product demand slate are fixed. The only variations permitted in the input/output balance of the EU refining circuit as a whole are as follows:

MTBE imports vary as defined by the specifications for oxygen content of gasoline.

Gasoline demand in tonnes/yr varies to maintain the energy content of the pool constant despite compositional changes.

Refineries' own consumption plus loss varies with intensity of processing.

Arab Heavy crude input varies as required by material balance.

Output of by-products, e.g. sulphur, varies as a resultant of above changes.

The substitution of MTBE for Arab Heavy crude in gasoline reformulation cases may be up to 10-12 Mt/yr. A change of this magnitude in refinery feedstock composition has a profound impact on the type and amount of processing additions required in any particular scenario.

7.2. INTERNAL CONSUMPTION AND LOSS

As shown in "Results" **Sections 5.1.3** & **5.2.3**., between 8% and 8.5% of refinery input in the 2000 base cases is either consumed as refinery fuel or leaves the refinery as "zero-value" products. These figures also indicate that severe simultaneous reformulation could increase this figure by 1.5 to 2 percentage points.

8. CO_2 EMISSIONS EFFECTS

All of the reformulation scenarios studied would increase global emissions of CO_2 to some extent. The magnitude of the increase in any given case is readily calculable from a knowledge of the hydrocarbon inputs, on a global basis, and of their respective carbon contents. For example, for each incremental tonne of Arab Heavy crude processed, 0.86 tonnes of carbon, contained in 3.15 tonnes of CO_2, will eventually find its way into the atmosphere via the combustion of fuel products and refinery fuel made from that crude increment. Similarly, the net carbon emissions associated with each marginal tonne of MTBE in total refinery feedstock can be calculated, taking into account the overall stoichiometry of the natural gas/methanol/MTBE synthesis process.

The increase in global CO_2 emissions attributable to transportation fuels' reformulation, including diesel at 55 cetane index, could be up to about 11 Mt/yr. However, if the diesel were to be reformulated to 58 CI, the global CO_2 emissions in 2010 could be 55 Mt/yr higher than in the unreformulated base 2010 case. To put these figures in perspective, it should be noted that total anthropogenic emissions of CO_2 are currently between 25,000 and 30,000 Mt/yr, with some forecasters predicting an increase to over 40,000 Mt/yr by 2010.

9. CONCLUSIONS

The cost of transportation fuels' reformulation is highly dependent on refinery configuration. Refineries without cat. cracking would not be able to meet a 25% maximum aromatics limit in gasoline. Refineries with cat. cracking would have to invest in sophisticated hydrogenation plant to permit meeting a 55 cetane index specification, or export a large proportion of their cat. cracked distillate components.

It follows from the previous conclusion that in a severe simultaneous reformulation of both fuels, the processing mix at most surviving refineries would tend to develop into a uniform configuration, containing cat cracking, hydrocracking and/or distillate hydrogenation, light reformate splitting and isomerization, benzene saturation, cat. naphtha desulphurization and hydrogen generation.

The real world response of the EU oil industry to a requirement for universal severe gasoline reformulation, whether alone or in combination with a diesel reformulation, would be a mix of three strategies, probably in the following order of preference :-

Network Strategy. To the extent possible, develop programmes for inter-refinery trading of "problem" components, to minimize investment exposure at very uncertain levels of return.

Consolidation Strategy. Shut down those simple refineries for which adequate exchanges could not be practicably or economically set up, and where no government or shareholder support were forthcoming for upgrading them to FCC status. Replace lost crude capacity as necessary with new or expanded hydroskimming trains at some existing FCC refineries. Invest at all surviving refineries in processing packages required for reformulation of the specified transportation fuels.

Standalone Strategy. Upgrade all the remaining simple refineries to FCC status. Invest at all surviving refineries in processing packages required for reformulation of specified transportation fuels.

Similarly the real world response to a severe diesel reformulation (without an accompanying gasoline reformulation) would be to trade components to the extent possible, and to invest in hydrogenation processing at those refineries unable to solve their diesel quality problem by inter-refinery transfer of components. The investments quoted in the following paragraphs are best judgement weighted averages, based on the costs of implementing a mix of the strategies described above.

The investment cost of implementing throughout the EU a severe gasoline reformulation package, comprising 0.5% benzene, 25% aromatics, 10 kPa reduction in average RVP, 100 ppm sulphur, about 10°C reduction at 90%D+L and 2.0% minimum oxygen content, would probably be in the range between G$20 and G$25. About G$9-12 of the total investment would be made in world-scale MTBE plants outside the EU.

Severe reformulation of EU diesel fuel in terms of 55 cetane index, 200 ppm sulphur content and a reduction of about 5%D+L @ 320°C would probably require investments in the range of G$10-13, all of which would be made by European refineries.

The investment cost of simultaneously implementing the above reformulations of gasoline and diesel is estimated to be in the range of G$30-40, depending on level of demand. In the combined reformulation, processing synergies and antagonisms would occur, but the net cost effect of these appears to be neutral.

The incremental investment cost per unit of cetane improvement increases very sharply above 55 CI Including a 58 cetane index specification in the diesel reformulation package instead of 55 increases costs to G$20-35 for diesel alone, and G$40-60 for simultaneous reformulation of both fuels.

Refineries' energy consumption, as a percentage of input, would increase with increasing severity of reformulation. Losses would also increase, largely because increasing demand for hydrogen would be met at the margin by the steam reforming process, which rejects to atmosphere a large proportion of the carbon content of its light hydrocarbon feed. Own consumption and loss in EU refineries could rise from about 8% of total input in the 2000 base case to over 11% for the most severe 2010 reformulation case.

Each of the reformulation options considered would generate a net increase in global emissions of CO_2. By 2010, this increase could in the worst case amount to over 55 million tonnes per year.

Severe reformulation of gasoline throughout the EU, whether alone or in combination with a diesel reformulation, would necessitate very large imports of MTBE or some equivalent high octane oxygenate into the Union. The volume of imports required could be up to 14 million tonnes per year by 2010, i.e. about seven times the amount assumed purchased from outside sources to meet currently foreseen demand and quality of gasoline in 2000.

The costs of applying reformulation legislation to only a portion of the EU's transportation fuels pool, e.g. by selectively targeting specific cities or local areas, would be lower on a pro rata basis (cost per tonne) than the costs for the corresponding reformulation on the total pool as published herein. The fundamental restructuring of the refining industry, which this study identifies as an inevitable consequence of Union-wide severe simultaneous reformulation, would not be required for reformulation to the same qualities on a localized scale.

The cost of a reformulation package is not necessarily equal to the sum of the costs of the same set of product quality adjustments individually, or sequentially on a stepwise basis. Extreme caution should be exercised in any comparison of a reformulation package evaluation with a cost curve evaluation

Assessment of the cost-effectiveness of any reformulation package as an emissions control measure must take into account the product quality interactions which are inevitable in a real-world refining environment

List of Appendices

The following appendices containing numerical data are available on request from CONCAWE.

APPENDIX I STUDY 1 (WITH 55 CETANE INDEX) ANALYSIS OF DATA

I .A.1-12	Standalone Refinery Investment Analysis	12 Pages
I. B.1-12	Industry Consolidation Investment Analysis	12 Pages
I. C.1-2	Networking Industry Investment Analysis	2 Pages
I. D.1-5	Investment in Process Units	5 Pages
I. E.1-4	Fixed Cost Increase	4 Pages
I. F.1-8	Material Balance	8 Pages
I. G.1-6	Unit Utilization	6 Pages
I. H.1-16	Product Qualities	16 Pages
I. I.1-4	Consumption and Losses	4 Pages
I. J.1-4	CO_2 Emissions	4 Pages

APPENDIX I I STUDY 1I (WITH 58 CETANE INDEX) ANALYSIS OF DATA

II.A.1-12	Standalone Refinery Investment Analysis	12 Pages
II. B.1-12	Industry Consolidation Investment Analysis	12 Pages
II. C.1-2	Networking Industry Investment Analysis	2 Pages
II. D.1-5	Investment in Process Units	5 Pages
II. E.1-4	Fixed Cost Increase	4 Pages
II. F.1-8	Material Balance	8 Pages
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