Market-driven considerations affecting the prospects of alternative road fuels

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Without significant intervention, demand for crude oil could rise by a further 25% by 2035, stemming from its use for transportation, particularly road transport. Many technologies for alternative fuels and substitute transport energy carriers are being researched, but successful implementation of these technologies at scale will require attention to consumer-behavioural and policy challenges as well as adapting existing or introducing new commercial value chains. In particular, there will be new capital-intensive roles for which there are no obvious contenders as yet. The legacy of diverse urban planning and fuel taxation policies and varying degrees of consumer inertia will lead to different rates of adoption of different alternative technologies in regional markets. In the absence of technology that provides a compelling consumer proposition, substitution of crude demand in mature markets will be challenging, as will be channelling exponential growth from growing markets like China into less crude-intensive road transport solutions.

1. Introduction

While some experts argue for a plentiful future supply of conventional and unconventional liquid fuels, given sufficient investment and free access for drilling [1], others find that annual production of conventional oil is probably approaching, if not already in, decline [2,3] and that affordable supply may not last even a decade. Alternative liquids are currently more expensive, often yield less net energy (and higher CO₂ emissions as a consequence) and cannot be produced in significant volumes [4].
Despite the high prices of the last eight years, demand for crude oil continues to grow. The annual price of Brent crude ranged between $12 and $40 per barrel between 1985 and 2004 but has been not less than $60 per barrel since 2005, and exceeded $110 per barrel in 2011 and 2012 [5,6]. Even if current historically high prices persist, some believe that global demand could still increase by 25% by 2035. Yet such forecasts already assume challenging targets in terms of moderating existing consumption within the Organization for Economic Co-operation and Development (OECD) and growing non-OECD demand. If crude oil supply cannot meet this notional demand or can only do so at prohibitively high prices, then less costly alternatives will be needed. As oil is the dominant road transport fuel, it is prudent to consider how viable alternatives for road fuels might emerge.

There is much technical research on alternative fuels and transportation, including unconventional oil, biofuels, natural gas and hydrogen fuels, conventional or electric vehicles (EVs) and mass transit systems [7]. However, whatever technologies are proposed, they bring market-related concerns that often receive limited attention, such as requirements for commercial infrastructure, the acceptability of changed vehicle range and refuelling norms, rates of market penetration and fleet replacement, and policy intervention. The more innovative the technological solution, the greater the potential market disruption and commercial impediments that need to be surmounted.

In this paper, I summarize potential demand for crude and the alternative technology options as context for discussing the human, logistical and market challenges to meeting the world’s road transport needs. Most of these challenges are barely amenable to a rigorous scientific analysis. Moreover, there are few historical analogues for how innovative alternatives may be adopted or what else might occur, should oil become effectively rationed by price. The scale and timing of these market challenges remain uncertain, but empirical evidence of successful innovation suggests they require recognition and resolution in step with technology and engineering advances if road transport is to achieve a smooth transition to whatever comes next.

2. Demand outlooks

Current global demand for crude oil and alternative liquids is approximately 85 million barrels per day, 30 billion barrels per year, 4 billion tonnes per year or 1000 barrels per second. The raw national figures that make up this total vary in consistency and quality. There are also some variations in the factors used to convert between barrels, tonnes and calorific equivalents, owing to variation in oil’s specific gravity. Hence, it is both difficult and of arguable value to attempt to pick a number with absolute precision, but the number is large, has grown significantly over the last 50 years and looks set to continue to grow for the foreseeable future.

Experts consistently predict that liquids demand could rise by as much as 25% by 2035. Table 1 summarizes some recent quantitative outlooks. These quantitative outlooks accompany qualitative scenarios which extrapolate current policies, technologies and behaviours, and characterize a ‘business-as-usual’ perspective. For many years and through many iterations of these outlooks, their authors have assumed that crude oil supply would be available to meet any demand outlook. In recent years, there has been a growing realization that easy-to-access and cheap crude may be dwindling and that the technical and pricing consequences of this will have some impact on demand. However, the recent outlooks in table 1 reflect such considerations and can be taken as a reasonable upper bound for demand.

A few commentators offer a more stringent base case [8,12], in which radical political, technological or behavioural change is forced onto the system to dampen demand. In effect, such outlooks assume, but do not always explicitly articulate, solutions to the challenges discussed in the rest of this paper. The reasons for offering such a constrained demand outlook are several—and it should be borne in mind that many of the agencies providing such outlooks have explicit political allegiances—not the least of which are (i) quelling concerns about the adequacy of oil supply and (ii) backsolving to meet climate change and CO₂ emissions targets, discussion of which is beyond the scope of this paper.
Table 1. Some outlooks for liquids demand growth.

<table>
<thead>
<tr>
<th>source</th>
<th>publication</th>
<th>name of scenario</th>
<th>global liquids demand (mln boe per day)</th>
<th>% change</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>2020: 96.7</td>
<td>+25.7</td>
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<td></td>
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<td></td>
<td>2035: 110.6</td>
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<td>2030: 108</td>
<td>+30.2</td>
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<td>2035: 112</td>
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<td>2030: 103</td>
<td>+18.4</td>
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<td>2025: 101.7</td>
<td>+24.3</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>2040: 108.6</td>
<td></td>
</tr>
</tbody>
</table>

\(^a\) Million barrels of oil equivalent per day; 1 barrel = 158.99 l; ‘oil equivalent’ includes gas, converted by thermal values to an equivalent quantity of crude.

\(^b\) Converted from quadrillion (10\(^{15}\)) British thermal units. 1 mln boe per day \(\approx\) 2.026 quads per year. Often energy demand is expressed in tonnes of oil equivalent (toe). Conversion to barrels or boe is problematic; for crude 1 tonne \(\approx\) 7.0–7.3 barrels, depending on API gravity; for other liquids, for example, condensate, the conversion factor is higher. Total global liquids consumption yields at present 7.9 boe per toe [5]. In analysis below where global or regional liquids data are given in toe and there is neither information on the mix of liquid types assumed nor an appropriate boe conversion factor given, I have left these data in toe to maintain internal consistency and an audit trail to the original sources.

Growth in liquids demand depends upon population and per capita consumption and generally increases with economic prosperity. Dividing global oil consumption by global population for 2010 (4.032 billion toe per year [5] by 6.89 billion population [13]) gives an annual per capita consumption of approximately 0.58 toe. Remarkably, the same sources also indicate the same average per capita oil consumption for 1985, while the IEA’s ‘Current Policies’ scenario gives figures for 2035 of 4.992 billion toe per year and 8.556 billion population—again 0.58 toe per year per capita per annum [8]. As global per capita liquids consumption has remained stable over the last 25 years, it is reasonable to assume that this continues in an environment lacking radical change.

Figure 1 shows global history and the IEA’s forecasts, globally and by major regions.

The global trend from 1985 to 2035 looks fairly mundane, but the regional outlook is more interesting. Per capita consumption in the OECD is projected to decrease by 18% while population increases by 11%, yielding an overall OECD consumption decline of 8%. By contrast, non-OECD per capita consumption is projected to increase by 26% while its population increases by 27% yielding an overall non-OECD consumption increase of 59%. China’s per capita consumption is projected to increase by 77% and India’s by 122%. This analysis is typical of the outlooks summarized in table 1, although differences in the granularity of reporting preclude direct comparison.

There is consensus that the major use of oil is for fuel, the major proportion of that is for transport, the main source of demand growth will be transport and the bulk of that is for road use (figures 2 and 3). Several sources anticipate the world’s road vehicle fleet growing from the current one billion to two billion by as early as 2020 and certainly by 2030 [15,16].

With more sophisticated analyses of historical data, one can see stark differences between mature OECD economies and maturing non-OECD economies. Considering just road sector energy consumption, figure 4 shows that higher gross domestic product (GDP) per capita is associated with greater use of energy. However, there is consistent evidence of saturation in mature economies, whereby road sector energy consumption visibly plateaus.
Hence, the challenge for the 2030s presented by a ‘business-as-usual’ outlook is daunting. Even if affordable oil supply can match global demand growth of 25% by 2035:

— How will overall liquids consumption per capita be reduced by as much as 18% in mature OECD economies?
— How will growing non-OECD economies with large populations keep both their overall and road sector per capita energy consumption down to levels well below historical OECD
2010 global transport energy consumption

total = ca. 2200 mtoe per year

by source
- electricity 1%
- biofuels 2%
- LPG/CNG 1%
- residual 8%
- jet fuel 10%
- gasoline 46%
- diesel 32%
- >96% from crude oil

by mode
- light duty 52%
- truck 17%
- rail 3%
- bus 4%
- marine 10%
- aviation 11%
- other 3%
- ~73% road transport

Figure 3. Transportation sector energy consumption segmented by source and mode. Source: World Economic Forum [14]. (Online version in colour.)

norms? When will per capita road sector energy consumption for the BRIC (Brazil–Russia–India–China) nations plateau, and at what level?

— To what extent can non-OECD growth in road transport energy demand be met, in a timely fashion, by alternatives to crude oil?

There are numerous mitigating factors—trends in urbanization, urban planning policy, mass transportation systems, variation in personal income and rising oil prices—that mean that the BRIC nations may never reach even EU levels of per capita road sector energy consumption. However, it looks quite probable that historical patterns will recur without significant progress in technology, energy efficiency and management of energy usage.

A less optimistic supply outlook turns up the heat further. Legitimate concern about the world’s ability to grow affordable crude supply sufficiently quickly [3], and the environmental consequences of succeeding in doing so [18,19] (against the odds, in my view), accelerate and increase the scale of the challenge: to find in good time an alternative to crude oil to fuel the increased road traffic demand expected to accompany economic growth.

3. Technical alternatives to crude oil for transportation

There is an extensive literature on different fuel and energy carriers as alternatives to crude oil as the primary energy source for road transportation fuel, with disagreement on their strengths, weaknesses and realistic potential. This brief overview serves as a context for some more qualitative market concerns that might inhibit or stimulate change.

A range of traditional commercial activities support road transportation:

— Fuel provision begins with exploring for and producing crude oil and natural gas, which are refined into fuels (gasoline, diesel and sometimes ethanol, compressed natural gas (CNG) and liquefied petroleum gas (LPG)). These are stored and distributed to supply networks of retail stations.
— Vehicle provision starts with the design and prototyping of road vehicles with internal combustion engines (ICEs) to run on these fuels. Manufacturing requires a network of suppliers to deliver components. Completed vehicles are distributed to branded franchises for sale.

— Consumers (motorists) buy or rent the vehicles and refuel them at retail stations. The accepted paradigm is that refuelling:

(i) can be performed by motorists themselves,
(ii) takes less than 10 min per refuelling including waiting time, and
(iii) consistently yields a substantial driving range for each refuelling (e.g. 400 miles for a European light passenger vehicle).

Figure 5 illustrates these activities with some simple flow diagrams.

Most would agree that the development of viable new propulsion technologies is a necessary part of any solution to a shortage of affordable oil. However, providing a new technology is not by itself a sufficient solution, because any disruptions to the flow of industry activities must be mitigated. The more radical the alternative technology, the more significant the potential disruption and the more impediments there are to adoption.

This resistance to change does not mean that the status quo is beyond improvement. ICEs are not particularly efficient, but crude oil has a remarkably high energy density. Although there are noticeable regional variations owing to differences in vehicle size and weight, in markets where gasoline is cheap there has been prolonged inefficiency in automotive design. A gasoline or diesel ICE vehicle (ICEV) uses only some 25–30% of its fuel energy for propulsion and accessories, with the residue being expended through cooling. In 2010, 71% of the USA’s primary energy supply petroleum was used for transportation, of which 75% was wasted, an even higher proportion of primary energy wastage than that encountered in electricity generation [20].

The simplest way to constrain oil demand is to mandate more fuel-efficient vehicles, which would minimally disrupt existing industry activities through a scale effect. While much effort has
been put into this, regional disparities are still evident, primarily owing to legacy variations in fuel tax and urban planning (figure 6).

In the USA, where low taxes have sustained relatively cheap gasoline, improved fuel economy has maintained performance in terms of miles per gallon (at a low level compared with Europe) while supporting increasingly large and heavy vehicles. Only in recent years—most noticeably in legislation in 2007 (Energy Independence and Security Act) and 2011 (new corporate average fuel economy (CAFE) standards)—has the USA made commitments to fuel economy standards that would bring it into line with other OECD markets.

The benefits of increased fuel economy do not all pass down to lower aggregate consumption. This is the so-called rebound effect [22,23]. Empirical evidence suggests that as fuel efficiency improvements make driving cheaper, consumers choose to drive more or to drive larger and more powerful cars (a direct rebound effect). In addition, they use the money saved on gasoline to purchase other goods and services that also consume energy (an indirect rebound effect). Hence, the aggregate reduction in road fuel and total energy consumption may not be as great as the improvement in vehicle fuel efficiency suggests.

With more radical technology we can consider alternative fuels for the ICE and alternative drivetrain technologies. These potential technologies are not all suitable for every type of road transportation. For example, the functional requirements of heavy duty commercial vehicles clearly differ from those of light duty passenger vehicles. I now briefly consider some of the alternatives shown in figure 7.

After fuel efficiency improvements, the next minimally disruptive adjustment to the status quo is to introduce alternative liquid fuels, so-called ‘drop-in’ fuels, such as ethanol or biodiesel, that can be added to oil fuels to produce blends that work with conventional ICES. The word ‘minimally’ hides a lot here. While biofuels would not impact downstream activities, such as retail distribution and motorists’ habits, the new upstream activities of bioethanol production and
distribution would be a major undertaking, although qualitatively similar to current activities. However, concerns about achieving sufficient scale, given the conflicts with food production, limit the production potential of biofuels. A notable exception to this is the Brazilian sugar cane ethanol industry [25] but most other biofuels require substantial subsidies. Few commentators foresee significant biofuels in the 2035 transport fuel mix. For example, the IEA [8] projects the percentage of demand met by biofuels to rise from 2.3% in 2009 to 4.6% in 2035 for the ‘Current Policies’ scenario but still only 6.2% in 2035 for its more stringent ‘New Policies’ scenario. This is a substantial increase but not a radical transition.

The use of alternative fossil fuels, such as natural gas (as CNG or liquefied natural gas (LNG)) and LPG, already present in many local markets, such as South Korea, Turkey and Poland, has significant potential. For example, in Turkey 37% of passenger vehicles currently run on LPG [26]. Global remaining recoverable reserves of natural gas are commensurate with those of crude oil

Figure 6. Standardized average fuel economy for passenger vehicle fleets in different regional markets. Source: UN Commission for Sustainable Development [21]. (Online version in colour.)

Figure 7. Alternative propulsion technology pathways. Adapted from [24]. (Online version in colour.)
(particularly since recent progress in cost-effective ways of accessing shale gas). On a calorific equivalence basis, global consumption of gas is about two-thirds of that of crude oil, but gas is less than a third the price of oil. As vehicles that run on CNG or LPG are already in production, this option could be scaled up relatively easily. Retrofitting vehicles with a high-pressure natural gas storage tank is a normal practice in markets where retail natural gas distribution exists. Distributing natural gas via existing gasoline retail outlets would be a viable and relatively low-cost operation.

However, natural gas vehicles still have a relatively high emissions footprint, similar to diesel on a well-to-wheel basis [15,27], and consequently there is little impetus for such a switch on environmental grounds. Also fuel retailers are less keen on the storage and supply of natural gas. So the ‘sell’ to consumers is a moderately difficult one—much the same as seen in the marginal success of diesel with motorists in the USA compared with its widespread penetration in Europe. Using gas and coal as a source of fuel, through gas-to-liquids (GtL) and coal-to-liquids (CtL) conversion technologies, will encounter similar environmental barriers in OECD economies as the upstream processing has significant environmental impacts, but CtL could prove more successful in coal-rich and crude oil-poor regions, for example, China.

Moving away from the ICE, EVs are far more efficient than ICEVs, and some EVs can recover energy from regenerative braking. EVs also have zero tailpipe emissions, and thus could significantly improve urban air quality. However, providing sufficient stored electricity is an issue. Rechargeable battery technologies currently struggle to deliver a battery-powered EV of manageable weight and size that will run for more than a theoretical 100 miles on a single charge—and in practice it is a lot less than 100 miles [28,29]. Charging from a standard EU 240 V domestic mains supply is possible as an overnight process. Fast charging is possible, although it can reduce battery life, but charging stations are costly to install and maintain in numbers, which presents investment challenges for potential operators. The EV can be enhanced by making removable or rotatable batteries (RBEVs) and offering fast-exchange drive-in stations.

It is not obvious that current EV models are attractive substitutes for conventional vehicles that are cheaper to buy and can run for 400–500 miles on a full tank of gasoline or diesel. This is not merely about average driving range, but about the full needs of the motorist in a single vehicle. Relatively few will migrate to an EV that meets their range needs 90% of the time, but cannot manage a moderate distance over a weekend or a long distance summer vacation, particularly to rural destinations without fast-charging facilities. The solution of ‘buying an EV as a second car’ will have some traction in the USA where average car ownership per household is already very high (1.87 vehicles per household [30]) and second vehicles often have a less onerous workload, but less so in other markets with constraints, such as lower household income and fewer parking spaces. Unless what EVs offer in terms of size, weight and effective range can get closer to the accepted paradigm of what can be achieved on a single refuelling stop—or ubiquitous fast recharging becomes available—then they have relatively little scope for market penetration.

In many ways, hybrid conventional fuel-EVs (HEVs) have the greatest short-term potential as substitutes for conventional ICEVs. The HEV carries the extra weight of both a battery array and a fuel tank, and consequently might only deliver a purely electric-powered range of 40 miles. Yet, the HEV conquers concerns of range anxiety and refuelling convenience by using conventional gasoline or diesel and the conventional refuelling infrastructure as necessary. Plug-in hybrid electric vehicles (PHEVs) give the further advantage of being rechargeable at home overnight if parking logistics permit. If propulsion efficiency can be boosted to take account of the extra weight, PHEVs would appear a much more effective way to transition to a less oil-intensive road transport paradigm. If incremental electricity generation and EV/HEV/PHEV and battery manufacture can be undertaken at scale in a way that yields a sufficient environmental improvement over conventional cars on a well-to-wheel basis, this should prove attractive to a much higher proportion of the light passenger vehicle market.

The problem of low battery charge capacity can be alleviated by fuel cells. Fuel cell electric vehicles (FCEVs) abandon combustion and oxidize their feedstock directly into electricity and exhaust gases. They are energy-efficient in use—far more so than the ICE—and work at lower
Table 2. Alternatives to crude oil for road-based propulsion.

<table>
<thead>
<tr>
<th>area of impact</th>
<th>propulsion alternative</th>
<th>liquid fuels (biofuels, GtL/CtL, additives)</th>
<th>gas (CNG, LNG, LPG)</th>
<th>hybrid electric vehicles (HEVs)</th>
<th>electric vehicles (EVs)</th>
<th>hydrogen fuel cell (FCEVs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>fuel provision</td>
<td>‘upstream’ production</td>
<td>Easiest technical solution but scalability of supply is critical.</td>
<td>Additional upstream capacity required.</td>
<td>Additional power generation capacity and incremental provision of feedstock required. Environmental improvement a function of source of electricity generation.</td>
<td>High investment in hydrogen production, itself requiring electricity generation.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>and ‘refining’</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>distribution networks</td>
<td>Blends can use gasoline or diesel infrastructure.</td>
<td>Additional bulk transport capacity needed.</td>
<td>Varies by market—need to ensure adequacy of local grid load-bearing capacity when operating at scale.</td>
<td>High investment in distribution and bulk storage.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>retail/refuelling</td>
<td>Low—additional pumps and notifications about blends.</td>
<td>Storage for refuelling at station, but also options for home refuelling via domestic mains gas.</td>
<td>Home charging plus continued use of legacy retail station infrastructure.</td>
<td>Possible to refit existing retail stations for hydrogen provision but likely investment costs are high.</td>
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<tr>
<td>vehicle provision</td>
<td>Minimal change—only engine tuning.</td>
<td>New fuel tanks. (N.B. Niche markets already supplied.)</td>
<td>New energy storage and drivetrain systems in place of (or in addition to) ICE.</td>
<td>Weight limits vehicle range and, hence, limits application to light duty vehicles.</td>
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<table>
<thead>
<tr>
<th>Area of Impact</th>
<th>Propulsion Alternative</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Liquid fuels (biofuels, GtL/CtL, additives)</td>
</tr>
<tr>
<td>Consumer/customer preference</td>
<td>Additional choice of liquid fuels at the pump. No significant change in behaviour required.</td>
</tr>
<tr>
<td></td>
<td>Moderate—new refuelling options but otherwise close to the status quo.</td>
</tr>
<tr>
<td></td>
<td>Electric range lower but impact less as ICE retained. New refuelling options should be seen as an added bonus.</td>
</tr>
<tr>
<td></td>
<td>Impact on range and refuelling paradigms significant. Perceived beneficial environmental impact, zero tailpipe emissions.</td>
</tr>
<tr>
<td>Fuel cost relative to gasoline/diesel (excluding taxation or subsidy)</td>
<td>Slightly cheaper, varies with market.</td>
</tr>
<tr>
<td>Vehicle costs relative to gasoline or diesel ICEVs (excluding taxation or subsidy)</td>
<td>Close to gasoline or diesel ICEVs.</td>
</tr>
<tr>
<td></td>
<td>Slightly more expensive for dual fuel models.</td>
</tr>
<tr>
<td></td>
<td>More expensive—battery replacement necessary before the end of vehicle life.</td>
</tr>
<tr>
<td></td>
<td>Greater complexity: there are more components to fail.</td>
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<tr>
<td></td>
<td>Considerable uncertainty about economics of technology direction as abandoning internal combustion can lead to significant vehicle efficiencies (e.g. heat radiation).</td>
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temperatures producing far less wasted heat. Hydrogen is by popular scientific consensus the most obvious feedstock for FCEVs and produces negligible harmful exhaust emissions. However, large-scale production of hydrogen is energy-intensive, requiring electricity to produce the hydrogen from a suitable source such as water or methane. The associated environmental impacts can therefore be substantial, although there are some exceptions: for example, Iceland uses its abundant geothermal electricity generation to produce hydrogen to fuel vehicles. Bulk hydrogen storage requires expensive high-pressure storage, as does in-vehicle containment, as the energy density per unit volume of hydrogen at any practicable pressure is significantly less than conventional fuel sources, which raises concerns about the safety and ease of refuelling.

For all alternative vehicles, vehicle design and the economics of manufacturing are equally vexing. Competitive costing is crucial in the automotive industry. Conventional vehicles benefit from decades of experience curve and economy-of-scale effects. Vehicles using new fuel sources are disadvantaged and, indeed, the further they stray from the gasoline-fuelled ICE paradigm, the more costly the vehicle might be in initial production. Moreover, the full lifetime costs of EVs are still unclear to consumers. For example, EVs might not support the same levels of longevity that conventional vehicles obtain. Today’s fixed battery arrays decline in charge retention and have a limited life in terms of the number of recharges they can support. Early adopters of EVs complain that the cost of replacing battery arrays is significant compared with the initial purchase price of the vehicle, which itself is higher than conventional vehicles of a similar specification. Companies such as Renault have sought to address this uncertainty with battery leasing schemes. HEVs with dual drivetrains are complex and potentially costly to maintain. On the other hand, pure EVs are a much simpler design than ICEVs and may require far less by way of day-to-day maintenance. Hence, the full lifetime cost of EV and HEV ownership is uncertain.

Many of the perceived technical shortcomings of alternative fuels are the subject of ongoing research and development efforts, and this review is not a definitive statement on their ultimate potential. Table 2 summarizes the salient features of current alternative fuel options.

4. Value chains and market-driven considerations

An assessment of the likelihood of success of each of the new technology and fuel types discussed above does not lend itself to a solution based purely on quantitative data, but rather requires a framework to organize more qualitative considerations. One approach is to think in terms of value chains. Figure 5 gives a simplified representation of a highly complex network of activities that transfer money in return for goods, services or taxation at multiple transaction points. Ultimately, all this is funded by the consumer. It is evident that if any value chain is working efficiently, every participant upstream of the consumer is at least breaking even in their particular role. But often the profit margins are quite slim and disruption caused by technological innovation at one step in the chain can impair or destroy the profit margin at another. Mature value chains tend to exhibit a degree of robustness, but radical innovation raises questions about where and how robust the profits will be in immature, unproved value chains.

The innovation we seek will therefore require some degree of coordination across a wide variety of industry participants to ensure the synchronized delivery of new types of vehicle and new fuels. The cost of switching will limit both consumers’ and suppliers’ willingness to experiment. At the same time, consumers will assess whether the affordability and utility of the new technology is acceptable with respect to established paradigms in areas such as refuelling and maintenance. Current participants and potential new entrants throughout the fuel and vehicle provision value chains will need to assess the potential impact on their existing activities and whether the risk and uncertainties and entry and exit costs for new activities are sufficiently manageable to warrant participation. Policy setters will need to examine macrolevel impacts, decide whether intervention is necessary to stimulate or regulate new market segments and attempt to steer the economies of those segments accordingly.

To formalize this, as current value chains adapt and new value chains emerge, it might help one to consider the interplay of technological innovation and three additional factors (figure 8):
— Consumers’ experience of owning, fuelling, driving and maintaining must not appreciably deteriorate by adopting innovative technology because they ultimately fund these value chains.

— Commercial participants throughout the value chain must have a reasonable degree of certainty that their activities will return an acceptable profit. Failing that, there must be low barriers to exit—a way to disengage without unreasonable penalty.

— Policy setters may support the previous two factors—encouraging positive consumer experience and managing the flow of value in new and existing chains—through, inter alia, subsidy and taxation.

Where a value chain has evolved sufficiently to support radical technical innovation, there is often either a strong commercial push or a strong consumer pull with little need for policy-driven intervention. I take as an example the digital revolution in the 1980s and 1990s, where shifts from analogue to digital media, such as from vinyl records to compact discs (CDs), were rapid:

— Technological innovation: development of CD players and media for music playback.

— Consumer experience: relatively low barriers to adoption (relatively low-cost item); considered a discretionary purchase so early adopters were audiophile hobbyists; initially high cost of players and replacement media traded off against superior quality sound, higher capacity, rapid access to tracks and durability.

— Commercial participation: alliance of major manufacturers (Sony and Philips) around an agreed standard; high uncertainty around consumer uptake but, with shared processing and fabrication facilities, only moderate cost to experiment; industry-wide participation driven by concern that success might cannibalize revenue streams from existing media sales.

— Policy setting: no perceived need to incentivize or regulate. However, hindsight suggests that some thought about digital copyright management might have been wise.

The digital revolution that adopted CDs was an efficient paradigm shift. The gradual migration from analogue to digital media (long-play vinyl record and compact tape cassette to CD, VHS to DVD, disc to iPod) was driven by (i) consumers accepting the risk and uncertainty that accompanied a perceived improvement in convenience, albeit at initially higher prices, (ii) content and hardware suppliers who were prepared to risk their investment in creating and promoting new products, and (iii) the use of existing and then (with the Internet) new low-cost distribution.
channels. The last 50 years have seen several such technology migrations in recorded storage media, by and large following very similar patterns of transition.

By comparison, radical technological innovation in transportation is a much less frequent and much slower process. After a house, a private vehicle is the most expensive purchase an average consumer makes and normally ties the buyer to a vehicle for some years. Depending on location and lifestyle, ownership or access to a vehicle is often perceived as mandatory rather than a discretionary choice, particularly in mature OECD economies. Reliability and proven technologies are important to motorists in such markets and barriers to experimentation with alternatives are high. In developing economies where there are far lower levels of vehicle ownership there may be a greater willingness to experiment, as evidenced by the success of low-cost, low-specification vehicles in India and China.

To understand better why transport is so resistant to innovation despite an apparent pressing societal need for change, the three factors that support the commercial uptake of innovative technology are here considered in greater detail.

(a) Consumers’ experience

From a consumer perspective, the traditional rule of thumb is that any replacement product or service has to have higher utility and/or be cheaper than the existing status quo. These two factors can be traded off, and in general a large improvement in one will accommodate a slight (but not massive) deterioration in the other. Traditional marketing nous will prioritize this consideration when launching a new product or service. And it does indeed make sense to ask: if a new fuel or vehicle has only the same utility as the traditional fuel or vehicle but costs more, why switch before the conventional option becomes prohibitively expensive or unobtainable?

Prima facie, the problem with the radically innovative technologies such as pure EVs is that they are perceived to be more expensive but of lower utility, being less convenient to ‘refuel’ and having a diminished range and unproven reliability. The EV does not have anything like the immediate appeal enjoyed by the CD on its introduction. For example, since 2000 combined EV and HEV numbers have reached only a few per cent of total new vehicle registrations (in 2011, 2.2% in the USA [29] and 1.3% in the UK [31]).

However, in energy markets additional dynamics are becoming visible. A growing and increasingly vocal segment of the population is prepared to forgo both relative utility and relative affordability in order to reduce environmental impact. For them, the long-term consequences of failure to address environmental issues outweigh the long-term consequences of reduced functionality road transportation. This is a rational position, but its proponents often demand that the consumer cost of the status quo be increased by higher taxation. This is tantamount to an admission that while there may be strong ethical reasons for migrating to a lower utility and less affordable replacement, a prerequisite of acceptance among the general population is to make the existing solution less affordable. Such an appeal implies that the majority is swayed more by the impact on the wallet than on the heart or the mind.

For now, many new fuels and vehicles have both low affordability and utility. Figure 9 shows my subjective placement of the technologies discussed earlier, relative to current conventional road vehicles at the centre. For comparison, CDs and MP3s are also plotted relative to their respective market incumbent at time of introduction.

Innovative products and services tend to enter or rapidly move to the lower-right quadrant. This represents the trade-off position of a product or service that is initially more costly but more fit for purpose. A product that gains traction within the market will move upwards as costs fall owing to technical improvements and economies of scale. With the exception of PHEVs, none of the technical solutions apparently occupies a viable position at present. This is alarming because many products have been available, or in gestation, for years. It seems naive to launch them as lower economy, lower utility items while expecting a mass market uptake. EVs will have niche appeal, but will not oust conventional ICEVs in terms of mass market penetration unless and until the utility improves and the relative economy can be guaranteed.
(b) Commercial participants

In both the fuelling and vehicle manufacture parts of the value chain, there are high barriers to both entry and exit. Participation is often capital intensive and takes years to pay back, so it is expensive to participate and potentially costly to walk away if investments do not deliver the expected returns. Consequently, participation in an (possibly unfamiliar) activity in an untested value chain is unattractive, particularly to companies that already have significant balance sheet exposure to capital employed with long payback times.

It is not clear that oil companies, which have occupied the entire traditional fuel value chain from exploration to retail, are sufficiently fit or willing to participate in any part of the new fuelling value chains. For example, for EVs the new value chain might include:

- establishing industry battery specifications;
- sourcing raw materials for batteries;
- manufacturing batteries;
- installing, operating and maintaining dedicated fast-charging facilities;
- providing charging facilities wherever vehicles park for extended periods;
- providing emergency battery replacement contracts to motorists;
- manufacturing recharging equipment; and
- organizing financing or point of sale equipment for public recharging locations (how do you pay when you plug in?).

Some of these activities are transactional. Some are labour intensive with unfamiliar safety and environmental challenges. Some are capital intensive yet may offer only modest returns. Some bring new types of brand liability. Most require competences that big oil companies do not have. Moreover, big oil companies do have existing investment opportunities that make much better returns for their shareholders than the, at best, utility-level returns probably from some of these activities.
This last point is made to good effect by Christensen [32, 33] with regard to the nature of disruptive innovation. Oil company executives acknowledge the likelihood of new value chains emerging to support disruptive technological innovation in energy markets. What they cannot see is how these activities can compare with opportunities in their existing business areas. If they think ahead, they see that lucrative fossil fuels production opportunities will eventually become scarce, and so being an early adopter in these new value chains might lay the foundation for repositioning the company, albeit with more modest returns. But those decisions are difficult to make by executives who would not see the commercial benefit of such a move in their working lifetime and who will not want to preside over a strategy that could be caricatured as ‘shrinking to victory’.

These new activities are neither financially attractive enough nor a sufficiently good fit with their core competences for major oil companies to pursue in place of the next big upstream project. Current conventional fuel retail is not a high-margin business: only non-fuel products, such as snacks and drinks, make a good return at retail stations. Large integrated oil companies make their money at the wellhead because the price of conventional crude oil significantly exceeds the finding, development and operating costs and the company retains part of this value, despite the fact that most of it accrues to the relevant government. In the last decade, spiralling capital costs have inflated big oil’s collective balance sheet leaving little scope to dilute returns on capital employed by making significant investments on unproven technologies in nascent fuel retail segments with only marginal net present value. Figure 10 shows that annual global upstream investment has risen sixfold since 1999, broadly in line with crude prices.

Despite their fundamental role in providing fuels today, oil companies are not natural participants in the new value chains. This aspect of the problem receives extraordinarily little critical attention. It cannot simply be assumed that market forces will ensure that suitable commercial participants will emerge with an integrated, fungible infrastructure to support all the activities in new value chains at a sufficient scale to make a substantial impact on crude consumption. However, a community of smaller players might appear, to service smaller and well-demarcated local markets, for example, a single megacity. Such small-scale development does not augur well for any activities that require global standardization or scale. With so many contending technologies and no uniquely viable solution, a patchwork solution may emerge, with a mix of different alternative fuels and drivetrain technologies from one market to the next.

Figure 10. Upstream industry capital investment and Brent dated oil price. Source: BP [5], OPEC [6], Lehmann Brothers, Barclays Capital [34]. (Online version in colour.)
(c) Policy setting

Without the compelling proposition of superior utility of affordability, a new product or service will generate scant interest in consumers, and consequently little interest in commercial participants. If there is still seen to be a case for promotion of the new product or service the solution is policy incentives. Available mechanisms might include the outright abolition of conventional fuels (cf. the abolition of the incandescent light bulb in Europe [35]), research and development incentives to accelerate technology maturation, the imposition of demanding performance standards for incumbent technologies, and subsidies or taxes that incentivize the desired consumer behaviour.

There are a number of concerns about the efficacy of such policies. The first is stability. Beneficiaries of subsidy or lowered taxation need to be sure that it will persist long enough to earn the expected benefit, which might take some years. For example, cheap electricity for recharging an EV might be needed for seven years to offset a higher EV purchase price. Consumers are often wary of government promises that policies will persist, certainly beyond its term of office. In countries where gasoline costs are relatively low and EVs command a price premium, it will take much longer to recover the incremental upfront cost. In such countries, there is more uncertainty about lifetime economics and less incentive to adopt energy-efficient alternative technologies.

Another concern for efficient policy setting is to ensure a consistent effect along the whole value chain. For example, there is no point subsidizing the purchase of FCEVs if hydrogen production, storage, distribution and retailing are not operationally and commercially viable. Value chains are extremely complex and sometimes causal interrelations are not clear. It can be difficult to apply a well-timed and internally consistent set of effective stimuli across a chain, as has been seen with attempts to stimulate domestic biofuel production in the USA, where there are high risks of inconsistent policies. The most important area to consider is infrastructure subsidies to offset the natural reluctance of commercial participants to make investments with decades-long payback timeframes. Government investment in infrastructure might be necessary.

Governments must also choose their goals. In a long-term, stable policy regime, de facto economic norms shape societal development. This makes it very difficult to compensate for unanticipated consequences of historic policy decisions. For example, taking account of exchange rates, a US gallon of gasoline currently costs about US$8.60 in the UK (including crude, refining and marketing costs, excise tax and value-added tax), $3.50 in the USA (including crude, refining and marketing costs, US Federal and State taxes) and $0.12 in Venezuela (a constant price, fixed in local currency). Without being judgemental about these taxation policies, they have had a profound impact on the way local consumer behaviour and transportation infrastructure (both road and alternative modes) have evolved. Doubtless in each case, policymakers felt this was the ‘right’ fuel tax or subsidy, but the long-term consequences of the transportation cultures they created were probably not thought through. To change one model for another without decades of transport infrastructure evolution would be difficult.

Finally, even where politicians know what the optimal strategic direction should be and understand the consequences, the corresponding policy initiatives might not be taken. Governments may well shy away from enacting or even proposing radical change necessary for a transport paradigm shift that will be unpopular with the majority of the general population, for fear of a short-termist reaction from their electorate.

5. Regional market variations

The examples of the interplay of consumer, corporate and governmental interests in the previous section show that effecting substantive change in road transport systems requires a holistic approach. Unless strong governmental edict can force change, there has to be a technology solution whose utility and economy attract consumers, societies have to seek collaborative solutions and a common agenda to incentivize players in the value chains, and policy intervention
will be necessary to stimulate the correct and timely evolution of value chains. Getting all the horses to pull in the same direction will be very difficult, and there will still be scope for wide variation in the solutions adopted between regions.

Even within today’s globalized economy, stark differences in road transport are visible in countries with comparable \textit{per capita} income. Economies with cheap fuel have developed energy-intensive transport systems that typically demonstrate:

- large fleets of inefficient, large and heavy vehicles;
- high levels of urban sprawl;
- lifestyle choices that require high passenger mileage; and
- low availability and usage of mass transit systems.

Urban development in the USA is the prime example. By contrast, where taxation is high, urban and lifestyle development have supported lower \textit{per capita} fuel consumption (see figure 4) with lower personal mobility and more widespread and better used mass transit. This is more the case in the development of Western Europe since the end of World War II.

The problem this phenomenon presents is simple to state but challenging to resolve. For the USA, the legacy of plentiful cheap gasoline and the assumption of its indefinite availability have shaped urban development. Sperling & Gordon [15] refer to this as an ‘innovation-deadening car-centric monoculture’, and while that is to some extent an exaggeration, the mix of US surface transport is extremely skewed towards road transport, which leaves relatively few levers to pull in terms of retreat.

The USA could certainly introduce more efficient ICE or HEV technologies. Roughly 5% of the total road fleet in replaced annually, implying that it takes at least 20 years to change the fleet without additional stimulus. Mitigating the rebound effects would require an economic disincentive to consume more fuel as vehicle fuel-efficiency rises. A new equilibrium could be established through taxation that incentivizes the purchase of more fuel-efficient vehicles, together with higher fuel taxation. The effect would be that motorists own a more efficient vehicle, pay less for this vehicle than for a similar but less fuel-efficient vehicle, drive the same distance, and pay the same amount for fuel as before by consuming less of a more expensive fuel. At present there are some examples of high vehicle sales taxation in Western economies (e.g. Danish sales tax on conventional vehicles is 105–180\% [36,37]) which the USA could emulate. This may seem rational, but the USA has an entrenched mindset on fuel taxation and, with good reason, the electorate has proved intransigent.

Any such taxation approach to policy needs to be accompanied by genuine options to change the norms of personal transport. The legacy position in the USA will not change significantly, and higher fuel taxation will not be a realistic proposition, until there are alternatives in place. These will not come about simply by making it painfully expensive to maintain current levels of driving. While there are some signs of a generational change in driving habits and expectations, by and large, people still want to commute to their place of work and to shop and socialize with companions in physical co-location. We engage in these activities in person because, for practical and social reasons, we need to, and if the motor vehicle is the only option, then people will drive whatever the cost. Some cities have alternatives, such as effective public transport or cycling capabilities, but in others a car is virtually the only choice. In London and Stockholm, the civic government has only been able to impose congestion charges on city centre road traffic because there are feasible mass transit alternatives.

Revising the US urban transport infrastructure, if possible, will require massive investment and far-reaching legislative intervention, which seems unlikely to occur in a timely fashion. I expect, rather, that over the next 30 years a combination of fuel-efficient vehicle design, modest penetration of light passenger EVs and PHEVs and moderate consumer discomfort will allow a marginal increase in overall vehicle miles, while reducing crude consumption to about 85\% of today’s levels. If the recent US shale gas bonanza continues without encountering regulatory hurdles, then natural gas could make significant inroads as a fuel for light delivery vehicles, more
so than many current outlooks suggest, but the impact of biofuels is likely to be minimal. There is huge uncertainty about any such predictions.

However, in non-OECD economies the transport future may be very different. For example, China’s expected economic growth is predicated on urbanization patterns that continue to move the population into megacities. China has 143 cities with a population of over 750,000
(accommodating roughly 25% of the population), and 55 of these are forecast to grow by a further 50% by 2025 [38]. China’s average per capita income remains low compared with OECD economies, but significant variations in personal wealth are visible, both within urban populations and between cities and regions. Growth in personal affluence is expected across the board, and car ownership is a widely held ambition.

In 2000, the Chinese market penetration of cars was extremely low, most vehicles were two-wheeled, and there was little room on city roads for four-wheeled motor vehicles. National mandates to control burgeoning car ownership met with little success, so individual cities enforced differing regulations. Beijing, a pro-car city, simply built more roads. In 1997, one million cars were registered in Beijing. By mid-2003, this had doubled to two million and by the beginning of 2010 had doubled again to four million [39]. By the end of 2010 an additional 700 000 cars had been registered, and the city imposed a lottery which limited new licence plate registrations to a mere 20 000 per month. By August 2012, there were over one million applicants for the 20 000 registered plates [39]. Similar approaches have been adopted elsewhere; Shanghai began auctioning new licence plates in 1998 and these now command as much as ¥60 000, which is more than the national average annual income [39]. But the simple fact is that road building cannot keep pace with demand for car ownership.

The Chinese car industry is concerned by these constraints. It has grown massively and is keen to satisfy burgeoning domestic demand with affordable but basic cars, while cars manufactured locally by overseas manufacturers also generally have lower specifications than their OECD counterparts. Hence, cars tend to be utilitarian rather than exemplars of leading edge fuel economy or emissions control. In May 2012, the national government announced a subsidy package of ¥6 billion for the purchase of fuel-efficient small cars (less than 1.6 l engine capacity, less than 6.3 l per 100 km fuel economy) [40]. Within months, notwithstanding civic registration constraints, car sales had increased by 14% year-on-year. China also has incentives in place to achieve a cumulative output of 5 million EVs and HEVs by 2020 [40], although this is hardly audacious given China’s overall production and fleet numbers. In 2011, China produced 18.4 million cars, some 23% of the global total [41], had 74.8 million passenger vehicles or 93.6 million total vehicles including trucks and registered 13.7 million new passenger vehicles (16.2 million total vehicles including trucks) [42]. The Chinese vehicle fleet has had compound annual growth of 17.3% for the last decade, but reached only 58 vehicles per 1000 population in 2010, compared with a US figure of 812. Figure 11 compares historic growth in the US and Chinese road vehicle fleets.

Maintaining this rate of growth in Chinese vehicle ownership will require trillions of dollars of investment in the coming decades, some of which could instead fund building alternative mass transit systems. Indeed, some 30 underground/metro lines are under construction, although many are reported to be experiencing financial difficulties [43,44]. But as urban residents move away to suburbs from densely packed city centres where they still work, the predominant transport investment is likely to be in roads and conventional ICEVs. China’s problem is that with growing affluence, burgeoning demand, municipalities scrambling to build enough roads to avoid congestion and automotive manufacturers keen to churn out basic functional vehicles, there is a genuine probability that China might default to replicating the US transportation monoculture. The trajectory of Chinese vehicle fleet growth (figure 11) does little to dispel these concerns.

6. Concluding remarks

In summary, to meet global liquids demand in the context of supply constraints, societies need to consider the following.

— To make a significant impact on crude consumption, scalable technology alternatives to dependence on crude oil need to be brought to market. The only scalable technology
alternatives are pure, hybrid or hydrogen fuel cell EVs, or liquids produced from natural gas or coal. Biofuels are likely to make a useful but only marginal contribution.

— Unusually for such a substantive technology shift, the mobility solution offered by EVs is currently inferior to that offered by existing motor vehicles and fails to meet the current needs of significant segments of the road transportation market.

— The mobility solution offered by alternative fossil fuels could be economically preferable to gasoline in many markets, but provides few if any environmental benefits.

— Widespread take-up of technology alternatives will require major actions in the following areas:

(i) Policy setting at urban, national and/or transnational (e.g. G20 or UN) level to incentivize consumer adoption of new technologies, possibly via radical changes in taxation of existing fuel and vehicle types.

(ii) Proactive stimulus of commercial participation in new value chains for support infrastructure (such as recharging/refuelling facilities), particularly in parts of those chains requiring substantive capital investment with long-term payback times.

(iii) Intervention to enable a broader range of transportation options within markets with entrenched car monocultures (for example, the USA).

It is unclear whether an adequate combination of policy steps and commercial participation will be delivered in time to allow alternative technologies to gain sufficient market traction to moderate consumption of crude oil. If the supply of affordable crude oil begins to fall short earlier than expected, the tensions caused by these phenomena will be more intense.

There are far too many uncertainties to speculate with any degree of confidence. However, there is a strong risk that OECD economies will rely upon merely incremental technology improvements that will come too slow and too late to deliver significant reductions in crude oil consumption. Similarly, there is a risk that technology choices and urban planning decisions in rapidly growing non-OECD economies (e.g. China) will emulate the US experience, thereby locking them into high per capita crude consumption from which it will be very difficult to retreat.

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