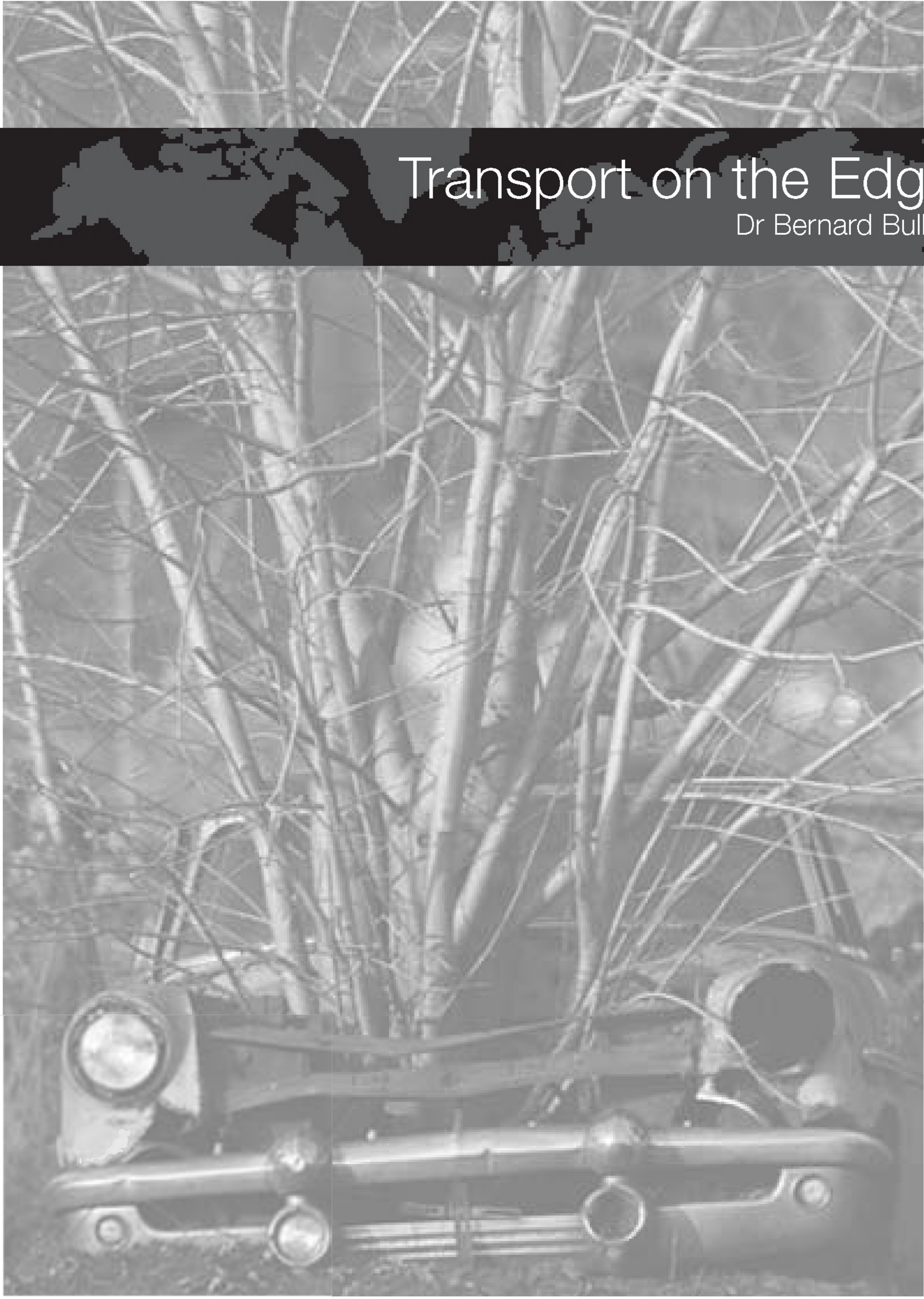


Transport on the Edge

Dr Bernard Bulkin

In the register of environmental issues, transport looms large. It is an urban, suburban, rural and international problem. It contributes to problems of local air quality, regional air quality, global climate change, land take, noise, congestion and loss of human life. It is not surprising that challenges to transport today are being driven by environmental issues above all others. However, other key drivers of change in the energy world are also important for transport: security of supply, diversity of supply, price – both absolute and its stability – and cultural changes in our society.

Road transport dominates the environmental issues but we note that, at least in the European Union (EU), air transport is the fastest-growing mode and represents an increasingly difficult problem in the battle against global climate change. Here I am concentrating on the technological opportunities for road transport, and on the policy implications of those technologies.

To introduce the subject of transport, it is useful to step back and put it in the context of the total picture for energy in the world. In this regard, we see that transport, though much talked about, accounts for only about 20 per cent of world primary energy. By far, industrial, domestic and agricultural uses of energy are the largest, and the energy used for generation of electricity also goes to these consumers.

But transport has one characteristic that is unique: it is essentially all fuelled by oil. Indeed, as oil has declined as a fuel for power generation, and is used less and less for home heating and industrial uses, we have been approaching a situation where the dominant use of oil is in transport. So transport policy must deal not just with the emissions issues around oil-fuelled vehicles, but also with the great fluctuations in the price of oil, the political issues affecting security of supply and the vulnerability inherent in a crucial infrastructure component that relies on a single fuel source.

Up until 1973, oil production followed the growth in gross domestic product (GDP). The dramatic change in the price of oil that occurred that year and the supply disruptions of 1978-79 changed this. There have been a number of years in the past quarter-century where oil production (and consumption) has decreased. Although the trend is clearly upwards, the rate of increase has been much slower than that of GDP. In the past decade, the growth of light trucks, sports utility vehicles (SUVs) and less fuel-efficient vehicles, particularly in the United States but also in the EU, has been moving the curve up. This has been further aggravated in the past five years by growth in demand from China and, to a lesser extent, from India. While they still represent only a small portion of demand (in 2000 there were three times as many private cars in Los Angeles as in all of India), the growth rates are very rapid.

So oil represents an important part of the energy picture for our society. Our overall primary energy in the United Kingdom is more than one-third oil. It is interesting to contrast this with Ethiopia, at the other extreme of development, where burning of biomass dominates. Even here, however, oil is in second place, used to supply the small number of cars, taxis and buses.

Fuel for road vehicles

Before we look at changes to the vehicle, we should therefore ask whether there are viable alternatives to oil as road transport fuel. And there are some. There has been, over the past few decades, a lot of interest in using liquefied propane/butane, usually sold as LPG (liquefied petroleum gas) or Autogas as a fuel for vehicles. In the United Kingdom, the government has provided tax incentives for this, and more than 1,500 stations now offer it. Many small fleets, such as vehicles from local councils, have converted to LPG. This has now probably peaked, as other alternatives come in. Independent tests have shown that for most vehicles there is little advantage in emissions reduction from LPG compared with ultra-low-sulphur gasoline or diesel. Similarly, compressed natural gas (CNG) has been used in some places, particularly where there is a surplus of gas with no good market for it. The cost of compression will always make this an expensive alternative.

Natural gas does offer possibilities, however. The most useful is the conversion of natural gas to liquid fuel, usually diesel. The set of chemical transformations to do this, known usually as gas to liquids or GTL, has been around since the 1930s, developed in Germany. A related process, converting coal to a gaseous mixture and then on to diesel or gasoline, was used by Germany during the war, and more recently in South Africa. Until fairly recently these processes were very expensive. Recent developments both in the catalysts and in the chemical engineering of the reactors have changed that situation, and new plants are being built, especially in Qatar, where there is a huge gas resource. The diesel fuel that results from this process, often known as FT diesel (the German inventors were Fischer and Tropsch), is very high cetane and virtually zero sulphur, so can be claimed to be the best diesel available.

Biofuels are also important, and will be more important in the future. Today's technology is mainly about making ethanol as a gasoline additive, usually up to 15 per cent, from corn, sugar beet or cane. It is widely used in the United States as an agricultural subsidy for corn growers, and in Brazil. But it is being investigated in places like the east of England, where there is a substantial sugar beet crop. Diesel fuel is also made from rapeseed oil, other seed oil crops, and used vegetable oils. All of this is today's technology for using biomass. But it is, for the most part, not a sensible approach in the long term, because it takes land away from food to use for fuel.

To understand how biofuels could work in the future, it is useful to go back to the gas-to-liquids process. The modern way of looking at this is called polygeneration, a term that I believe was first coined by Robert Williams of Princeton and NiWei Dou from Tsinghua University. In polygeneration, gas, coal or heavy oil is converted to a mixture of carbon monoxide and hydrogen known as synthesis gas, or syngas. Coal syngas was burned in homes for generations in the United Kingdom, where it was known as town gas, and it is still in use in this form in Chinese cities today. Syngas can be converted to diesel fuel, used for power generation or heat, or made into high-value chemicals. By generating energy in all these different forms, and being able to vary the quantities of each, we optimize the economic possibilities for the process.

Now consider the same approach for biofuels. If we start with corn, instead of just getting food or ethanol, we take a polygeneration view. Most of the life of the corn plant is devoted to growing stalk and leaves. Modern corn cultivation produces only one ear of corn per plant. The stalk and leaves are waste, known as stover, and have a negative value as they have to be taken away. What we need for biofuels to be viable are biotechnological processes that convert stover to fuel components such as ethanol, speciality and bulk chemicals, and energy. Then we will really have something of value to society.

To summarize the alternatives to gasoline and diesel derived from oil:

- Fuels such as LPG and CNG may survive in small niches, but they are unlikely to be important for the long term. They require vehicle conversions or specialized vehicles, and do not offer very big advantages to the environment. Policy should really abandon these to the market.

- Gas to liquids can mean very clean diesel fuel as far as local emissions are concerned. It offers no special advantage on carbon emissions. Because costs have come down, plants will be built to take advantage of “stranded” gas and bring it to market. Development of GTL commercially offers a form of diversification for road transport fuels, opening up new suppliers competing for the market. It needs no special policy encouragement.
- Biofuels today are expensive, requiring considerable subsidies, which some governments have been willing to provide, mainly to support farmers. But it is possible to foresee how the tools of biotechnology could lower these costs dramatically, and make it possible to utilize a variety of agricultural waste products, such as stover, rice straw and even fen cuttings, to produce fuel. Where food and fuel can be co-produced, the carbon cost of fertilizer and cultivation can be spread across the products, and there is an overall positive impact on climate change.

New kinds of vehicles

But what about the vehicles themselves? What technologies can we expect that might make an impact on the environmental and supply issues associated with road transport? We will look at several alternatives, but especially at hybrid vehicles and fuel-cell vehicles, and will explain how all of these work. A good place to start is the all-electric battery-powered vehicle.

Schematically, a battery-powered vehicle draws its power from the electricity grid, uses that to charge batteries carried on board the vehicle, and then draws down on the batteries to drive electric motors that turn the wheels. Power technology allows the energy from braking to be captured by a generator and to feed the batteries as well. This is known as regenerative braking.

While there has been improvement in battery technology over the past few decades, it has not been possible to achieve the energy densities required to build a vehicle that has the power and range expected by customers. In other words, we need too much battery per car, and the result is that all electric vehicles are good for is driving batteries around in. This has occurred despite fairly massive research programmes and, in California, government mandates requiring electric vehicles (mandates that have had to be modified or withdrawn because of lack of technological progress). The overall environmental impact of the battery electric vehicle depends on the mix of fuels used to generate electricity for the grid. So at this time, and for the foreseeable future, battery electric vehicles are not the answer.

A much more important approach is the hybrid electric vehicle. This is similar to the battery electric vehicle, except that the grid is replaced by an internal combustion (IC) engine, powering a generator to charge the batteries. At first glance one might ask what the benefit is; we still have gasoline or diesel as the fuel, and all the associated emissions. But there are several reasons why the hybrid is a good solution.

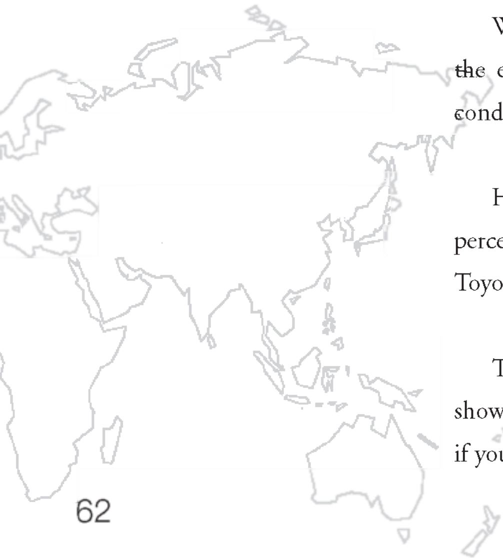
- Electric motors are efficient and, coupled with the energy captured from regenerative braking, give a good benefit to fuel economy.
- The internal combustion engine can be smaller – probably half the size of the engine required for today's cars.
- Because acceleration can draw down more on the batteries, it is possible to run the IC engine at constant rpm (revolutions per minute), choosing a range where it is at its most efficient.
- When the car is stopped in traffic or for any other reason, or any time the batteries are fully charged, the IC engine can be shut off.

All of these aspects of a hybrid vehicle mean a significant improvement in fuel economy and a reduction in emissions. Improvements of greater than 50 per cent are possible for vehicles of comparable size and equipment. The improvement achieved will depend on the mix of city and highway driving, on external temperature, on driving style and many other factors, but generally the more adverse the conditions the better the hybrid fares by comparison with the IC-engine car of today.

What has been described is the so-called series hybrid. There is also a parallel hybrid, in which both the electric motors and the IC engine can give power to the wheels. Some vehicles and driving conditions will favour the series version, some the parallel version.

Hybrid vehicles are here today. They are commercially available, although they represent a small percentage of the market. The most widely sold to date is the Toyota Prius, but other models from Toyota, Honda, Ford and General Motors, representing different sorts of hybrids, are also available.

The display on the driver's dashboard in a Prius shows fuel consumption, of course, but it also shows when the driver is capturing energy through braking. The reason for showing this is important: if you brake hard to stop, the generator does not have the capacity to capture the energy, while gradual



braking allows much more to be regenerated. This display gives the driver feedback that leads to an alteration of behaviour. Another display available to the driver indicates what mode the engine, battery and braking system are using. At very low ambient temperatures, -25ºC, the car can still achieve more than 40 mpg (less than 7 litres/100km), whereas normal IC-engine cars would almost certainly be below 10 mpg (28 litres/100km) in such conditions.

Hybrids are not just useful for cars – they are important for buses and other urban heavy-goods vehicles as well. Indeed, the urban bus or garbage-collection vehicle is probably the best use of the hybrid design. We have already indicated that the advantage of the hybrid is that the IC engine can run at constant rpm, avoiding the inefficiencies that come in acceleration and deceleration.

Urban buses and garbage collection vehicles are always running in this inefficient portion of the cycle, so they derive maximum benefit from hybridization. A number of US cities, including Seattle and New York, have already made big investments in hybrid buses and are reporting improvements in fuel economy of 40 per cent, and even bigger reductions in emissions of nitrogen oxides and particulates. China has also started a programme to develop and implement hybrid buses for its major cities.

So to sum up on hybrid vehicles:

- Hybrids are the right choice for urban buses, rubbish-collection vehicles, other urban fleets and private cars. They give benefits for local and global air quality.
- The specification of these vehicles is an area of control for government, usually at the local or regional level, and should be pursued aggressively to maximize the benefits.
- Hybrid cars are commercial today, and policy measures – whether incentives to purchase or to use (such as the exemption from the congestion charge that hybrids enjoy in London) – could bring them into the car population more rapidly.
- Hybrids are a big win. With a combination of hybrids and biofuels, a 50 per cent reduction of carbon emissions from road transport is a realistic goal in the medium term.

Now I want to turn our attention to fuel cells, the final technology to consider. There is a similarity with electric and hybrid vehicles. Once again, we have electric motors driving the wheels, and a regenerative braking system. Now, however, instead of the internal combustion engine of the hybrid, we have a fuel-cell stack powered by hydrogen. But the design concept is similar.

What is this fuel-cell stack, and how does it work? A fuel cell is just the reverse of the experiment we are familiar with from school, namely the electrolysis of water. In that experiment, electricity is passed through water and converts the water to hydrogen and oxygen. In a fuel cell, hydrogen and oxygen (from air) are combined across a membrane so as to allow the energy that is released to be captured as electricity. A platinum catalyst coats the membrane so as to lower the energy barrier for the reaction to take place. The only by-products of generating electricity in this way are air depleted of some of its oxygen, water and a small amount of heat.

To use this concept in a vehicle, a number of these fuel cells are assembled into a stack, and in this way powers of up to 100 kilowatts may be generated. Some time ago Toyota showed that all the components required for a fuel-cell vehicle could be fitted into the chassis of a conventional vehicle. Toyota, Daimler-Chrysler, Ford, General Motors and others have since built such prototype vehicles. But simply taking a vehicle based around a 100-year-old concept and putting a new powertrain in it is not very interesting. A more exciting concept is that shown by General Motors in its concept car, the Autonomy, and in a more recent version called the Sequel. This vehicle completely redesigns the car based on the idea that it will be powered by a fuel cell and use electricity for all its systems.

In the Autonomy concept, the fuel, fuel-cell stack, and all the motors and accessories are in the base, called the skateboard. The top contains the seats and upper chassis shell, and plugs into the base to connect to the driver's controls and displays. In this way, an owner could choose to change tops periodically, at modest cost, leaving the same base. Manufacturing would be efficient, as only the tops would vary from model to model.

All of the components fit inside the base, including tanks for storing hydrogen under high pressure. Because the vehicle is completely electric, there is no need for mechanical linkages between the driver and wheels, as we have in today's steering-wheel-driven vehicles. Rather, this car is completely drive-by-wire, and can be steered, speeded up and slowed down using a joystick.

It is logical at this point to ask where the hydrogen will come from. There is lots of hydrogen in the world; unfortunately most of it is attached to oxygen or carbon. We need to get it free from them and into the form of H_2 gas. Today, hydrogen made for chemical processes is generally produced from natural gas, using the same process we discussed earlier, via syngas. Ideally we would make the hydrogen from solar power via electrolysis of water, but to do this today is prohibitively expensive. Either efficiencies of solar cells have to increase or the costs must come down dramatically before we could start to do this commercially. Moreover, we still have a long way to go to get fossil fuels, and particularly coal, out of the power generation mix. From a policy point of view, it would seem that it will be several decades before we would want to divert any of our renewable energy to making hydrogen. An alternative to this view is that the solar power used to produce hydrogen for Europe could be in, for example, the Sahara desert. There the hydrogen could be liquefied and transported to Europe. This solution does somewhat overlook the shortage of freshwater in the Sahara for electrolysis, and would, today in any case, be extremely expensive.

There has also been considerable discussion of production of hydrogen from nuclear power – either from electricity by electrolysis, or by thermal splitting of water. Neither of these seems likely in the short to medium term, given the difficulty of building nuclear reactors for power generation, but it might be a longer-term outcome.

Fuel cells are much more expensive than internal combustion engines, and the biggest factor in this is the cost of platinum. To achieve the power required, fuel-cell stacks in the vehicles that have been built to date use 100 to 200 grams of platinum, which is 50 to 100 times more platinum than is used in a catalytic converter. Manufacturers have a goal of getting this down to 20 grams, still ten times more than in today's vehicles. And of the 155 tonnes of platinum produced every year, mainly in South Africa, 50 already go into catalytic converters. Some of the rest goes to other industrial processes, such as petroleum refining, and a lot goes for jewellery. The demand for platinum has been driven by increasing wealth in China, where platinum jewellery is much favoured.

What all these numbers mean is that even as few as a million fuel-cell cars (there are 800 million vehicles in the world today) would take two-thirds of current platinum production. While this production could surely be increased, one wonders by how much. And while ultimately the platinum would be largely recycled, it would be at least ten years before this started to happen in any significant amounts.

A significant barrier therefore remains to fuel-cell vehicles becoming important in the market today. We have discussed some parts of this barrier, but not all the components. The technology is not all there yet. True, companies have built vehicles and driven them on the road. There are two fuel-cell-powered buses operating in London and some in a few other cities. But there are still unresolved issues, such as operation of the vehicles in sub-freezing weather, for example – especially where the car is left on the street for a week between use, as many urban motorists do. Fuel cells operate wet and cannot be subjected to repeated freeze-thaw cycles.

Cost continues to be a problem – it is 10 to 100 times greater than for the comparable IC-engine powertrain (less for the total vehicle, of course). I have heard one auto industry technology leader state that the last fuel-cell vehicle they built cost $500,000. Mass manufacturing will help with this, but some of the costs do not go down as they are fixed parts of the vehicle. As mentioned, a big part of this is the platinum content, which takes us back to a technical problem.

Even if we have working vehicles at reasonable cost, we still need a fuelling infrastructure for the hydrogen. This probably means stations with cryogenic distribution and storage, with high-pressure dispensing, so as to get sufficient hydrogen on to the site and into the vehicle to give a reasonable range (say 300 miles without refuelling). And there is the whole infrastructure for production and distribution, all of which is new. Generally, infrastructure is not an interesting issue. It is mainly a question of money, but a lot of money, say $1.7 billion for London alone. It is not possible to build a business model for this investment that has a reasonable return. Studies at Argonne National Laboratory in the US have shown that the cost of distribution is also likely to be very high, at least $1/kg just to distribute the fuel.

Finally there is the challenge of reliability and durability of the vehicles. When you buy an IC-engine vehicle today, you are buying 100 years of evolution of the technology, and the last 25 years have been spectacular in terms of reliability and durability. Customers do not expect a car to break down, and they are rarely disappointed. Fuel-cell vehicles need to achieve this immediately, or customers will turn against them. This is a very tough challenge for the manufacturers.

Today, there is more investment in new powertrain technologies that could be alternatives to the internal combustion engine than there has been since spark ignition and diesel engines came to dominate the scene. It seems likely that for the next 30 years, hybrids will be the technology with the greatest chance of making it big in the road transport market. Fuel cells will come later, at least in the EU and United States. In China, things might be different, as problems of air quality, a desire to lead in a new technology, lower power requirements for vehicles (as eight-speaker stereos and air conditioning are not demanded) and the need to build a new infrastructure for fuelling make fuel cells somewhat more attractive.

In any case, customer expectations are high, and it will not be easy for new technologies to meet them. Hybrids allow a role for biofuels in the fuel mix, and combined, these two solutions can have a very big impact on carbon emissions and local air quality. In all of this there remain many scientific challenges as well as big opportunities to contribute to step changes in what we drive.

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