When will hybrid technologies dominate the heavy-duty vehicle market?

Forecasting Using Innovation Diffusion Models

JESPER BRAUER

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## Abstract

Hybrid-electric technologies have recently been introduced into the market for heavy-duty vehicles (HDVs). However, challenging an established technology with a new and untried technology is difficult, also under the best conditions. Forecasting is a vital tool in product portfolio management, since it provides guidance on how much resources a firm should allocate on new innovative projects and products and when and where to enter the market.

Therefore, this thesis forecasts the market penetration of hybrid HDVs in Europe by usage of innovation diffusion models – based on three different market scenarios assuming no, some and considerable incentives or legislative CO₂ for HDVs. Hybrid-electric, hydraulic hybrid and flywheel hybrid vehicles are considered and an analogical approach is used based on sales data for radial tyres, disc brakes and anti-lock braking systems.

The result from a non-linear regression analysis indicated that innovation diffusion models of mixed influence are capable of predicting future market demand, not only of hybrid HDVs, but also of other HDVs with new innovative technologies or solutions. Therefore, it was suggested that innovation diffusion modeling should be a standard tool in the strategic planning of a HDV firm’s all new innovative products.

All market scenarios resulted in a rather low diffusion speed of hybrid HDVs during the first ten years, but the speed increased then rapidly during the next ten years such that 40-50 percent of the HDV market was penetrated in 2030. In the most hybrid-friendly scenario, the market was nearly fully penetrated after 50 years since the first introduction in 2010, while in the least hybrid-friendly scenario additional ten years was needed to fully penetrate the HDV market. The forecasts may be affected by possible pre-diffusion, the emergence of a dominant design or the diffusion acceleration effect.

One of the major challenges of using innovation diffusion models for sales forecasting of hybrid HDVs, was to find appropriate and sufficient analogous sales data. Therefore, Thomas (1985) analogous approach was further developed to be more focused on finding analogous sales data from internal, external or public sources.

**Key-words:** Hybrid vehicle, Heavy-duty vehicle, Market penetration, Product portfolio management, Forecast, Innovation, Diffusion, Bass model, Analogous product
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Hybrid vehicle technologies offer significantly reduced fuel consumption and greenhouse-gas (GHG) emissions, but are associated with increased vehicle complexity, weight and purchase cost (NAS, 2010). Hybrid-electric technologies have been available for cars for several years and recently these technologies have been introduced into the market also for heavy-duty vehicles (HDVs) by market entry of hybridized refuse collectors and city buses. However, challenging an established technology with a new and untried technology is difficult, also under the best conditions (Weiss and Dale, 1998). In addition, there are other competing technologies that also reduce fuel consumption and GHG emissions, such as (pure) electric vehicle technologies, low rolling resistance tyres and lightweight materials (AEA, 2011). Therefore, it can be unfavourable for a firm in the HDV industry to allocate too much resources, too early, on hybrid projects and products. Especially, since late market entrants might develop superior skills for the market being developed, at considerable expense, by the first-movers (Tidd, 2010).

On the other hand, the consequences for entering the hybrid HDV market late can be significant, since first-movers often outsell late-movers (Shankar et al., 1998). Advantages that might accrue early entrants include the acquisition of market knowledge (which enables fine-tuning and second-generation products to be introduced before competitors), the freedom to charge a premium until competitive products are launched, the possibility to create greater barriers to entry for potential competitive offerings and enhanced market image due to being the technological leader (Tidd, 2010).

It is obvious that there is an urgent need for guidance on how much resources a firm in the HDV industry should allocate on hybrid projects and products and when it might be as most advantageous to launch hybrid HDVs. Market forecasts provide such guidance, but forecasting demand for new technologies is difficult (Mohr et al., 2010). Therefore, it is not surprising that the forecasted market penetrations of hybrid HDVs in AEA (2011) and Murphy (2011) differ considerably. Both these forecasts seem to be based on a combination of judgmental techniques and simple time series analyses, such as trend line analysis.

Generally, there are five categories of new product forecasting techniques (Kahn, 2006): i) judgmental techniques; ii) customer/market research techniques; iii) time series analyses; iv) regression analyses; v) other quantitative techniques. Innovation diffusion models, such as the Bass (1969) model, belong to the third category and are particularly well suited to forecast the long-term sales patterns of new technologies and products (Lilien and Rangaswamy, 2003). Some of the largest U.S. corporations have used the Bass model, including IBM, Sears and AT&T (Rogers, 2003). Several authors have used diffusion models for forecasting the sales of alternative powertrain technologies in the automobile market, e.g. McManus and Senter (2009; plug-in hybrid-electric vehicles), Muraleedharakurup et al. (2010; hybrid-electric vehicles) and Park et al. (2011; hydrogen fuel cell vehicles).

The purpose of this thesis is to forecast the market penetration of hybrid HDVs by usage of innovation diffusion models. Two main research questions are addressed:
1. How capable are innovation diffusion models of representing the diffusion of new innovative products in the HDV market?
2. When will hybrid technologies dominate the heavy-duty vehicle market in Europe?

Hybrid-electric, hydraulic hybrid and flywheel hybrid vehicles will be considered and Thomas (1985) analogical approach will be used, since basically no sales data are available yet.

The thesis is structured as follows. First, characteristics of the HDV industry and market are presented and thereafter different hybrid technologies are described. Then, the theoretic framework used by the author is explained and the essential mathematical diffusion models are derived. This is followed by an estimation of the market potentials for hybrid HDVs for three different market scenarios and identification of analogous products. Then, customer values and diffusion parameters are estimated and three different market penetrations (one for each market scenario) of hybrid HDVs are calculated. These results are then analyzed and discussed. Finally, an extended method for estimating market growth for new products is presented followed by a discussion of opportunities for future research.
2 HDV industry and market

The European Automobile Manufacturers Association (ACEA), represents the interests of the sixteen European car, truck and bus manufacturers at EU level. ACEA uses the following weight categories for heavy-duty vehicles (AEA, 2011):

1. Commercial vehicles: 3.5 ton – 16 ton Gross Vehicle Weight (GVW, the actual weight of the fully loaded vehicle or trailer, including all cargo, passengers and optional equipment).
2. Commercial vehicles: Buses and coaches 3.5 ton – 16 ton GVW.
3. Heavy commercial vehicles: Heavy vehicles >16 ton GVW.
4. Heavy buses and coaches: Buses and coaches >16 ton GVW.

This thesis will focus on heavy-duty vehicles over 16 ton GVW, i.e. vehicles in the categories 3 and 4. Furthermore, AEA (2011) divides HDVs into eight different mission categories (or segments):

1. **Service/Delivery (3.5 ton – 7.5 ton)**. Urban operation including frequent stop start.
2. **Urban delivery/Collection**. Distribution in cities or suburban areas including frequent stop start driving.
3. **Municipal utility**. Typical duty cycle is low speed urban operation with frequent stop starts. Typical vehicle is a refuse truck.
4. **Regional delivery/Collection**. Regional delivery of consumer goods from a central warehouse. Includes periods of constant high speed and urban operation (also mountain road goods collection, etc).
5. **Long haulage**. Long periods of constant high speed travel with very few periods of urban operation (e.g. delivery to international sites, more than one day trip).
6. **Construction**. Vehicles operating on and off-site (e.g. concrete mixers and tipper trucks).
7. **Bus**. Low speed travel with frequent stop starts in cities or suburban areas. Also interurban travel.
8. **Coach**. Long periods of constant high speed travel with periods of urban operation.

The last seven categories will be considered in this thesis. Examples of vehicles from six of these categories are shown in Figure 1.
2.1 Vehicle manufacturers

According to AEA (2011), the EU HDV market is dominated by seven major European manufacturers (see Table 1), who also account for an estimated 40% of worldwide HDV production. In the buses and coaches sub-sector there are also a significant number of smaller manufacturers (or bodybuilders) accounting for approximately 25% of all new vehicle registrations.

The HDV market is highly complex compared to the market for light-duty vehicles (AEA, 2011). The Original Equipment Manufacturers (OEMs) are for the most part not responsible for the final vehicle configuration other than the powertrain, chassis and cab. Essentially all rigid trucks will go through bodybuilders to provide the additional body or superstructure and any additional auxiliaries (e.g. tail lifts, cement mixers, refuse collection systems, etc) for specific customer requirements. Road tractors, in contrast, are essentially finished products although there may be some additional modifications. In addition, the end performance or characteristics of the full articulated vehicle (i.e. the road tractor with semi-trailer) will be highly dependent on the characteristics of the semi-trailer type pulled by the tractor unit.

Top seven trailer manufacturers account for over 50% of new trailer registrations. The rest of the trailer and body-builder sector is highly diverse with thousands of organizations, often only operating in local markets.
Table 1. Summary of the major European heavy-duty vehicle manufacturers and bus builders. Major manufacturer groups accounting for over 93% EU HDV registrations highlighted in bold. The major manufacturers also supply engines and chassis to the vehicle builders like VDL. From AEA (2011).

<table>
<thead>
<tr>
<th>Name</th>
<th>Brands and HDV Types Covered</th>
<th>Head Office</th>
</tr>
</thead>
<tbody>
<tr>
<td>DAF Trucks</td>
<td>DAF Trucks</td>
<td>Eindhoven (Netherlands)</td>
</tr>
<tr>
<td>VDL Group</td>
<td>VDL Bus and Coach</td>
<td>Valkenswaard (Netherlands)</td>
</tr>
<tr>
<td>Daimler AG</td>
<td>Mercedes-Benz Trucks</td>
<td>Stuttgart (Germany)</td>
</tr>
<tr>
<td></td>
<td>Evobus (Mercedes-Benz, Setra)</td>
<td></td>
</tr>
<tr>
<td>Ford</td>
<td>Ford trucks (large vans), minibuses</td>
<td>Köln (Germany)</td>
</tr>
<tr>
<td>BMC</td>
<td>BMC trucks and buses/coaches</td>
<td>Izmir (Turkey)</td>
</tr>
<tr>
<td>M.A.N.</td>
<td>MAN trucks and buses/coaches, Neoplan coaches</td>
<td>München (Germany)</td>
</tr>
<tr>
<td>Renault Trucks</td>
<td>The Renault Truck and Bus business has been owned by Volvo since 2001</td>
<td>Saint-Priest (France)</td>
</tr>
<tr>
<td>Scania</td>
<td>Scania trucks, buses/coaches</td>
<td>Södertälje (Sweden)</td>
</tr>
<tr>
<td>Volkswagen</td>
<td>VW trucks (large vans), minibuses</td>
<td>Wolfsburg (Germany)</td>
</tr>
<tr>
<td>Volvo Trucks</td>
<td>Volvo Trucks and Volvo buses/coaches</td>
<td>Göteborg (Sweden)</td>
</tr>
<tr>
<td></td>
<td>(also Renault trucks, buses – see above)</td>
<td></td>
</tr>
<tr>
<td>Iveco (Fiat)</td>
<td>Iveco (trucks)</td>
<td>Turin (Italy)</td>
</tr>
<tr>
<td></td>
<td>- Iveco Irisbus (buses/coaches).</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Iveco Magirus (fire fighting and civil protection vehicles)</td>
<td></td>
</tr>
<tr>
<td>Mitsubishi Fuso</td>
<td>Trucks (3.5-7.5-t segment)</td>
<td>Stuttgart (Germany)</td>
</tr>
<tr>
<td>Alexander Dennis</td>
<td>Bus and coach chassis and bodies, also includes Plaxton coaches</td>
<td>Edinburgh (UK)</td>
</tr>
<tr>
<td>Wright Group</td>
<td>Bus bodies (built on Volvo and Scania chassis)</td>
<td>Northern Ireland (UK)</td>
</tr>
<tr>
<td>Optare</td>
<td>Bus and coach chassis</td>
<td>Lancashire (UK)</td>
</tr>
<tr>
<td>Van Hool</td>
<td>Manufacturer of buses, coaches, trolleybuses, and trailers</td>
<td>Koningshooikt (Belgium)</td>
</tr>
<tr>
<td>Solaris</td>
<td>bus, coach and trolleybus manufacturer</td>
<td>Bolesławiec-Osieidle and Środa Wielkopolska (Poland)</td>
</tr>
<tr>
<td>SOR</td>
<td>Manufacturer of buses, coaches and trolleybuses</td>
<td>Libchavy (Czech Republic)</td>
</tr>
</tbody>
</table>

2.2 HDV market
The following Figure 2 and Figure 3 present summaries of the time-series of registrations of new trucks and buses and coaches in the EU27.
Figure 2. EU27 New registrations of rigid trucks and road tractors (an articulated vehicle consists of a road tractor coupled to a semi-trailer). From AEA (2011).

Figure 3. EU27 New registrations of buses and coaches. From AEA (2011).

In Figure 4 and Figure 5, sales have been allocated to the vehicle categories that were presented in the beginning of section 4.
2.3 Customers
The majority of freight operators are small in size, with 85% of operators having fewer than ten vehicles and with 35% of operators only have one vehicle. The EU bus industry tends to be dominated by large national or international companies, while the coach sector is made up of a considerable number of much smaller operators.

Figure 6 shows the voice of HDV fleet managers in U.S (there might be differences between the voice of U.S and European fleet managers, but unfortunately no similar European study was found). According to the market research study by Frost and Sullivan (2011), fuel efficiency is the most desired powertrain technology when purchasing a new vehicle. This is because the fuel is the main operating cost for most transport companies (ACEA, 2010). For instance, the total operating costs for a 40-tonne tractor-semitrailer combination is about 30 percent (see Figure 7). Still burns a 40-tonne truck built today around a third less fuel than one made in the 1970s. Table 2 shows the average annual mileage and fuel cost for the different vehicle categories.

Figure 7. Total operating costs for a 40-tonne tractor-semitrailer combination. From ACEA (2010).
Table 2. Average annual mileage and fuel cost for the different vehicle categories. Source: AEA (2011).

<table>
<thead>
<tr>
<th></th>
<th>Average Annual Mileage (km)</th>
<th>Average New Vehicle Fuel Consumption (l/100km)</th>
<th>Average Annual Fuel Cost (average fuel price: €1/l) (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban delivery, Collection</td>
<td>40,000</td>
<td>21.0</td>
<td>8,400</td>
</tr>
<tr>
<td>Municipal utility</td>
<td>25,000</td>
<td>55.2</td>
<td>13,800</td>
</tr>
<tr>
<td>Regional delivery, Collection</td>
<td>60,000</td>
<td>25.3</td>
<td>15,100</td>
</tr>
<tr>
<td>Long haulage</td>
<td>130,000</td>
<td>30.6</td>
<td>39,800</td>
</tr>
<tr>
<td>Construction</td>
<td>40,000(^1) – 60,000(^2)</td>
<td>26.8</td>
<td>13,400</td>
</tr>
<tr>
<td>Bus</td>
<td>50,000</td>
<td>36.0</td>
<td>18,000</td>
</tr>
<tr>
<td>Coach</td>
<td>52,000</td>
<td>27.7</td>
<td>14,404</td>
</tr>
</tbody>
</table>

\(^1\)Heavy construction (60% off-road)
\(^2\)Light construction (10% off-road, e.g. concrete mixers, tipper trucks)

According to AEA (2011), the European HDV market is already more significantly focused on improving fuel efficiency due to high fuel prices compared to the rest of the world. As a result, the European manufacturers of HDVs are at the forefront of efficient HDVs.

2.4 Emission regulations

According to AEA (2011), there is an urgent need to reduce emissions of greenhouse gases from all sectors of the global economy in order to avoid a dangerous climate change. A number of international and national policies and commitments have been put in place over recent years to ensure that emissions from particular sectors of the economy start to reduce, and across the EU, overall GHG emissions are on a declining trend. However, emissions from the transport sector continue to increase and HDVs are estimated to account for around 26% of all CO\(_2\) emissions from road transport in the EU. CO\(_2\) emissions are directly related to the amount (i.e. the fuel consumption) and type of fuel burned in the engine (NAS, 2010). For instance, typical diesel fuel is approximately 86 percent carbon by mass, while natural gas is only around 75 percent carbon by mass. In addition, biofuels have the advantage of carbon uptake in the feedstock when producing the fuel. Figure 8 shows relative energy consumptions and GHG emissions for different vehicle categories.

The primary EU approach to control of emissions from HDVs has been to directly regulate emissions standards for new vehicles (see Figure 9), where the strictest standard, Euro VI, will become mandatory for manufacturers in 2013. However, these Euro standards only regulate emissions that affect air quality, not CO\(_2\) or other GHG. In practice, many of the engine modifications required to limit the regulated emissions have also decreased the fuel efficiency of the engines and therefore led to an increase in CO\(_2\) emissions (AEA, 2011). Legislation has been developed to address CO\(_2\) emissions from cars (from 2012 to 2015, car manufacturers will need to ensure that their new vehicle fleets are capable of complying with the fleet-weighted target of 130 g CO\(_2\)/km), but not yet for heavier commercial vehicles. The Japanese Government has set vehicle emission standards for HDVs, which requires an average 12% improvement in fuel efficiency relative to 2002 across multiple HDV
classes by 2015. However, this mainly involves smaller distribution trucks and is supported by strong incentive programs for hybrid solutions. Furthermore, the EU has introduced directives on driver training, government procurement and road user charging, all of which have an influence on HDV emissions.

Figure 8. Estimated breakdown of the EU HDV energy consumption by mission profile for 2010 (GHG emissions follow the same proportional split as energy consumption). From AEA (2011).

There are a large number of different technologies which can be applied and are being developed to reduce GHG emissions targeting powertrain efficiency improvement, reduction of vehicle losses and improvement in driver behavior (AEA, 2011). Technologies targeting powertrain efficiency improvement have the potential for the largest reduction in GHG emissions. The large variation in vehicle duty cycle also has an impact on the benefit any one technology will have (different technologies offer benefits over different duty cycles). Many powertrain technologies have greatest

Figure 9. HDV emissions (percent Euro 0). From ACEA (2009).
benefit over urban cycles with a high degree of stop start operation. Technologies aimed at reducing vehicle drag losses, on the other side, give greatest benefit to those operating over long distances at constant high speeds.

Alternative fuel powertrains are not significantly used in heavy trucks, except in a few countries (AEA, 2011). However, there is more widespread use of alternatively powered buses across a number of countries. According to Murphy (2011), hybrid-electric buses and light-duty trucks have been available for some years and are now gathering market momentum, but remain a long way short of the market penetration seen by hybrid cars, which was estimated at around 0.7% of the global new light vehicle market in 2010. The consulting company Frost and Sullivan (2011) estimated that the global hybrid commercial (medium and heavy commercial vehicles) production was 6,300 units in 2009. Furthermore, electric trucks and buses are entering the market, as are hybrid-hydraulic trucks (Murphy, 2011).
3 Hybrid vehicles

According to a report by NAS in 2010, a hybrid vehicle can be defined as a vehicle that combines at least two power sources, such as internal combustion engines (ICEs), electric drives, and hydraulic drives. The ultimate goal of the hybrid vehicle is to provide the equivalent power, range, and safety as a conventional vehicle while reducing fuel consumption and harmful emissions. This thesis will consider three types of hybrids: hybrid-electric vehicles, hydraulic hybrid vehicles and flywheel hybrid vehicles.

3.1 Hybrid-electric vehicles

A hybrid-electric vehicle (HEV) combines electric and mechanical power devices (see Figure 10). The main components of an HEV that differentiate it from a standard ICE vehicle are the electric machine (motor and generator), energy storage (e.g., battery or supercapacitors), and power electronics (NAS, 2010). The electric machine absorbs braking energy, stores it in the energy storage system, and uses it to meet acceleration and peak power demands.

![Diagram of a hybrid-electric bus](image)

**Figure 10. A series hybrid-electric bus (from www.scania.com).**

HEVs have the potential to realize several advantages, including the following (NAS, 2010):

- Regenerative braking (see Figure 11). A regenerative brake is a system that reduces vehicle speed by converting some of its kinetic energy into a storable form for future use instead of dissipating it as heat as with a conventional brake. Approximately 60 percent of the total energy spent in the U.S. Federal Urban Driving Schedule is used to overcome the effect of inertia and that, theoretically, up to 50 percent of this energy could be recovered. In
addition, regenerative braking can reduce brake wear and the resulting fine particulate dust.

Figure 11. The main functions of a parallel hybrid-electric system (from www.volvo.com).

- Higher electric machine efficiency (for instance, the moving parts of an electrical machine consist primarily of the armature or rotor and bearings).

- Reduced emissions through smoothening of transients and idle elimination (operate at best efficiency).

- Engine shutoff is possible and thereby, fuel consumption, emissions and noise vibration and harshness can be reduced. In the case of utility vehicles, the power take-off can be electrified.

- Accessory electrification allows parasitic loads to run on an as-needed basis. In addition, electrified accessories are often more efficient than belt-driven ones.

- Better drivability, since an electric machine reacts faster to a throttle input than an ICE. Furthermore, torque from the ICE and the electric drive train can be combined whenever needed in certain configurations.

HEV disadvantages include the following (NAS, 2010):

1. When the vehicle is starting from standstill, it is the electric motor (E/G) that drives, providing high torque from the start. The gearbox and the powertrain management unit (P+PMU) automatically manage gear changing, engaging of the power sources and charging.

2. At higher speeds, the diesel engine (D) is started and both engines work in parallel (hence the parallel hybrid).

3. When the engine is braking, the electric motor (E/G) works as a generator and delivers energy to the batteries (B).
• Increased power train and electronic complexity and thereby overall system reliability can be lower.
• Increased vehicle mass due to addition of components.
• Increased cost due to additional components and complexity of the power management.
• If not optimized for the appropriate drive cycle, benefits may not be fully realized (or fuel consumption may even increase).

3.1.1 Vehicle architecture
A number of different system architectures are being considered to meet different applications. They are broadly classified as series, parallel, and power split. The selection of system architecture depends mainly on the application.

Series hybrid-electric architecture
In a series HEV, as illustrated in Figure 12, an electric generator, coupled to an ICE, supplies electricity to the electric machine to propel the truck and to the energy storage system when it needs to be recharged.

![Series Hybrid-Electric Architecture](image)

*Figure 12. A series hybrid-electric architecture (the grey square represents a differential gear).*

The series hybrid-electric architecture is characterized by (NAS, 2010):

• An engine that can run at its optimum performance (and thereby greatly reducing fuel consumption), since the ICE and vehicle speeds are decoupled and only the electric machine is connected to the wheels.

• Large energy storage system pack, electric machine and engine (and thereby added weight), since the electric machine is the only one connected to the wheels.

• Flexible vehicle layout due to the elimination of the mechanical driveshaft. For instance, the elimination of the mechanical driveshaft makes it possible to lower the bus floor for improved wheelchair access in city buses.

Parallel hybrid-electric architecture
Parallel hybrids have mechanical connections to the wheels from both the electric machine and the engine, as illustrated in Figure 13. The electric machine can be located anywhere between the output
engine shaft and the wheels. These vehicles do not need a dedicated generator, since the electric machine can be used as a generator to recharge the batteries.

![Diagram of parallel hybrid-electric architecture](image1)

**Figure 13.** A parallel hybrid-electric architecture (grey squares – mechanical transmissions).

The parallel hybrid-electric architecture is characterized by (NAS, 2010):

- The possibility of downsizing both the engine and the electric machine compared to series hybrids, since the electric machine and the engine are both coupled directly to the wheels and as a result, they can share the power during acceleration. In addition, it is possible to increase the hybridization degree by downsizing the engine and upsizing the electric machine (in applications that require extended high-power operation, such as long haulage trucks, this possibility is limited).
- Different types of configurations: In a starter-alternator type, the electric machine is connected to the engine crankshaft directly on the shaft or coupled through a belt. In a pre-transmission type, the electric machine is located in between the clutch and the transmission and finally in post-transmission type, the electric machine is located after the transmission and has not the benefit of gear ratio changes.

**Power split hybrid-electric architecture**

Power split hybrids try to combine the best aspects of both series and parallel hybrids. As shown in Figure 14, this system divides the engine power along two paths: one goes to the generator to produce electricity, and one goes through a mechanical gear system to drive the wheels. In addition, a regenerative system uses the kinetic energy of deceleration and braking to produce electricity, which is stored in the energy storage system.

![Diagram of power split hybrid-electric architecture](image2)

**Figure 14.** A power split hybrid-electric architecture (grey squares – mechanical transmissions).
3.1.2 Plug-in hybrids
Plug-in hybrids differ from HEVs by their ability to recharge the energy storage system through the electric grid. All the HEV configurations described in section 3.1.1 can be used for plug-in hybrids (NAS, 2010). The vehicles offer the possibility to be recharged, for instance at bus stops or during loading/unloading.

3.1.3 Batteries
The battery’s contribution to the vehicle’s overall power is growing rapidly. In addition, the choice of battery affects not only the cost, reliability, service life, packaging space and weight, but also “green” issues of the vehicle itself. The battery system represents approximately one-third of the overall increase in the cost of hybridization (NAS, 2010).

3.1.4 Power management
Fuel consumption reductions can be realized only after optimization of power management based on an appropriate driving cycle. The main objective of a power management control algorithm in a hybrid vehicle is to calculate the optimum operating point of the overall system for any amount of power demanded from the driver. The cost criteria are often fuel economy and emissions (NAS, 2010).

3.2 Hydraulic hybrid vehicles
A hydraulic hybrid vehicle combines hydraulic and mechanical components (see figure 15). The four main components of a hydraulic hybrid power train are the working fluid, fluid reservoir, hydraulic pump/motor (in a parallel hybrid system) or in-wheel motors and pumps (in a series hybrid system), and an accumulator (NAS, 2010). The hydraulic accumulator stores the energy (as highly compressed nitrogen gas) and a variable displacement pump acts as a motor while driving the wheels and as a generator while absorbing regenerative braking energy. Such a system suits heavy-duty vehicles that are operating with high-power and low-energy requirements, including stop-and-go driving profiles (e.g., refuse trucks and city buses). Hydraulic hybrids have during tests demonstrated considerable fuel savings for heavy-duty applications, where hundreds of launch/stop cycles characterize the longest portion of the operation day (NAS, 2010).
3.3 Flywheel hybrid vehicles

A flywheel hybrid has a potential of considerable fuel savings. An additional flywheel (see Figure 16) stores and releases energy from and to the vehicle driveline. The flywheel stores energy during braking, then releasing it to supplement or the flywheel temporarily replace the engine output. The technology is more effective for vehicles with an urban duty cycle (AEA, 2011).

Figure 16. A flywheel hybrid (from www.optare.com).
3.4 Hybrid technology payback period

Table 3 shows estimated energy benefit compared to a conventional diesel vehicle and the estimated payback period for the different hybrid technologies and electric vehicles (AEA, 2011). The fuel cost in Table 2 has been used to calculate the payback period for the different vehicle categories. Large fleet operators usually want a two to three years payback period. Hybrid technologies falling outside the desired payback period can have other benefits which make them attractive to operators and therefore justifiable. In addition, the adoption of low carbon technologies may also be driven from a business strategy rather than purely commercial aspect, since some companies may promote low carbon technology as part of their corporate social responsibility targets.

Table 3. Estimated energy benefit and payback period.

<table>
<thead>
<tr>
<th></th>
<th>Hybrid-electric vehicles</th>
<th>Hydraulic hybrid vehicles</th>
<th>Flywheel hybrid vehicles</th>
<th>Electric vehicles</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EB (%)</td>
<td>TC (€k)</td>
<td>PP (y)</td>
<td>EB (%)</td>
</tr>
<tr>
<td>Urban delivery, Collection</td>
<td>20</td>
<td>24</td>
<td>14.3</td>
<td>10</td>
</tr>
<tr>
<td>Municipal utility</td>
<td>20</td>
<td>24</td>
<td>8.7</td>
<td>15</td>
</tr>
<tr>
<td>Regional delivery, Collection</td>
<td>10</td>
<td>24</td>
<td>15.8</td>
<td>N/A</td>
</tr>
<tr>
<td>Long haulage</td>
<td>7</td>
<td>24</td>
<td>5.6</td>
<td>N/A</td>
</tr>
<tr>
<td>Construction¹</td>
<td>10</td>
<td>24</td>
<td>17.9</td>
<td>N/A</td>
</tr>
<tr>
<td>Bus</td>
<td>30</td>
<td>24</td>
<td>4.4</td>
<td>15</td>
</tr>
<tr>
<td>Coach</td>
<td>10</td>
<td>24</td>
<td>16.7</td>
<td>N/A</td>
</tr>
</tbody>
</table>

EB – Energy Benefit (% improvement versus conventional diesel)
TC – Technology Cost, PP – Payback Period

¹Was not presented in AEA (2011), therefore estimated here.
²Electricity cost related to fuel cost.
4 Diffusion of innovations

According to Rogers (2005), diffusion of innovations is concerned with how innovations, defined as ideas or practices that are perceived as new, are spread. He stated that “Diffusion is the process through which an innovation spreads via communication channels over time among the members of a social system. This is a social sciences definition of diffusion, one that is not to be confused with the thermodynamic definition of diffusion. Diffusion occurs in complex systems where networks connecting system members are overlapping, multiple and complex”.

4.1 Origins of research on diffusion

Social and technological change as a field of research has its origin in the nineteenth century and one of the pioneers, the French sociologist Tarde (1903), emphasized the important role of opinion leaders in the “imitation” process and suggested an S-shaped diffusion curve. The early research was to a great extent theoretical, but became more empirical after Ryan and Gross’ well known study on the spread of hybrid corn among Iowa farmers (1943). The interest for diffusion increased, and the total number of diffusion studies rose from 27 in 1941 to 423 in 1959 (Katz et al., 1963). The research on diffusion has its theoretical and empirical roots in a great number of disciplines such as anthropology, sociology, medical sociology, education, geography, politics, industrial economy, communication and marketing (Ruiz-Conde, 2004), but around 1960 the field was divided into two independent traditions, one sociological and one economic (Roback, 2006). The economic tradition has primarily seen diffusion as the spread of a new product among potential buyers, while the sociological tradition has a wider view and the objects of innovation are not always physical in character, but could also be an idea, a procedure or a piece of news. The diffusion concept received special attention in marketing, since firms competing in the marketplace wanted a tool to help them face one of the most risky decisions; that of developing and introducing new products into the marketplace (Ruiz-Conde, 2004).

The interest in innovation and diffusion as an academic field of research has exploded since Rogers in 1962 presented his work “Diffusion of Innovations”, which is the most cited work in diffusion research (Roback, 2006). According to Rogers (2003), diffusion is a social process in which actors create and share information through communication. Opinion leaders and change agents working within social structures and systems have critical roles and therefore, a focus on the relative advantage of an innovation is insufficient, since different social systems will have different values and beliefs, which will influence the costs, benefits and compatibility of an innovation. In addition, different social structures will determine the most appropriate channels of communication as well as the type and influence of opinion leaders and change agents (Tidd, 2010). Rogers model of diffusion is as a process which an innovation is communicated through certain channels over time among the members of a social system (members of a social system may be individuals, informal groups, organizations, and/or subsystems). Rogers defines the innovation is an idea, practice, or object perceived as new by an individual or other unit of adoption.
Members of a social system adopt an innovation in a sequence, so that individuals can be distinguished in terms of time of adoption. The term innovativeness of an adopter is the degree to which an individual or another unit of adoption is relatively earlier in adopting new ideas than other members of a system. Rogers (2003) used the time of adoption for categorizing the adopting population (see Figure 17). He assumed that the distribution of adopter adoptions over time was normal. The mean $\mu$ and multiples of the standard deviation $\sigma$ of the normal distribution were used to divide a normal adopter distribution into five categories: Innovators, early adopters, early majority, late majority, and laggards.

### 4.2 Factors influencing diffusion

The variables that have been identified as affecting the diffusion and adoption of innovations can be grouped into three categories: characteristics of the innovation itself; characteristics of the individual or organizational adopters; and characteristics of the environment (e.g. market environment and communications network) (Tidd, 2010). The most important characteristics of an innovation are (Rogers, 2003):

- **Relative Advantage** – the degree to which an innovation is perceived as better than the idea it supersedes (or competing products). It may be measured in economic terms, but important factors are also social prestige, convenience and satisfaction. It is whether an individual perceives the innovation as advantageous, rather than if it objectively is advantageous, that is important. The greater the perceived relative advantage of an innovation, the higher rate of adoption (the relative speed with which an innovation is adopted by members of a social system).

- **Compatibility** – the degree to which an innovation is perceived as being consistent with existing values, past experiences, and needs of potential adopters. There are two distinct aspects of compatibility: existing skills and practices, and values and norms. If an innovation is incompatible with the values and norms of a social system, it will not be adopted as fast as an innovation that is compatible, since a new value system often first must be adopted,
which is a relatively slow process. Furthermore, network externalities can affect the adoption process, since the cost of adoption and use (as distinct from form the cost of purchase) may be influenced by the availability of information about the technology from other users, the availability of trained skilled users, technical assistance and maintenance, and the availability of complementary innovations (Tidd, 2010).

- Complexity – the degree to which an innovation is perceived as difficult to understand and use. Innovations that are simpler to understand by the members of a social system are adopted more rapidly than complicated innovations that require the adopters to develop new skills and understandings.
- Trialability – the degree to which an innovation may be experimented with on a limited basis. A trial allows a member of a social system to assess the innovation’s advantages and potential risks and thereby reducing some of the uncertainty associated with the innovation. As a result, an innovation with a high degree of trialability will generally be adopted more quickly than an innovation with a low degree of trialability.
- Observability – the degree to which the results of an innovation are visible to others. The easier it is for the members of a social system to see the results of an innovation, the more likely they are to adopt it.

In predicting the rate of adoption of an innovation, these five factors explain 49-87% of the variance (Tidd, 2010).

### 4.3 Types of innovation diffusion models

Innovation diffusion models have traditionally been used for predictive purposes, but may also be used in the context of descriptive and normative purposes. Mahajan et al. (1990, 1993) identified three different types of applications for diffusion models:

1. Sales forecasting (e.g. prediction of the demand of a certain innovation in the market and hence to gaining insights into its future success or failure).
2. Hypothesis testing (e.g. testing of hypotheses about differences in the diffusion process of an innovation in different countries).
3. Normative guidelines (e.g. development of optimal strategies for marketing variables such as price, advertising or for the timing of product introductions).

Dosi (1991) suggested that innovation diffusion models can be categorized according to the following characteristics:

1. Heterogeneity versus uniformity of potential adopters of innovations: Are all agents the same and do they have similar incentives to adopt an innovation? Or, do they differ in some structural characteristics, or in their capabilities of efficiently acquiring new products and processes of production. Entirely homogeneous adopters correspond to an aggregate-level diffusion model where the market-level behavior is described without any direct microeconomic effects caused by individual adopters’ decisions (Roberts and Lattin, 2000). On the contrary, entirely heterogeneous adopters correspond to an individual-level diffusion model where the individual adoption process is modeled.
2. Perfect versus imperfect information: Can the adopting agents be assumed to have sufficient information about the nature and future developments of any one technology? Or, is
information diffusion about the existence and attributes of a particular innovation an essential determinant of innovation diffusion?

3. Non-increasing versus increasing returns in new technological developments: Under what circumstances can the use or production of an innovation lead to constant or decreasing returns? On the contrary, are there factors, which can give rise to size-related economies of scale, various sorts of learning processes, and, generally, dynamic increasing returns?

4. Importance of history for the patterns of diffusion: Learning history, path dependency, and long-term dynamics. This point refers to the two preceding ones. Most is going to depend on the existence of dynamic increasing returns, on the feedback processes between the number of adopters of the technology and the changing incentives to further adopt it. When these circumstances occur, one is clearly in the domain of path-dependent, non-ergodic processes and as a result, history counts for both individual patterns of behavior and in terms of the general long-term dynamics of the system.

5. Interaction between supply and demand of innovations: When can one reasonably assume that the innovation to be adopted is supplied once-and-for-all, and conversely, when is it correct to assume a continuous process of improvement in its technical characteristics – which also make adoption easier and enlarges the set of potential users? How important are changes in supply conditions, first of all prices, for the changing pace of innovation diffusion?

6. Diffusion in demand versus diffusion in supply: Diffusion processes are often related to new goods, whose manufacturer wants to sell to as many customers as possible. However, another side of the diffusion process is related to the diffusion of the manufacturing capacity of these new goods among the producers themselves. The theoretical representation of such diffusions concerns the conditions of imitation of an innovation, i.e. technological appropriability, possibly entry- and mobility-barriers and tacitness versus universality of technical knowledge.

7. The forces driving diffusion: Are these forces mainly exogenous, such as general changes in relative prices and macro demand growth? Or, can they be considered to be mainly endogenous, such as learning in the manufacturing of the innovation, learning-by-using and network effects?

8. Behavior and choice of individuals or individual organizations: At one extreme, decision processes about adoption or rejection of new innovations may be represented as optimizations of the returns on the new innovations, i.e. the agents exhibit a rational or optimizing behavior. At the other extreme, agents may exhibit an institutionalized behavior, i.e. a behavior that is rather routinized and influenced by specific visions and norms.

9. Equilibrium versus disequilibrium dynamics of diffusion: Equilibrium dynamics of diffusion is characterized by micro diffusion decisions that are postulated to be reciprocally consistent and rational micro-behavior that all turns out to be fulfilled in their objectives. Disequilibrium dynamics of diffusion is characterized by process attractors that change themselves as a result of the action of the agents or diffusion processes that are explicitly based on the trial-and-error efforts of the agents.
Frenzel-Baudisch and Grupp (2006) added a tenth point to Dosi’s nine points:

10. Forecasting ability of the model: Does the model have the ability to forecast the diffusion of an innovation? Or, has it been developed for descriptive or normative usage only?

Then, based on these ten points, they classified ten different types of innovation diffusion models (see Tables 4a and 4b). Their compilation showed that the Bass model had the best forecasting abilities of all the compared models. The Bass model is an aggregate demand model, which is the most common type of diffusion models (Ruiz-Conde, 2004). Models with a lower aggregation level have primarily been used for brand sales investigations. This thesis focuses on aggregate-level diffusion models that can be used for sales forecasting.


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<tr>
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<tbody>
<tr>
<td>1</td>
<td>-</td>
<td>Homogeneous adopters</td>
<td>Heterogeneous adopters – preference drivers adoption</td>
<td>Homogeneous adopters</td>
<td>Heterogeneous adopters</td>
</tr>
<tr>
<td>2</td>
<td>-</td>
<td>Imperfect information as information is the driving force to adoption</td>
<td>Perfect information</td>
<td>Perfect information</td>
<td>Imperfect information</td>
</tr>
<tr>
<td>3</td>
<td>-</td>
<td>Non-increasing returns</td>
<td>Non-increasing returns</td>
<td>Decreasing returns drive adoption</td>
<td>Non-increasing returns</td>
</tr>
<tr>
<td>4</td>
<td>-</td>
<td>History counts: previous adoption effects the next over imitation</td>
<td>Change in technology quality or preference structure</td>
<td>Negative historical stock and order effects</td>
<td>Change in technology quality or preference structure</td>
</tr>
<tr>
<td>5</td>
<td>-</td>
<td>No interaction</td>
<td>Product utility yielded or demand preferences change over time</td>
<td>Stock and order effects</td>
<td>Product utility yielded or demand preferences change over time</td>
</tr>
<tr>
<td>6</td>
<td>Both</td>
<td>Diffusion in demand</td>
<td>Diffusion demand/supply</td>
<td>Diffusion in supply</td>
<td>Diffusion in demand</td>
</tr>
<tr>
<td>7</td>
<td>-</td>
<td>Exogenous: communication efforts and behaviour</td>
<td>Exogenous – price, preference, technology quality</td>
<td>Endogenous – stock and order effects and expectations</td>
<td>Endogenous: learning; exogenous: information flows, preferences risk aversion</td>
</tr>
<tr>
<td>8</td>
<td>-</td>
<td>Routinized</td>
<td>-</td>
<td>Rational</td>
<td>-</td>
</tr>
<tr>
<td>9</td>
<td>-</td>
<td>Equilibrium: market potential for innovation is pre-set</td>
<td>Equilibrium</td>
<td>Equilibrium</td>
<td>Equilibrium</td>
</tr>
<tr>
<td>10</td>
<td>No explicit forecasting ability</td>
<td>Excellent forecasting abilities</td>
<td>No explicit forecasting ability</td>
<td>No forecasting ability</td>
<td>No explicit forecasting ability</td>
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</tbody>
</table>

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<th></th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Heterogeneous adopters: two or more populations competing</td>
<td>Homogeneous adopters</td>
<td>Homogeneous adopters</td>
<td>Homogeneous adopters</td>
<td>Heterogeneous adopters</td>
</tr>
<tr>
<td>2</td>
<td>-</td>
<td>Imperfect information</td>
<td>Perfect information</td>
<td>Imperfect information</td>
<td>Imperfect information</td>
</tr>
<tr>
<td>3</td>
<td>-</td>
<td>Increasing returns</td>
<td>Increasing returns by network effects and learning</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>Historical evolution of niche population</td>
<td>Learning as uncertainty reduction, investment risk is avoided</td>
<td>Network externalities formed by historical decisions</td>
<td>Learning as uncertainty reduction in networks</td>
<td>Imitation of widespread techniques/technological regimes</td>
</tr>
<tr>
<td>5</td>
<td>-</td>
<td>None</td>
<td>None</td>
<td>Promoter of inventions</td>
<td>R&amp;D policies based on sales respectively profits</td>
</tr>
<tr>
<td>6</td>
<td>-</td>
<td>Diffusion in demand</td>
<td>Diffusion demand</td>
<td>Diffusion in demand</td>
<td>Diffusion in supply</td>
</tr>
<tr>
<td>7</td>
<td>Endogenous: density of market</td>
<td>Endogenous: learning and its costs</td>
<td>Endogenous – network externalities</td>
<td>Endogenous and exogenous</td>
<td>Endogenous: Environmental selection</td>
</tr>
<tr>
<td>8</td>
<td>-</td>
<td>-</td>
<td>Rational</td>
<td>Routinized</td>
<td>Routinized</td>
</tr>
<tr>
<td>9</td>
<td>-</td>
<td>Disequilibrium</td>
<td>Disequilibrium</td>
<td>Disequilibrium</td>
<td>Disequilibrium</td>
</tr>
<tr>
<td>10</td>
<td>No explicit forecasting ability</td>
<td>No forecasting ability</td>
<td>No forecasting ability</td>
<td>Data-constrained forecasting ability</td>
<td>No forecasting ability</td>
</tr>
</tbody>
</table>

4.4 Aggregate diffusion models
Ruiz-Conde (2004) states that aggregate-level diffusion models divide the total market into segments and try to capture the movement from one segment to the next. A diffusion function describes how the diffusion process evolves over time $t$ and is usually defined as the solution $y = y(t)$ of a differential equation $dy/dt = f(y,t)$, where the function $f(y,t)$ determines the shape of the diffusion curve.

Communication channels form the means through which the innovation is spread among the members of a social system. A distinction is made between external communication (e.g. through advertising) and internal communication (e.g. interpersonal communication). These two forms of communication are complementary and they can play different roles during the adoption process. External communication is very effective in the beginning of the adoption process and internal communication is more suited to influencing behaviour when the adoption process has already started (Ruiz-Conde, 2004). The influence intensity, on the members of the social system, is dependent on both the characteristics of the innovation and the characteristics of the agents within the social system. Ruiz-Conde suggests that previous adopters of an innovation will influence
potential adopters to imitate them in their decision to adopt the innovation. This imitation (or interaction) effect will accelerate the diffusion process, since the probability of a potential adopter adopting the innovation at a certain moment of time depends on the number of previous adopters.

4.4.1 Segments

An adopter (or an adopting unit) can be defined as a company or organization in the case of industrial products and an individual or a group of individuals in the case of consumer products. Figure 18 shows the general structure of a diffusion model for the case where each purchase refers to the sale of one unit of a durable product. Mahajan and Muller (1979) divided the market into three segments:

1. Untapped Market – this segment includes all consumers (or customers) who do not know that the innovation exists or who, for whatever reason, are not considered as possible consumers of that innovation in the time period $t$.

2. Effective Potential Market – this segment includes all consumers from segment one who are now potential consumers of the innovation in the time period $t$.

3. Current Market – this segment includes all consumers who have already bought the innovation in the time period $t$, i.e. the adopters of the innovation.

<table>
<thead>
<tr>
<th>Segment 1: Untapped Market</th>
<th>Nomenclature</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_1(t) = TM(t) - M(t)$</td>
<td>TM(t) Total number of individuals in the market in time period $t$</td>
</tr>
<tr>
<td>$m(t)$</td>
<td>M(t) Number of potential adopters of the innovation in time period $t$</td>
</tr>
<tr>
<td>Segment 2: Effective Potential Market</td>
<td>N(t) Number of adopters of the innovation (current adopters) in time period $t$</td>
</tr>
<tr>
<td>$S_2(t) = M(t) - N(t)$</td>
<td>m(t) Number of individuals transferred from the untapped market segment to the effective potential market segment between time period $t$ and $t+1$</td>
</tr>
<tr>
<td>$n(t)$</td>
<td>n(t) Number of individuals transferred from the effective potential market segment to the current market segment between time period $t$ and $t+1$</td>
</tr>
<tr>
<td>Segment 3: Current Market</td>
<td></td>
</tr>
<tr>
<td>$N(t)$</td>
<td></td>
</tr>
</tbody>
</table>

Figure 18. Consumer (or customer) flows across the market segments within the diffusion process. Durable products context. Sources: Ruiz-Conde (2004) and Mahajan and Muller (1979).

The number of individuals in each segment in the time period $t + 1$ is given by the following equations:

$$
\begin{align*}
S_1(t + 1) &= S_1(t) + TM(t + 1) - TM(t) - m(t) \\
S_2(t + 1) &= S_2(t) + m(t) - n(t) \\
N(t + 1) &= N(t) + n(t)
\end{align*}
$$

These equations describe flows among consumer segments in innovation diffusion processes and represent the basis of the classical diffusion models and some extensions of these models (Mahajan
According to Ruiz-Conde (2004), the flow of consumers from the second segment to the third segment is studied in most models, i.e. the number of adopters $n(t)$ at time $t$.

Figure 19 shows another example of a general structure of a diffusion model. Here each purchase refers to the sale of one unit of a non-durable product. The market is divided into four consumer segments (Hahn et al., 1994):

1. Non-triers – this segment includes all potential consumers who have not tried the innovation at time $t$.
2. Triers – this segment includes all consumers who had not tried the innovation by the time period $t-1$, but try the innovation at time $t$.
3. Non-repeaters – this segment includes all consumers who have tried the innovation by the time period $t-1$, but are not repurchasing the product at time $t$.
4. Repeaters – this segment includes all consumers who have tried the innovation by the time period $t-1$, and are repurchasing it at time $t$.

The total number of potential consumers of the product is described by:

$$N = N_1(t) + N_2(t) + N_3(t) + N_4(t)$$

and the dynamic flows through the different segments are represented by

---

**Nomenclature**

- $N_i(t)$ Number of consumers in segment $i$ in the time period $t$, $i = 1, 2, 3$ and 4
- $\alpha(t)$ Fraction of non-triers in the time period $t-1$ who try the innovation in $t$
- $\gamma_1(t)$ Fraction of triers in the time period $t-1$ who repurchase the innovation in $t$
- $\gamma_2(t)$ Fraction of repeaters in the time period $t-1$ who repurchase the innovation in $t$
- $\gamma_3(t)$ Fraction of non-repeaters in the time period $t-1$ who repurchase the innovation in $t$
\[
\begin{align*}
N_1(t) &= (1 - \alpha(t))N_1(t-1) \\
N_2(t) &= \alpha(t)N_1(t-1) \\
N_3(t) &= (1 - \gamma_1(t))N_2(t-1) + (1 - \gamma_2(t))N_4(t-1) + (1 - \gamma_3(t))N_5(t-1) \\
N_4(t) &= \gamma_1(t)N_2(t-1) + \gamma_2(t)N_4(t-1) + \gamma_3(t)N_5(t-1)
\end{align*}
\] 

(3)

Hahn et al. (1994) used these equations when he extended the classical diffusion model (designed for durable innovations) and analyzed non-durable innovations with repeat purchases.

4.4.2 Diffusion models of external influence

In a diffusion model of external influence, the rate of diffusion is assumed to depend solely on the number of potential adopters. Some important pioneering works on diffusion models of external influence are those of Fourn and Woodlock (1960) that investigated the sales prediction for consumer products and Coleman et al. (1966) that investigated the diffusion of a new medicine among a group of doctors. A diffusion model of external influence can mathematically be described by (Ruiz-Condé, 2004):

\[
n(t) = \frac{dN(t)}{dt} = a(M - N(t))
\]

(4)

where \(n(t)\) is the number of adopters at time \(t\) and \(M\) is the potential market (total number of potential adopters in the social system). \(N(t)\) is the cumulative number of adopters at time \(t\), i.e.:

\[
N(t) = \int_0^t n(t)dt
\]

(5)

The parameter of external influence \(a\) represents the degree of intensity of the source of external influence (or the probability of a randomly chosen individual being reached by this source of influence). Equation (4) shows that the constant external source of influence reaches a fixed proportion of the population at any given moment in time. External influence comes not only from the promotional strategies found in the market (external communication), but also from the intrinsic tendency of an individual company or person to innovate (also called innate innovativeness).

Integration of equation (4) and the condition \(N(t_0) = N_0\) gives the following cumulative distribution of adopters:

\[
N(t) = M\left(1 - e^{at}\right)
\]

(6)

Ruiz-Condé summarized the main assumptions that underlie diffusion models of external influence:

- The population of potential adopters is limited and remains constant through time and eventually all members of the population adopt the innovation.
- The diffusion process arises from a source of constant influence (independent of the number of adopters) and the impact is equal for all non-adopters.
Since a model of external influence assumes that the spread of an innovation depends exclusively on information coming from external sources, it does not consider any diffusion resulting from interaction between previous and potential adopters. As a consequence, Ruiz-Conde suggested that such a model should only be appropriate for innovations that are neither socially remarkable nor complex, since the diffusion will not be influenced by personal communication between the members of the social system.

4.4.3 Diffusion models of internal influence

In a diffusion model of internal influence, the rate of diffusion is assumed to be proportional to both the number of potential adopters (i.e. the distance remaining from a predetermined market saturation level) and the level of diffusion reached. Some important pioneering works on diffusion models of internal influence are those of Griliches (1957) who investigated diffusion of hybrid corn among farmers from various geographical regions and Mansfield (1961), who investigated the substitution of established technology and the diffusion of new technology and innovations among different companies. A diffusion model of internal influence (or pure imitation) can mathematically be described by (Ruiz-Conde, 2004):

\[ n(t) = \frac{dN(t)}{dt} = bN(t)(M - N(t)) \]  

(7)

where the parameter of internal influence \( b \) can be considered to be an index of potential adopters’ imitation of previous adopters. The parameter shows the impact on the adoption of the innovation of interpersonal communication and interactions among the members of a social system.

Integration of (7) and the condition \( N(t_0) = N_0 \geq 1 \) gives the following cumulative distribution of adopters:

\[ N(t) = \frac{M}{1 + \frac{(M - N_0)}{N_0} e^{-bM(t-t_0)}} \]  

(8)

The main assumptions that underlie diffusion models of internal influence are according to Ruiz-Conde:

- The population of potential adopters is limited and remains constant through time and eventually all members of the population adopt the innovation.
- The population is homogenous.
- All adopters are imitators and the probability of two individuals making contact is equal for any two individuals.
- The rate of adoption does depend on both the number of previous adopters and on the maximum number of potential adopters that still have not adopted.

An internal influence model, which is an epidemiological type of model, is based on the existence of communication between the members of the social system. This social interaction is represented in
the model by the product of previous and potential adopters (see equation (7)). The probability of adoption will increase as the number of adopters increase in the social system. Ruiz-Conde stated that “this is a logical process as the greater the number of previous adopters, the more information there will be in the market on the characteristics, advantages and previous adopters’ experience of the innovation, which would reduce the risk aversion of potential adopters and favour the decision to adopt”.

\[ H(t) = \frac{1}{1 + e^{-\delta(t-t_0)}} \] (9)

where \( H(t) = N(t)/M \) and \( \delta = b/2 \). Furthermore, the Gompertz diffusion model is also directly related to the internal influence model (Ruiz-Conde, 2004). The Gompertz function can be expressed as:

\[ n(t) = \frac{dN(t)}{dt} = bN(t)(\ln M - \ln N(t)) \] (10)

which after integration, takes the following form:

\[ N(t) = M \exp\left( -\left( \frac{\ln \frac{M}{N_0}}{b} \exp(-bt) \right) \right) \] (11)

**Figure 20.** The Fisher-Pry model is often used for technology-driven adoptions where new technology displaces old technology. From Vanston and Hodges (2004).
Even though the Gompertz model also results in an S-shaped curve, the point of inflexion is reached at 37 percent ($e^{-tM}$), instead of 50 percent, which is the case with the logistic function.

### 4.4.4 Diffusion models of mixed influence

A diffusion model of mixed influence assumes that both types of influence are active in the decision to adopt an innovation. By combining the diffusion models of external and internal influence, i.e. equation (4) and (7), a diffusion model of mixed influence (or the fundamental diffusion model) is obtained (Mahajan and Peterson, 1985):

\[
\frac{dN(t)}{dt} = (a + bN(t))(M - N(t))
\]  
(12)

Integration of (12) and the condition $N(t_0) = N_0$ gives the following cumulative distribution of adopters:

\[
N(t) = \frac{M - \frac{a(M - N_0)}{(a + bN_0)} \exp(-(a + bM)(t - t_0))}{1 + \frac{b(M - N_0)}{(a + bN_0)} \exp(-(a + bM)(t - t_0))}
\]  
(13)

The diffusion model of mixed influence is capable of representing both external and internal influence and it is the most widely used diffusion model (Ruiz-Conde, 2004). If $M = m$, $b = q/m$ and $a = p$ is substituted into equation (12), we obtain:

\[
\frac{dN(t)}{dt} = \left( p + q \frac{N(t)}{m} \right)(m - N(t))
\]  
(14)

which is the Bass (1969) model. He defined $p$ and $q$ as the parameter of innovation and imitation, respectively. The parameter $m$ is the market potential. The Bass model has large acceptance in the field of innovation diffusion (Mahajan et al., 2000). He pioneered the introduction of diffusion models into the marketing research field by repackaging diffusion understandings in a form that were usable by marketing scholars (Rogers, 2003). He proposed that the adoption process of a new durable consumer product has similarities with the spread of an epidemic, i.e. people who have not adopted the product are infected by those who have and are influenced by external sources, such as advertising (Ruiz-Conde, 2004). Bass investigated the diffusion of consumer durables (e.g. electric refrigerators, home freezers, room air conditioners and power lawn mowers) and predicted the sales for these products with a very good accuracy. Ruiz-Conde claims that many other authors have used the Bass model for sales prediction of a wide variety of products, in various countries, and also obtained good results.

If we assume that the initial time and cumulative distribution of adopters are equal to zero, i.e. $t_0 = 0$ and $N_0 = 0$, a solution to equation (14) can be expressed as:

\[
N(t) = m \frac{1 - e^{-(p+q)t}}{1 + \frac{q}{p} e^{-(p+q)t}} = mF(t)
\]  
(15)
where

\[
F(t) = \frac{1 - e^{-(p+q)t}}{1 + \frac{q}{p} e^{-(p+q)t}}
\]

is the cumulative distribution function (or the fraction of potential adopters that has adopted the product by time \(t\)).

**4.4.5 Assumptions behind diffusion models of mixed influence**

A diffusion model of mixed influence (the fundamental diffusion model, see equations (12) and 14) is based on several restrictive assumptions that might reduce the realistic nature of the modelled innovation diffusion process. According to Ruiz-Conde (2004), the most central assumptions are:

1. The diffusion process is a binary process (consumers or customers have two options: to adopt or reject the innovation) and population is homogeneous (all individuals behave equally when deciding whether or not to adopt an innovation).

2. The population of adopters does not vary (the size of the social system is fixed, finite and known or can be estimated).

3. The parameters of external and internal influence do not change (they are the same for all potential adopters, regardless of their characteristics and the time of adoption).

4. Only one adoption per adopter is permitted (repeat purchases, replacements or multiple adoptions are not allowed).

5. Geographical frontiers do not alter (an innovation is restricted to a geographical area or a certain marketing sector).

6. The innovation is diffused in isolation (the diffusion of an innovation is independent of all other innovations, i.e. product interactions and competition among firms do not affect the diffusion process).

7. The essential characteristics of the innovation or its perception do not change (i.e. they do not significantly change during the innovation’s life time).

8. There are no supply restrictions (the diffusion models are demand models).

9. The impact of marketing strategies is only implicitly captured by the model parameters (no direct inclusion of marketing mix variables).

Ruiz-Conde reviewed more than 90 diffusion models and her overview showed that researchers have relaxed up to five of these restrictive assumptions by improving the original diffusion model of mixed influence.

**4.4.6 Multiple adoptions**

Norton and Bass (1992) relaxed the fourth assumption in section 4.4.5 by introducing the following expression:
\[ m = cM \]  \hspace{1cm} (17)

where \( c \) is the average number of units bought per unit of time per user and \( M \) is the upper limit of the number of users. Sales will approach \( cM \) as the number of users approaches \( M \). If \( F(t) \) (see equation (16)) represents the fraction of the market that has been penetrated by time \( t \), the sales at time \( t \) will be

\[ S(t) = mF(t) \]  \hspace{1cm} (18)

Sales are proportional to the cumulative distribution function of the adoption rate. In section 5 this function will be used to determine the market penetration.
5 Hybrid HDV market forecast

In this section the diffusion and market penetration of hybrid heavy-duty vehicles in Europe will be estimated by a mathematical model. Three hybrid technologies will be considered: hybrid-electric vehicles, hydraulic hybrid vehicles and flywheel hybrid vehicles. The Bass model (see section 4.4.4) will be used and the model requires the estimation of three parameters: the coefficient of external influence $p$, the coefficient of internal influence $q$, and the market potential $m$. If no or very limited amount of historical sales data is available, parameter estimates can be obtained by using either expert judgements or the diffusion history of analogous products (Mahajan et al, 1990). However, analogous products must be chosen carefully. Thomas (1985) states: “Unfortunately, while the use of analogies appears to be very useful (and some would argue, inevitable) for estimating demand, it can also be problematic. First, the presumption that if two things are alike in some respects, they are necessarily alike in others is itself false. Similarities need to be carefully qualified to in invoke the assumption that existing product sales histories can be used to estimate growth of a new product. Second, even though a product might be evaluated to be similar, there is no reason to believe that a one-to-one mapping of a growth estimate from the existing product(s) to the new product is defensible”. Therefore, he suggested a five-step method where the analogies and the Bass parameters are determined in a systematic way:

1. Estimation of the market potential.
2. Identification of similar products.
3. Estimation of customer values.
4. Estimation of diffusion parameters for similar products.
5. Estimation of sales.

An analogical approach based on Thomas (1985) five-step method will be used, due to the non-existence of historical sales data for hybrid heavy-duty vehicles. The following sections describe the steps, one by one.

5.1 Estimation of the market potential

According to Thomas (1985), the market potential $m$ for the new product can preferably be estimated from a primary market study, since the size of $m$ may depend on marketing variables (especially price) and environmental variables and the effects of these factors may be designed into the market study. However, in this work the market potential is estimated from secondary sources of data. Three scenarios will be considered based on the work by AEA (2011):

1. **BAU – Business as Usual.** The assumptions include natural development of powertrain and vehicle based efficiency improvements. Benefits are offset to a significant degree by in-year increases in fuel consumption of 3% following the introduction of Euro VI in 2013 and a purely speculative Euro VII in 2018. Introduction of significant alternative fuel or powertrain options (e.g. hybrid) is assumed to be restricted. No incentives or legislative CO2 for HDV is are assumed.
2. **CET – Cost Effective Technology.** Includes technologies of new and emerging technology, which have a payback period for the operator of around two to three years along with some uptake of electric and hybrid vehicles by early adopters. The rate of natural improvement for conventional diesel fuelled vehicles in both powertrain and vehicle efficiency remains constant with that assumed for the BAU scenario. Some incentives or legislative CO₂ for HDV are assumed.

3. **CT – Challenging Technology.** The scenario proposes uptake rates for all technologies expected to be commercialised between 2010 and 2030 by vehicle mission profile regardless of the length of time required to achieve technology payback. Uptake rates of technology are aggressive and represent a likely maximum benefit. The natural rate of improvement of powertrains for conventional diesel fuelled vehicles is at an increased rate as this assumes a greater focus on improved design such as reduction in friction, improved combustion and increased turbocharging as fuel consumption will be the main driver rather than cost. Incentives or legislative CO₂ for HDV are assumed.

As can be seen in Figures 2 and 3, the market size for HDVs is very fluctuating and therefore, the **market penetration potential** of hybrid HDVs will be used instead of the **market potential** of hybrid HDVs. The market potential \( m \) in equation (18) is substituted by

\[
m = em_{HDV}
\]  

(19)

where \( e \) is the market penetration potential of hybrids of the total HDV market \( m_{HDV} \). We get

\[
L(t) = \frac{S(t)}{m_{HDV}} = eF(t)
\]  

(20)

where \( L(t) \) is the market penetration of hybrid HDVs. Table 5 shows AEA’s (2011) forecasted market penetration in 2030 for the three different market scenarios that were presented above. The share of HDV sales have been determined by the data in Figure 4 (the category Service/Delivery was excluded since this thesis focuses on heavy-duty vehicles over 16 ton GVW) and Figure 5. The total sales of buses and coaches were estimated to be 10% of truck sales.

Now, it assumed that all vehicles, except electric vehicles, finally will be fitted with a hybrid system, since hybrid technologies offer significant energy benefits for conventional vehicles solely fitted with internal combustion engines (see Table 3). Furthermore, the interrelationships between the market penetrations for hybrid, hydraulic hybrid, flywheel hybrid and electric vehicles (for a certain scenario) in Table 5 are assumed not to change after 2030. Thereby, it is possible to determine the “final” (after the hybrid HDV diffusion process) market penetrations for hybrid and electric HDVs. Table 6 shows the result of these calculations, and the market penetration potential \( e \) of hybrid HDVs will be 99.1% for the BAU scenario, 98.6% for the CET scenario and 92.6% for the CT scenario.
Table 5. Forecasted market penetration in 2030 for different scenarios.

<table>
<thead>
<tr>
<th>Share of HDV sales (%)</th>
<th>Hybrid-electric vehicles</th>
<th>Hydraulic hybrid vehicles</th>
<th>Flywheel hybrid vehicles</th>
<th>Electric vehicles</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BAU (%)</td>
<td>CET (%)</td>
<td>CT (%)</td>
<td>BAU (%)</td>
</tr>
<tr>
<td>Urban delivery, Collection</td>
<td>7.5</td>
<td>5</td>
<td>10</td>
<td>25</td>
</tr>
<tr>
<td>Municipal utility</td>
<td>7.6</td>
<td>5</td>
<td>5</td>
<td>30</td>
</tr>
<tr>
<td>Regional delivery, Collection</td>
<td>22.8</td>
<td>5</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Long haulage</td>
<td>36.4</td>
<td>0.5</td>
<td>2</td>
<td>10</td>
</tr>
<tr>
<td>Construction¹</td>
<td>16.6</td>
<td>5</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Bus</td>
<td>6.9</td>
<td>5.5</td>
<td>18</td>
<td>40</td>
</tr>
<tr>
<td>Coach</td>
<td>2.2</td>
<td>N/A</td>
<td>2</td>
<td>10</td>
</tr>
<tr>
<td>HDV market penetration</td>
<td>3.3</td>
<td>5.1</td>
<td>14.7</td>
<td>N/A</td>
</tr>
</tbody>
</table>

¹Was not presented in AEA (2011), therefore estimated here.

Table 6. Estimated market penetration after the hybrid HDV diffusion process.

<table>
<thead>
<tr>
<th>Hybrid-electric vehicles</th>
<th>Hydraulic hybrid vehicles</th>
<th>Flywheel hybrid vehicles</th>
<th>Hybrid vehicles (Σ)</th>
<th>Electric vehicles</th>
</tr>
</thead>
<tbody>
<tr>
<td>BAU</td>
<td>99.1%</td>
<td>N/A</td>
<td>99.1%</td>
<td>0.9%</td>
</tr>
<tr>
<td>CET</td>
<td>71.8%</td>
<td>N/A</td>
<td>26.8%</td>
<td>98.6%</td>
</tr>
<tr>
<td>CT</td>
<td>43.5%</td>
<td>13%</td>
<td>36.1%</td>
<td>92.6%</td>
</tr>
</tbody>
</table>

5.2 Identification of similar products

According to Thomas (1985), a set of existing products that have characteristics “similar” to the new product concept (or prototype) shall be identified. The products should be selected with key attributes similar to the new product and criteria that define the analogy include such factors as those in Figure 21.
 Following a procedure similar to that illustrated in Figure 21, a set of candidate products (or technologies) were identified as potentially similar to hybrid heavy-duty vehicles, at least on selected characteristics. Such products included different engine, driveline and vehicle technologies such as catalytic converter, automated transmission, low rolling resistance tyres and aerodynamic fairings (e.g. cab deflectors and side panels). However, of the candidate-similar products, several could not be used because of lack of adequate sales history. Sales histories for different car technologies were found in literature, but both the market structure, buyer behavior and marketing strategy are fundamental different for cars, which are consumer products, and HDVs, which are industrial products (see Kotler and Keller (2006) for a comparison of characteristics of business markets and consumer markets). As a consequence, the following products/technologies were finally chosen:

- **Radial tyre.** Radial-ply tyres offer higher durability than conventional (cross-ply or bias-ply) tyres and this is a very important factor in fleet operating costs (Watson, 1999). Tyre life, excluding retreading, can be from 40-100% greater than that of conventional tyres. In addition, radial tyre life can be extended about three times by regrooving and multiple retreading. Radial-ply truck tyres give a reduction in fuel consumption of 6-10% through their lower rolling resistance. The main disadvantage is that conventional tyres are more suited to poor road conditions and overloading. Therefore, a major contributing factor to the slow growth of the radicalization of truck tyres in developing countries has been the slow progress in the construction of paved surfaces (asphalt, concrete or tarmac) in their road networks.

- **Disc brake.** Disc brakes are able to work at high temperatures, without losing braking performance, for longer periods than conventional drum brakes (Gorenc, 2006). They are 30 to 40 percent lighter in weight than drum brakes, and have approximately one-fourth the number of parts of drum brakes. Although disc brakes have a higher purchase price, they usually last longer than drum brakes, making them the more cost-effective alternative. The main disadvantage is that drum brakes offer better robustness and reliability during off-road conditions, due to their almost completely sealed housings.
- **Anti-lock brake system (ABS).** ABS distributes the braking force evenly between the different wheels of the vehicle and prevents any of the tyres locking during braking. An ABS system offers maximum braking force while maintaining steerability and safety and thereby reducing the stopping distance under most conditions including emergency braking conditions. The EU legislation started with heavy commercial vehicles in 1991. All new heavy trucks over 16 ton and suitable for towing trailers over 12 ton should be fitted with ABS as standard as of October 1991 (WABCO, 2004). ABS has then been phased in progressively as a mandatory requirement for all other commercial vehicles by 31.03.2001.

### 5.3 Estimation of customer values

Thomas (1985) suggests an estimation of customer values (or importance weights, preferences) $v_i$ for $i = 1, 2, ..., k$ new product key attributes and customer perceptions $x_{ij}$ about the extent (or beliefs about the extent) to which $j = 1, 2, ..., m$ analogous products have attribute $i$. This can be done in a primary market study, or by a combination of secondary data and expert judgment. Here the latter alternative will be used. Knowledge about hybrid technologies (see section 3), the chosen three analogous products/technologies (see section 5.2) and key-desired benefits of powertrain technologies among HDV customers (see Figure 6), were used to determine the values in Table 7.

Notice that the importance weights are different for the different market scenarios.

**Table 7. Key attributes, importance weights and customer perceptions about the extent the analogous products/technologies have the key attributes.**

<table>
<thead>
<tr>
<th>$i$</th>
<th>Key attributes</th>
<th>$v_i$</th>
<th>Radial tyres ($x_{i1}$)</th>
<th>Disc brakes ($x_{i2}$)</th>
<th>ABS ($x_{i3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>BAU</td>
<td>CET</td>
<td>CT</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Higher initial purchase price (excluding possible incentives)</td>
<td>0.4</td>
<td>0.3</td>
<td>0.2</td>
<td>0.4</td>
</tr>
<tr>
<td>2</td>
<td>Decreased operating costs</td>
<td>0.4</td>
<td>0.3</td>
<td>0.2</td>
<td>0.7</td>
</tr>
<tr>
<td>3</td>
<td>Decreased reliability</td>
<td>0.2</td>
<td>0.2</td>
<td>0.1</td>
<td>0.8</td>
</tr>
<tr>
<td>4</td>
<td>Meets new critical legislative requirements</td>
<td>N/A</td>
<td>0.1</td>
<td>0.4</td>
<td>N/A</td>
</tr>
<tr>
<td>5</td>
<td>Environmentally friendly</td>
<td>0</td>
<td>0.1</td>
<td>0.1</td>
<td>1</td>
</tr>
</tbody>
</table>

### 5.4 Estimation of diffusion parameters for similar products

An estimation of the diffusion model parameters ($p_i$ and $q_i$) for each of the selected analogous products is suggested by Thomas (1985). Standard criteria should be applied for evaluating the stability of these parameter estimates. Figure 22 shows the diffusion curves for the chosen three analogous products/technologies.

Non-linear regression in Matlab (R2011a) was used to determine the diffusion model parameters for equation (16) and (20) from the sales data shown in Figure 22. Figures 22-24 and Table 8 show the result from the curve fits. The results of these analyses were significant at a 95% confidence level and had very high values of $R^2$ (a value closer to 1 indicates a better curve fit).
Figure 22. Diffusion curves for disc brakes, ABS and radial tyres in Europe (Western Europe). Disc brakes and ABS sales data from Timoney and Timoney (2003) and radial tyre sales data from TSMG (2008).

Figure 23. Market penetration of radial tyres in Europe (Western Europe).
Figure 24. Market penetration of disc brakes in Europe (Western Europe).

Figure 25. Market penetration of ABS in Europe (Western Europe).

Table 8. Obtained diffusion model parameters and goodness of fit values ($R^2$) from the non-linear regression.

<table>
<thead>
<tr>
<th>$j$</th>
<th>Product/Technology</th>
<th>$p_j \times 10^{-3}$</th>
<th>$q_j$</th>
<th>Coefficient of multiple determination $R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Radial tyres</td>
<td>4.92</td>
<td>0.164</td>
<td>0.9945</td>
</tr>
<tr>
<td>2</td>
<td>Disc brakes</td>
<td>0.818</td>
<td>0.149</td>
<td>0.9965</td>
</tr>
<tr>
<td>3</td>
<td>ABS</td>
<td>0.0386</td>
<td>0.344</td>
<td>0.9972</td>
</tr>
</tbody>
</table>
5.5 Estimation of sales

The following equations should be used to estimate the diffusion parameters $p'$ and $q'$ for the new innovative product (Thomas, 1985):

\[ p' = \sum_{j=1}^{m} \sum_{i=1}^{k} v_{ij} p_j \]  \hspace{1cm} (21)

\[ q' = \sum_{j=1}^{m} \sum_{i=1}^{k} v_{ij} q_j \]  \hspace{1cm} (22)

Table 9 shows the result from using these equations with the values in Tables 7 and 8. Finally, the market penetration for hybrid HDVs in Europe (see Figure 26 and Table 10, 2010 has been assumed to be the introduction year of hybrid HDVs) can be determined with equations (16) and (20) and the values in Tables 6 and 9.

**Table 9. Estimated diffusion model parameters for hybrid heavy-duty vehicles in Europe.**

<table>
<thead>
<tr>
<th>Scenario</th>
<th>$p'$ ((10^{-3}))</th>
<th>$q'$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BAU</td>
<td>3.19</td>
<td>0.181</td>
</tr>
<tr>
<td>CET</td>
<td>3.09</td>
<td>0.195</td>
</tr>
<tr>
<td>CT</td>
<td>2.10</td>
<td>0.245</td>
</tr>
</tbody>
</table>

*Figure 26. Market penetration of hybrid heavy-duty vehicles in Europe.*
Table 10. Market penetration of hybrid heavy-duty vehicles in Europe, total and split into the different hybrid technologies (the split is based on the interrelationships between the different hybrid technologies in Table 6).

<table>
<thead>
<tr>
<th></th>
<th>Hybrid vehicles (Σ)</th>
<th>Hybrid-electric vehicles</th>
<th>Hydraulic hybrid vehicles</th>
<th>Flywheel hybrid vehicles</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2020 (%) 2030 (%) 2040 (%)</td>
<td>2020 (%) 2030 (%) 2040 (%)</td>
<td>2020 (%) 2030 (%) 2040 (%)</td>
<td>2020 (%) 2030 (%) 2040 (%)</td>
</tr>
<tr>
<td>BAU</td>
<td>8.34 39.8 80.5</td>
<td>8.34 39.8 80.5</td>
<td>N/A N/A N/A</td>
<td>N/A N/A N/A</td>
</tr>
<tr>
<td>CET</td>
<td>8.76 44.0 84.4</td>
<td>6.38 32.0 61.5</td>
<td>N/A N/A N/A</td>
<td>2.38 12.0 22.9</td>
</tr>
<tr>
<td>CT</td>
<td>7.81 50.2 86.5</td>
<td>3.66 23.5 40.5</td>
<td>1.1 7.05 12.1</td>
<td>3.04 19.6 33.7</td>
</tr>
</tbody>
</table>

5.6 Discussion

Sultan et al. (1990) carried out a meta-analysis of 213 applications of diffusion models and they reported average values of 0.03 and 0.38 for the coefficients of external (p) and internal influence (q), respectively. Their findings suggest that the diffusion process is affected more by imitation factors such as word of mouth than by innate innovativeness of the consumers (or customers). The values in Table 8 support their findings and indicate that the innovativeness among HDV customers is even lower.

The three diffusion curves in Figure 26 have the same characteristics and the differences between them are relatively small. The largest difference occurs approximately after 23 years since first introduction. In that case the difference in market penetration between the CT scenario and BAU scenario is approximately 12 percentages. In the CT scenario, hybrid technologies will be almost fully diffused after 50 years since first introduction, while in the BAU scenario, additional ten years are needed to fully penetrate the market (notice that the “final” market penetration of hybrids is different for the different scenarios due to different estimated “final” market penetration of electric HDVs). Furthermore, all scenarios result in a rather low penetration rate of hybrid HDVs during the first ten years. The diffusion speed increases then rapidly during the next ten years such that 40-50 percent of the HDV market is penetrated in 2030.

Table 5 shows that AEA’s (2011) forecasted market penetration for year 2030 is significantly lower than the one presented in Table 10. The CT penetration in Table 10 for year 2030 is a factor 1.6 higher than AEA’s penetration and the BAU penetration is as high as a factor 12.1 higher than AEA’s forecasted penetration. This indicates that the forecast presented here might be too optimistic and that more analogous products should be used or usage of other weights or perception values in Table 7. On the other hand, in Murphy (2011), Frost and Sullivan forecast that hybrids will account for 8% of the market for trucks over 8800 kg in 2015 and that 72% of the hybrid trucks will be hybrid-electric and the remainder vehicles hydraulic hybrids. This is more optimistic than any of the forecasted market penetrations in Table 10, who reach this level first in 2020.

The CT scenario results in a slightly lower market penetration during the first 11-13 years than the two other scenarios (see Figure 26 and Table 10). This is inconsistent and should be considered as a model error.
6 Conclusions

Forecasts for the market penetration of hybrid HDVs in Europe have been determined by a diffusion model of mixed influence. Three different market scenarios were used and resulted in three different market penetrations of hybrid-electric, hydraulic hybrid and flywheel hybrid vehicles. The following conclusions can be drawn:

- The very high values of $R^2$ from the non-linear regression in Matlab (see Table 8) indicate that the diffusion of new technologies and products among HDV customers can be very well described by a diffusion model of mixed influence such as the Bass model. As a result, such models are capable of predicting future market demand, not only of hybrid HDVs, but also of other HDVs with new innovative technologies or solutions. Therefore, it is suggested that innovation diffusion modeling should be a standard tool (combined with other techniques such as judgmental and customer/market research techniques) in the strategic planning of a HDV firm’s all new innovative products.

- One of the major challenges of using innovation diffusion models for sales forecasting of new products or technologies, is to find appropriate and sufficient analogous sales data (or adoption data). Therefore, Thomas (1985) analogous approach has been further developed and is presented in Figure 27. This extended method is more focused on finding appropriate and sufficient sales data than Thomas five-step method. Internal sources can, for instance, be databases containing the firm’s own sales statistics, while external sources can be commercial sources such as trade and research associations or educational institutions. If a firm is willing to share some of its own sales data, it might even be possible to get some sales data from its competitors or suppliers. Public sources are usually free, and include government departments and agencies and public libraries, and so on. Another extension of the proposed method in Figure 27, is the inclusion of various possible (or probable) market scenarios, resulting in a more comprehensive forecast and thereby a better picture of the future. Furthermore, new data and changed conditions require updated forecasts. As a consequence, the forecasts should be revised continuously and be based also on real sales data (and not only on analogous data) when such data is available.

- According to Peres et al. (2010), there is a great body of evidence suggesting that the overall temporal pattern of diffusion of innovation accelerates over time, i.e. a product launched today diffuses faster than a similar product did in the past. Van den Bulte (2000) showed that the average annual acceleration between 1946 and 1980 has been around 2% for consumer electronics and household products. Although, a slower acceleration should be expected for industrial products and products related to the heavy-duty industry, this effect should be taken into consideration when selecting analogous products and interpreting the forecasted sales.

- Researchers have found that if the market is unstable, the smooth S-curve may not start directly after the introduction of a first new product, but first after an erratic process of diffusion (Tidd and Bessant, 2009). This pre-diffusion phase ends when the regular S-shaped diffusion curve begins. Tidd and Bessant state that the pre-diffusion phase is very risky, since it can last a very long time. If the spread of hybrid HDVs among the customers will be
preceded by a pre-diffusion phase, a time-lag shall be added to the forecasted market penetrations.

- In this thesis it is assumed that several different hybrid technologies will co-exist rather than converge into a single dominant design. How likely is this scenario? Factors in favour of one design to emerge include compatibility, technological superiority, bandwagon effect, financial strength, brand reputation, pricing strategy, timing of entry and marketing communications (Van de Kaa et al., 2007). However, a dominant design may, in particular, be expected in the case of network externalities (or network effects), i.e. the benefits from using a technology or product increase with the number of other users of the same technology or product (Vries et al., 2011). In the hybrid HDV case, indirect network effects may arise, since bigger networks can give rise to more widely available service facilities. Factors that foster the co-existence of multiple designs include persistency and distinct features resulting in product niches, i.e. dominant designs can appear in product categories, while the overall technology lacks a single dominant design (Vries et al., 2011). The authors also state that although a majority of researchers assume that a dominant design will always emerge, several designs may compete for decades, without one technology being locked in as a dominant design. Whether a dominant hybrid HDV technology emerge or not, the obtained forecasts for the total diffusion of hybrid HDVs should be relatively unaffected.

- Hybrid vehicles and many of the hybrid technologies are very complex and require considerable research and development before they reach their full potential. Factors, such as emission regulations, fuel prices, incentives, production capacity of hybrid batteries, and the development of a recharging infrastructure, complicate the forecasting work further. Therefore, future work should include more (and more appropriate) analogous products and a more advanced diffusion model with additional of the restrictive assumptions released (see section 4.4.5). For instance, it would be interesting to investigate the effects of successive product generations, increased fuel prices, incentives (directly included in the model) or the impact of marketing strategies (i.e. direct inclusion of marketing mix variables). Furthermore, it would be very interesting to analyse other markets, such as Asia and Latin America.
Figure 27. Extended method for estimating market growth for new products.

1. Determine possible market scenarios for the new product.
2. Estimate market potential for the new product (for each scenario).
3. Estimate customer values for key new product attributes (for each scenario).
4. Identify a set of existing products having characteristics analogous to the new product.
5. Obtain sales history (or adoption data) for each analogous product.
6. Appropriate and sufficient sales data? Yes/No.
7. Select diffusion model and estimate the model parameters for each analogous product by regression analysis.
8. Calculate the model parameters for the new product (for each scenario).
9. Calculate sales for each scenario.
10. Estimate customer perceptions about the extent the analogous products having the key new product attributes.

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