Co-Optimization of Fuels & Engines (Co-Optima) Initiative

John Farrell, National Renewable Energy Lab

SAE 13th International Conference on Engines & Vehicles - Capri, Italy
September 13, 2017

better fuels | better vehicles | sooner
Acknowledgments

DOE Sponsors:

Alicia Lindauer and Borka Kostova (BETO)
Kevin Stork, Gurpreet Singh, Leo Breton, and Mike Weismiller (VTO)

Co-Optima Technical Team Leads:

Dan Gaspar (PNNL), Paul Miles (SNL), Jim Szybist (ORNL), Jennifer Dunn (ANL), Matt McNenly (LLNL), Doug Longman (ANL)

Other Co-Optima Leadership Team Members:

John Holladay (PNNL), Robert Wagner (ORNL), Chris Moen (SNL)
Goal: better fuels and better vehicles sooner

Fuel and Engine Co-Optimization

- What **fuel properties** maximize engine performance?
- How do **engine parameters** affect efficiency?
- What **fuel and engine combinations** are sustainable, affordable, and scalable?
Governing Hypotheses

Central Engine Hypothesis
There are engine architectures and strategies that provide higher thermodynamic efficiencies than are available from modern internal combustion engines; new fuels are required to maximize efficiency and operability across a wide speed / load range.

Central Fuel Hypothesis
If we identify target values for the critical fuel properties that maximize efficiency and emissions performance for a given engine architecture, then fuels that have properties with those values (regardless of chemical composition) will provide comparable performance.
Two Parallel R&D Projects

**Light-Duty**
- Boosted SI (Near-term)
- Multi-mode SI/ACI (Mid-term)

**Medium/Heavy-Duty**
- Mixing Controlled (Near-term)
- Kinetically Controlled (Longer-term)
High-level goals and outcomes

**Light-duty**
- Up to 15% fuel economy (FE) improvement*
  - boosted SI and multi-mode SI/ACI

**Heavy-duty**
- Up to 4% FE improvement (worth $5B/year)*
  - Potential lower cost path to meeting next tier of criteria emissions regulations

**Fuels**
- Diversifying resource base
- Providing economic options to fuel providers to accommodate changing global fuel demands
- Increasing supply of domestically sourced fuel by up to 25 billion gallons/year

**Cross-cutting goals**
- Stimulate domestic economy
- Adding up to 500,000 new jobs
- Providing clean-energy options

---

* Beyond projected results of current R&D efforts. The team is actively engaging with OEMs, fuel providers, and other key stakeholders to refine goals and approaches to measuring fuel economy improvements.
Co-Optima Team

Nine national labs, 13 universities

> 100 researchers, > 75 projects

External Advisory Board

77 stakeholder organizations

Budget: FY16: $26M
FY17: $24.5M
Objective: identify fuel properties that optimize engine performance, independent of composition,* allowing the market to define the best means to blend and provide these fuels.

* We are not going to recommend that any specific blendstocks be included in future fuels.
Systematic Blendstock Survey

Objective: identify a broad range of feasible blendstock options

Primary focus: identify blendstocks with desired properties that have a strong potential to be sourced from biomass
Potential Benefits of Biomass Sourced Fuel

**Technical**
- Tailor fuel properties desired in the blendstock
- Add value to refiners – blend up low quality (inexpensive) petroleum blendstocks
- Help refiners balance global trends in transportation fuel use

**Societal**
- Reliable domestic energy options that are affordable & efficient
- Strengthens energy security by increasing supply, diversity, reliability
- Retain $260 billion in the U.S.
- Add 1.1M direct jobs
- Expand U.S. science/technology leadership

**Environmental**
- Reduce emissions, including CO₂ emissions, by 450 million tons (7%) annually
- Improved soil, water, and air quality

Introducing New Fuels and Engines Impacts a Large Body of Stakeholders

- Energy Companies
- Refiners
- Biofuel Producers
- Fuel Distribution
- Government/Regulatory Agencies
- LD OEMs
- HD OEMs
- Retail
- Consumer
- Society
USCAR
David Brooks

American Petroleum Institute
Bill Cannella

Fuels Institute
John Eichberger

Truck & Engine Manufacturers Assn
Roger Gault

Advanced Biofuels Association
Michael McAdams

Flint Hills Resources
Chris Pritchard

EPA
Paul Machiele

CA Air Resources Board
James Guthrie

UL
Edgar Wolff-Klammer

University Experts
Ralph Cavalieri (WSU, emeritus)
David Foster (U. Wisconsin, emeritus)

Industry Expert
John Wall (Cummins, retired)
Co-Optima Scope

• Focusing only on liquid fuels
• Identify blendstocks to blend into petroleum base fuel
• Considering only non-food-based biofuel feedstocks
  Assessing WTW emissions for biofuel options (GHG, water, etc)
• Considering hybridized/non-hybridized solutions
• Provide data, tools, and knowledge to stakeholders - objective is not to “pick winners”
Two Parallel R&D Projects

Light-Duty
- Boosted SI
  - Near-term
- Multi-mode SI/ACI
  - Mid-term

Medium/Heavy-Duty
- Mixing Controlled
  - Near-term
- Kinetically Controlled
  - Longer-term
Timeline

- Light Duty
  - Stoichiometric SI (Oct’15 - Oct’18)
  - Multi-mode SI/ACI (Oct’19 - Oct’24)
  - Boosted Downsized (Oct’15 - Oct’18)
- Medium/Heavy Duty
  - Overall Lean Compression Ignition (Oct’15 - Oct’19)
  - Mixing controlled (Oct’15 - Oct’24)
  - Kinetically controlled (Oct’15 - Oct’24)
  - Cross-cutting Tool Development (Oct’15 - Oct’24)

- Project start
- TRL 4 achieved
- Foundational tasks
- Co-optimization project
- Cross-cutting tool development
- Offramp (core program, FOAs, etc)
Foundational Technical Questions

What fuels do engines really want?

What fuels should we make?

What will work in the real world?
Question 1: What fuels do engines really want?

Approach:

Conduct engine experiments and simulations that delineate fuel property impacts on engine performance.
Theoretical foundation: “merit function”

Engine efficiency can be expressed as a product of various “efficiencies”:

\[ \eta_{th} = \eta_{\text{ideal}} \times \eta_{glh} \times \eta_{\text{comb}} \times \eta_{\text{pump}} \times \eta_{ht} \times \eta_{\text{emiss}} \ldots \]

\[ \eta_{\text{ideal}} = 1 - \frac{1}{CR^{\gamma-1}} \]

- \( \eta_{glh} \) = combustion phasing ("degree of constant V combustion")
- \( \eta_{\text{comb}} \) = combustion efficiency
- \( \eta_{\text{pump}} \) = pumping losses
- \( \eta_{ht} \) = heat transfer losses
- \( \eta_{\text{emiss}} \) = emission control losses
Theoretical foundation: “merit function”

Since we are interested in relative efficiency, we can differentiate to get:

\[
\frac{d\eta_{th}}{\eta_{th}} = \frac{d\eta_{CR}}{\eta_{CR}} + \frac{d\eta_{\gamma}}{\eta_{\gamma}} + \frac{d\eta_{glh}}{\eta_{glh}} + \frac{d\eta_{comb}}{\eta_{comb}} + \frac{d\eta_{pump}}{\eta_{pump}} + \frac{d\eta_{ht}}{\eta_{ht}} + \frac{d\eta_{emiss}}{\eta_{emiss}} + \ldots
\]

How can we relate these terms to fuel properties?

- RON, octane sensitivity, HOV
- PMI, $T_{c,90}$
- Flame Speed
- HOV
Efficiency merit function approach

Merit = \( \alpha \cdot f(\text{RON}) \) + \( \beta \cdot f(K, S) \) + \( \gamma \cdot f(\text{HOV}) \)

- Octane Index
  - RON
  - Octane Sensitivity
    - Octane Sensitivity
      - \( \beta \cdot f(K, S) \)
  - Flame Speed
    - \( \varepsilon \cdot f(S_L) \)
- Charge Cooling
  - Heat of Vaporization
    - \( \gamma \cdot f(\text{HOV}) \)
  - PM Emissions
    - \( \zeta \cdot f(\text{PMI}) \)
  - Catalyst Light-off Temp (cold start)
    - \( \eta \cdot f(T_{c,90,conv}) \)

Dilution Tolerance

Emissions Penalties
Efficiency merit function approach

\[
Merit = \frac{(RON_{mix} - 91)}{1.6} - K \frac{(S_{mix} - 8)}{1.6} \\
+ 0.085 \left[ \frac{ON}{kJ/kg_{mix}} \right] \cdot \left[ \frac{(HoV_{fuel} / (AFR_{mix} + 1)) - (415[kJ/kg] / (14.0[-] + 1))}{1.6} \right] \\
+ \frac{(HoV_{mix} / (AFR_{mix} + 1)) - (415[kJ/kg] / (14.0[-] + 1))}{15.2} \frac{(S_{Lmix} - 46[cm/s])}{5.4} \\
- H \left( PMI_{mix} - 1.6 \right) \left[ 0.7 + 0.5 \left( PMI_{mix} - 1.4 \right) \right] + 0.008^\circ C^{-1} \left( T_{c,90,conv} - T_{c,90,mix} \right)
\]
Decoupling S and HOV impacts

• With DI, increasing S from 0 to ~11 at RON=100 yields more than half the combustion phasing advance of RON 106, S~12 fuel

• All RON 100, S~11 fuels have similar knock-limited performance gains over ic8: no evident HoV benefit

Experimental details: Single cylinder version of GM Ecotec 2.0L, 9.2: CR; side-mounted DI or upstream fuel injection; load sweeps at an intake manifold temp of 50 °C; sweep intake manifold T for max load at 2 different CA50 phasing
Upstream injected (UI) 100 RON, S ≈ 11 fuels have higher peak IMEP at constant CA50 than iso-octane (RON 100, S =0), and HoV has little effect (S is dominant)

- Direct injection (DI) of iso-octane has HoV benefit, but less than S ≈ 11 effect
- DI of S ≈ 11 fuels also has HoV benefit, which increases with manifold temp.
Question 2: What fuels should we make?

Approach:

Identify blendstock options that provide key properties
Tiered blendstock identification

Can it be a fuel blendstock?

Does it provide desired performance?

Does it merit focused experiments and analysis?

# blendstocks:

- Tier 1: > 400
- Tier 2: ~ 40
- Tier 3: < 10
Tier 1

> 470 blendstocks

14 chemical families

Identify broad range of potential hydrocarbon and oxygenated blendstocks

Utilize property information on blendstocks from literature or estimates to identify Tier 2 blendstocks

Hydrocarbons
- Normal paraffins
- Iso-paraffins
- Cycloparaffins
- Olefins
- Aromatics
- Multi-ring aromatics

Alcohols
- Furans
- Ethers
- Carbonyls
  - Ketones
  - Aldehydes
- Esters
  - Volatile fatty acid esters
  - Fatty esters
- Carboxylic Acids

Present in commercial fuels

Not present in commercial fuels

A major goal of Co-Optima is to conduct a comprehensive and consistent survey of blendstock options:

What blendstocks are able to increase boosted SI performance?
Tiered blendstock identification

**Tier 1**

> 470 blendstocks

14 chemical families

Identify broad range of potential hydrocarbon and oxygenated blendstocks

Utilize property information on blendstocks from literature or estimates to identify Tier 2 blendstocks

- Determine Boiling Point And Melting Point
- Apply Solubility Criteria (e.g., solubility parameter)
- Apply Corrosion Metric
- Identify Known Toxicity Issues
- Determine Fuel Handling Safety (e.g., rapid peroxide former)
- Biodegradation
- Reject if $T_m > -10\,^\circ C$ and $T_b$ or $T_{90}$ not in target range ($20\,^\circ C < T_b < 165\,^\circ C$)
- Reject if insoluble in hydrocarbon fuels within required temperature range
- Reject if the material is too corrosive for metals in fueling systems
- Reject if Category 1 or 2 carcinogen or reproductive toxin
- Reject if fuel is hazardous or unstable, not addressed with antioxidants
- Reject if less anaerobically biodegradable than MTBE and highly water soluble

Gasoline-Like
- $T_b < 165\,^\circ C$ or $T_{90} < 165\,^\circ C$

**Autoignition Reactivity Metrics**

ACI Engine
- Wide range of RON/CN

Diesel-Like
- $T_b < 338\,^\circ C$ or $T_{90} < 338\,^\circ C$

Diesel Engine
- CN > 40

**Advanced SI Fuel Candidates**

SI Engine High RON
**Tier 1 blendstock screening**

**Tier 1**

- > 470 blendstocks
- 14 chemical families

**Tier 2**

- 41 blendstocks
- 10 chemical families

**Tier 3**

Which blendstocks merit comprehensive, consistent, and rigorous study and analysis?

---

**Identify broad range of potential hydrocarbon and oxygenated blendstocks**

Utilize property information on blendstocks from literature or estimates to identify Tier 2 blendstocks

**Measure blendstock properties**

Evaluate blendstock performance in BOBs at 10-30% blend levels

Remove candidates from list if improved data indicate they do not meet criteria

Add new candidates as our understanding improves of how fuel structure impacts key properties
## Boosted SI Tier 2 blendstocks

<table>
<thead>
<tr>
<th>Alcohols (9)</th>
<th>Esters (13)</th>
<th>Furans</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Methanol</td>
<td>16 Ethyl acetate</td>
<td>33 2,5-Dimethylfuran/2-methylfuran</td>
</tr>
<tr>
<td>2 Ethanol</td>
<td>17 Ethyl butanoate</td>
<td></td>
</tr>
<tr>
<td>3 1-Propanol</td>
<td>18 Ethyl isobutanoate</td>
<td></td>
</tr>
<tr>
<td>4 Isopropanol</td>
<td>19 Isopropyl acetate</td>
<td></td>
</tr>
<tr>
<td>5 1-Butanol</td>
<td>20 Butyl acetate</td>
<td></td>
</tr>
<tr>
<td>6 2-Butanol</td>
<td>21 2-Methylpropyl acetate</td>
<td></td>
</tr>
<tr>
<td>7 Isobutanol</td>
<td>22 3-Methylpropyl acetate</td>
<td></td>
</tr>
<tr>
<td>8 2-Methylbutan-1-ol</td>
<td>23 mixed esters</td>
<td></td>
</tr>
<tr>
<td>9 2-Pentanol</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ethers</th>
<th>Ketones (9)</th>
<th>Branched alkanes</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 Anisole</td>
<td>24 2-Butanone</td>
<td>34 2,2,3-Trimethylbutane</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Alkenes</th>
<th>Multicomponent mixtures (6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>35 Diisobutylene</td>
<td>36 Methanol-to-gasoline</td>
</tr>
<tr>
<td>37 Ethanol-to-gasoline</td>
<td>38 Bioreformate via multistage pyrolysis</td>
</tr>
<tr>
<td>39 Bioreformate via catalytic conversion of sugar</td>
<td>40 Mixed aromatics via catalytic fast pyrolysis</td>
</tr>
<tr>
<td>41 Aromatics and olefins via pyrolysis-derived sugars</td>
<td></td>
</tr>
</tbody>
</table>
Tier 2 to Tier 3 transition criteria

1. Achieve merit function score \( \geq \) E10 premium when blended in petroleum BOB*

2. Meet current critical fuel specs (RVP, distillation, oxidative stability, etc.) when blended in petroleum BOB*

3. No “showstopper” barriers
   - Candidates must have viable path to potential market introduction by \( \sim \) 2025 - 2030

Tier 2->3 transition allows focused effort on blendstocks with greatest potential to meet Co-Optima goals

* BOB = blendstock for oxygenate blending; evaluated at blend levels of 10, 20, and 30% by volume
Example blendstock data: RVP

- Methanol
- Methyl acetate
- Ethanol
- Methyl furan
- Methyl ethyl ketone
- Ethyl acetate

Ingredients:
- 1-butanol, 2-butanol, iso-butanol,
- 3-methyl-1-butanol, di-isobutylene,
- 2-methyl-1-butanol, butyl acetate,
- 2,4 dimethyl-3-pentanone,
- anisole, 2-pentanone
Determining blending behavior
High-potential blendstocks identified

Properties provided by chemical families:
- Alcohols
- Furans
- Alkenes
- Aromatics
- Ketones
- Cycloalkanes
- Alkanes
- Ethers
- Esters

Average contribution to merit function for highest scoring blendstocks:

RON = Research octane number; S = Sensitivity ($S = RON - MON$); HOV = heat of vaporization
Question 3: What will work in the real world?

Approach:
Conduct comparative, systems-level analyses of economic, environmental, state of technology, and market factors.

Assess likelihood of commercial scale impact by 2025-2030.
Analysis Metrics

Technology Readiness
- State of technology: Fuel production
- State of technology: Vehicle use
- Conversion technology readiness level
- Feedstock sensitivity
- Process robustness
- Feedstock quality
- # of viable pathways

Environmental
- Carbon efficiency
- Target yield
- Life cycle greenhouse gas emissions
- Life cycle water
- Life cycle fossil energy use

Economics
- Target cost
- Needed cost reduction
- Co-product economics
- Feedstock cost
- Alternative high-value use

Market
- Uncertainty
- Regulatory requirements
- Geographic factors
- Political factors
- Vehicle compatibility
- Infrastructure compatibility

Assessed only for blendstocks produced from biomass
Assessed for both fossil and renewable blendstocks
<table>
<thead>
<tr>
<th>Screening assessment results</th>
<th>Technology readiness</th>
<th>Economics</th>
<th>Environmental</th>
<th>Infrastructure compatibility, etc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethanol</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Methanol</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1-Butanol</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2-methyl butanol</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2-Butanol</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>iso-Butanol</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Guerbet alcohols</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Furan mixture</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Methyl acetate</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ethyl acetate</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Favorable**
- **Neutral**
- **Unfavorable**
- **Insufficient data**

<table>
<thead>
<tr>
<th>Gasification/catalysis</th>
<th>Fermentation</th>
<th>Hydrolysis/catalysis</th>
<th>Pyrolysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>36</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
High-potential blendstocks identified

Properties provided by chemical families:
- RON
- S
- HOV
- Alcohols
- Furans
- Alkenes
- Aromatics
- Ketones
- Cycloalkanes
- Alkanes
- Ethers
- Esters

Average contribution to merit function for highest scoring blendstocks

Eight representative blendstocks selected for more detailed evaluation

- Ethanol
- n-Propanol
- Isopropanol
- Isobutanol
- Cyclopentanone
- Di-isobutylene
- Furan mixture
- Aromatics

RON = Research octane number; S = Sensitivity (S = RON – MON); HOV = heat of vaporization
Current boosted SI blendstock efforts

- Refine property measurements, improve blend models, and conduct more detailed compatibility studies
- Conduct engine tests to confirm performance and assess potential to meet FE targets
- Carry out emissions control experiments to assess impacts on efficiency and durability
- Conduct detailed life cycle, techno-economic analyses, and refinery integration studies
Next steps

- Refine merit function and establish technical basis for advanced gasoline fuel specification for boosted SI by end of FY18
- Conduct more rigorous assessments of Tier 3 candidates
- Assess candidates for potential follow-on scale-up studies
- Expand LD efforts – multi-mode SI-ACI
- Expand MD/HD efforts
- Continue strong engagement with stakeholders to help focus R&D on options that provide “wins” for broad range of stakeholders
Co-Optima Website

https://energy.gov/eere/bioenergy/co-optimization-fuels-engines

FY 2016 Year in Review Highlights

https://www.nrel.gov/docs/fy17osti/67595.pdf
Detailed overview available from FY17 VTO AMR presentations

https://www.annualmeritreview.energy.gov
2017 Project Peer Review—Co-Optimization of Fuels and Engines

The Bioenergy Technologies Office hosted its 2017 Project Peer Review on March 6-9, 2017, in Denver, Colorado. The presentations from the Co-Optimization of Fuels and Engines sessions are available to view and download below. For detailed session descriptions and presentation titles, view the 2017 Project Peer Review Program Booklet.

- Co-Optima Overview
- High-Performance Fuels
- Analysis of Sustainability, Supply, Economics, Risk and Trade (ASSERT)
- Market Transformation

https://energy.gov/eere/bioenergy/downloads/2017-project-peer-review-co-optimization-fuels-and-engines
Thank You!
Technical Approach

- Identify potential blendstocks
- Identify candidates via Tier 1 screening
- Conduct exploratory engine testing
- Develop engine efficiency merit function
- Tailor pathways to improve properties
- Identify viable production pathways
- Measure properties and relate to structure
- Develop (nonlinear) blending models
- Develop combustion kinetic models
- Refine merit function via engine sim.
- Refine merit function via engine exp.
- Assess scalability, affordability via TEA
- Assess sustainability via LCA
- Identify/assess retail/infrastructure barriers
- Run scenario analysis tool ("co-optimizer")
- Vehicle-level assessments (e.g., emissions control, cold start, etc.)
- Confirm performance of blendstock candidates
- Validate merit function/central fuel hypothesis
- Begin convening external stakeholders to define strategies for market introduction
- Develop fuel spec (if appropriate)
- Market introduction support continues
- Identify options that maximize efficiency while meeting stakeholder constraints
- Confirm potential to meet fuel economy improvement goal
- Multi-team project work concludes
- Map properties to efficiency “What fuels to engines want?”
- Expand blendstock options “What fuels should we make?”
- Identify barriers to use “What will work in real world?”
- Identifying options “How do we co-optimize?”
<table>
<thead>
<tr>
<th>University Partners</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cornell / UCSD</td>
</tr>
<tr>
<td>Identify differences in combustion characteristics of diesel/biofuel blends vs petroleum-based fuels</td>
</tr>
<tr>
<td>Univ. Michigan</td>
</tr>
<tr>
<td>Develop engine combustion model to simulate key parameters while reducing computational expense 80%</td>
</tr>
<tr>
<td>U. Mich. - Dearborn/Oakland U.</td>
</tr>
<tr>
<td>Use a miniature ignition screening RCM to study ignition properties/combustion characteristics of alternative fuels.</td>
</tr>
<tr>
<td>Univ. Alabama</td>
</tr>
<tr>
<td>Examine combustion properties of biofuels and blends using advanced diagnostics under realistic ACI engine conditions.</td>
</tr>
</tbody>
</table>
Integration With Industry

Co-Optima Research

Basic technological components are integrated to establish that pieces will work together

Public Private Partnerships

Technology validated adequately to enable industry, either alone in collaboration with national labs and universities, to continue product development

Initiation of active R&D

Technology Readiness Level (TRL)

See https://en.wikipedia.org/wiki/Technology_readiness_level
Boosted SI
Near-term

Multi-mode SI/ACI
Mid-term

Mixing Controlled
Near-term

Kinetically Controlled
Longer-term
Fuel property database*

Tier 1

> 470 blendstocks

14 chemical families

Identify broad range of potential hydrocarbon and oxygenated blendstocks

Utilize property information on blendstocks from literature or estimates to identify Tier 2 blendstocks

* Publicly accessible: https://fuelsdb.nrel.gov/fmi/webd#FuelEngineCoOptimization
Tier 1 blendstock screening

Tier 1

> 470 blendstocks

14 chemical families

Identify broad range of potential hydrocarbon and oxygenated blendstocks

Utilize property information on blendstocks from literature or estimates to identify Tier 2 blendstocks

Hydrocarbons
Normal paraffins
Iso-paraffins
Cycloparaffins
Olefins
Multi-ring aromatics

Alcohols
Furans
Ethers
Carbonyls
Ketones
Aldehydes

Esters
Volatile fatty acid esters
Fatty esters
Carboxylic Acids

Normal paraffins
Iso-paraffins
Cycloparaffins
Olefins
Alcohols

Aromatics
Ketones
Volatile fatty acid esters
Furans
Ethers

Multi-ring aromatics
Aldehydes
Fatty esters
Carboxylic acids

YES

YES FOR SOME

NO