

Analysis of potential direct rebound effects associated with hybrid Lexus RX400h

Rebound Research Report 5

Zurich, 31 Mar 2009
JD, PdH

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Umfrage zum Lexus RX400h

Vielen Dank, dass Sie sich Zeit nehmen, diesen Fragebogen auszufüllen!

Bitte beachten Sie Folgendes:

- Der Fragebogen richtet sich an überlegte Personen in Ihrem Haushalt, welche das RX am meisten fahrfähig sind. Bei Firmen richtet sich der Fragebogen an diejenige Person, welche beim Beschaffungsentscheid federführend war.
- Die ETH Zürich kennt weder Ihren Namen noch Ihre Adresse! Ihre Angaben bleiben deshalb streng anonym.
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A. Fragen zum Einsatz Ihres Autos

- Werdet Sie den Lexus RX400h persönlich fahren oder haben Sie im Namen einer Firma/Organisation/Institution den Beschaffungsentscheid für andere Nutzer/innen gefällt?
 Ja, ich werde persönlich fahren nein, ich habe nur den Beschaffungsentscheid gefällt.
- Wann haben Sie den RX400h bestellt/gekauft? Leasing Kredit Barzahlung
 Wann wurde der RX400h ausgeliefert? Jahr: _____ Monat: _____
- Wie haben Sie Ihren RX400h erworben?
 Leasing Kredit Barzahlung
- Zu welchem Zweck verwenden Sie den RX400h hauptsächlich? (Nur 1 Antwort!)
 Fahrt zur Arbeit/Ausbildung Einkauf, Besorgungen Taxi-/Ödente* für Kinder, Betagte, usw.
 Geschäfts-/Dienstfahrten Freizeit andere Zwecke
- Wird/wurde für den RX400h ein Vorgängerauto verkauft, eingetauscht oder abgetrossen? Falls ja, welches:

Marke	Modell	Motorgröße (in Liter)	Teilbrennstoff	Schaltung	Baujahr	Leister	Kilometerstand
_____	_____	_____	_____	_____	_____	_____	_____ km

Wie viel ist dieses Vorgängerauto in den letzten 12 Monaten vor dem RX-Kauf gefahren? ca. _____ km
- Ob es in Ihrem Haushalt (oder in Ihrer Firma) weitere Fahrzeuge ausser dem RX400h? Falls ja, welche:
 (inkl. Autos von Lebenspartnern, in noch zu Hause befindenen erwachsenen Kindern und weiteren im Haushalt lebenden Personen)

Marke	Modell	Motorgröße (in Liter)	Teilbrennstoff	Schaltung	Baujahr	Leister	Kilometerstand
_____	_____	_____	_____	_____	_____	_____	_____ km
_____	_____	_____	_____	_____	_____	_____	_____ km
_____	_____	_____	_____	_____	_____	_____	_____ km

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Nachbefragung Käufer/Innen Lexus RX, Seite 1 von 1

Änderungen beim Autobesitz Ihres Haushaltes

- Im Juni 2006 haben Sie uns auf die Frage nach allen Autos Ihres Haushaltes folgende Fahrzeuge genannt:
 → Bitte geben Sie uns für jedes Fahrzeug an, ob es noch im Haushalt vorhanden ist oder nicht.
 → Bitte geben Sie ausserdem den heutigen Zähler des Kilometerzählers dieser Fahrzeuge an.
 (Für das Fahrzeug nicht mehr vorhanden ist, so geben Sie bitte den letzten Km-Stand an.)

Marke und Modell, Baujahr (JK, beifert oder geliefert)	Km-Stand Juni 2006	Noch im Besitz des Abute*	Km-Stand heute
Auto-Nr. 1 Lexus RX400h, ausgeliefert Apr. 2006	400	<input type="checkbox"/> Ja <input type="checkbox"/> Nein	_____
Auto-Nr. 2 Mercedes-Benz A-Klasse, Baujahr 2001	47500	<input type="checkbox"/> Ja <input type="checkbox"/> Nein	_____

*falls das Fahrzeug verkauft/verleigert/verschrotet wurde, bitte den letzten Km-Stand angeben.

- Sind in Ihrem Haushalt (bisher (seit Juni 2006) weitere Autos dazugekommen? nein Ja, und zwar:
 (Alle Personen, die in derselben Wohnung leben, bilden einen gemeinsamen Haushalt.)

Auto A, das seit Juni 2006 dazugekommen ist:

Marke	Modell	Motorgröße (in Liter)	Teilbrennstoff	Schaltung	Baujahr	Wann gekauft/
_____	_____	_____	_____	_____	_____	Monat/Jahr

a) Km-Stand bei Kauf/Übernahme: _____ Km-Stand heute: _____
 c) Hat dieses Auto ein Vorgängerauto ersetzt? nein Ja, und zwar aus obiger Liste Auto-Nr. _____

Auto B, das seit Juni 2006 dazugekommen ist:

Marke	Modell	Motorgröße (in Liter)	Teilbrennstoff	Schaltung	Baujahr	Wann gekauft/
_____	_____	_____	_____	_____	_____	Monat/Jahr

b) Km-Stand bei Kauf/Übernahme: _____ Km-Stand heute: _____
 c) Hat dieses Auto ein Vorgängerauto ersetzt? nein Ja, und zwar aus obiger Liste Auto-Nr. _____

Anmerkungen: _____

Herzlichen Dank für das Ausfüllen des Fragebogens!

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Abstract

Hybrid power trains are considered to be a promising technology to decrease fuel consumption of passenger cars. However, the introduction of more efficient technology is often accompanied by rebound effects, which counteract the potential positive effect of increased efficiency. Three kinds of direct rebound effects could possibly occur when buying hybrid cars: (1) people could tend to switch from small and/or already fuel-efficient cars to the new hybrid car, (2) the average vehicle ownership could increase, if the hybrid car is often purchased without disposing of an already owned vehicle, and (3) the number of miles driven could increase. This study investigates whether these potential direct rebound effects can be empirically observed in the case of the second-most sold hybrid vehicle in Switzerland, the Lexus RX 400h. Two groups of Lexus vehicle owners serve as experimental and control group: owners of the Lexus gasoline-electric hybrid RX400h and of the conventional internal combustion engine Lexus RX300. The data needed for the purpose of these investigations were obtained through two mail-back surveys with a time interval of roughly one year (return rates: 43% and 71%, respectively). Most importantly, two consecutive odometer readings for all cars in the respective households were collected, allowing the computation of vehicle kilometers traveled by all vehicles in the household. Regarding the switch from the previously owned car to the new bought Lexus RX, buyers of hybrid Lexus RX400h do not exhibit an increase in car size compared to the control group, so the first potential rebound effect is not present. On the contrary, despite the 165 kg extra weight of the hybrid power train, hybrid car buyers only have an additional increase in car weight 95 kg compared to the control group. While the difference in rated CO₂ emissions between hybrid RX400h and conventional RX300 is 92 g CO₂/km, the observed difference between the two groups even is 20% larger at 109 g CO₂/km. The second possible direct rebound effect, increase in car ownership, cannot be confirmed as on differences between the experimental and the control group in car transaction and car ownership can be detected. The third possible direct rebound effect has not been observed either: People driving the RX400h do not drive more kilometers than purchasers of the RX300, neither with respect to all household vehicles nor when regarding the hybrid vehicle alone, i.e. no vehicle kilometer rebound effect could be found. In conclusion, at present hybrid electric vehicles can rightly be considered a technology effective in lowering overall CO₂ emissions. Hence socio-psychological rebound effects could not be detected for the investigated Lexus RX, being a crossover SUV.

Keywords

Hybrid cars, hybrid electric vehicle, direct rebound effect, fuel consumption, energy conservation, kilometeric performance, energy-efficiency, socio-psychological rebound, consumer behavior

1 Introduction

Hybrid electric vehicles (HEV) are widely considered one of the most viable alternative propulsion systems to help reduce fuel usage and decrease CO₂ and other emissions in cars. An increasing number of car manufacturers produce hybrid vehicles (Toyota, Lexus, Honda, amongst others) or are developing hybrids that will enter the market in the coming years. Currently, the Swiss automobile market is dominated by cars with gasoline and diesel powered internal combustion engines (ICEs), while HEVs make up approx. 1.1% of Swiss car sales in 2007 (auto-schweiz, 2008). To help promote the market entry of HEVs, many cantons in Switzerland offer tax breaks for such vehicles, and further incentive schemes are being examined on a federal level.

The introduction of more efficient technologies is often accompanied by rebound effects, which counteract the positive effect of increased efficiency. To ensure that state-sponsored energy conservation measures are effective, the occurrence of a strong rebound effect must be ruled out. Three kinds of direct rebound effects could possibly occur when buying hybrid cars: (i) people could tend to switch from small and/or already fuel-efficient cars to the new hybrid car, (ii) the average vehicle ownership could increase, if the hybrid car is often purchased without disposing of an already owned vehicle, and (iii) the number of miles driven could increase. Previous studies (de Haan et al., 2007, 2006c, 2006b, 2006a) have determined that for the most-sold hybrid vehicle in Switzerland, Toyota Prius, rebound effects occur neither for vehicle size nor for vehicle ownership. The Toyota Prius survey however did not allow testing for the occurrence of a direct rebound effect in the amount of kilometers driven.

The original Toyota Prius survey design has been improved and extended for the investigation of the second-most sold hybrid electric vehicle, Lexus' RX400h. Two surveys were sent out (April 2006 and July 2007) to Swiss owners of the Lexus RX400h and the otherwise identical, conventional internal combustion engine non-hybrid RX300, which serve as the control group. The surveys were anonymous, but unique identifiers allowed collecting, and matching, odometer readings of all the cars in the surveyed households at the times of the two surveys. This enabled us to compute kilometers traveled in those 15 months both for the hybrid vehicle and for the total household car fleet.

The aim of this report is thus to analyze the occurrence of all three direct rebound effects possibly associated with the purchase of hybrid Lexus RX400h: (i) possible increase in car size; (ii) possible increase in car ownership; and (iii) possible increase in mileage. With the improved survey design, for the first time we are able to gain insight into the previously unexamined rebound effect regarding the amount of kilometers driven. This will further establish whether hybrid vehicles should rightly be considered a technology effective in lowering overall CO₂ emissions in the Swiss population.

1. Introduction

2 Rebound effects with hybrid vehicles

2.1 Rebound effect theory

Energy conservation measures often rely on new technologies that use less energy resources to produce the same amount of services (e.g. transport, heating, entertainment, etc.) for the user. These energy efficient technologies lead to lower fuel costs during operation. When trying to anticipate the overall energy savings due to a particular new technology, it is important to consider changes in the demand of these services as a (direct or indirect) result of the increased energy efficiency. I.e., the enhanced energy efficiency of a given new technology has ancillary effects that may mitigate or even completely compromise the intended energy savings effect. For example, if the energy efficiency of a car is increased by technological innovations, 100km can be driven with less fuel and hence at a lower cost. This lower cost could have the consequence that people drive more and longer because mobility has become cheaper.

The diminishing factor that can be present in energy conservation measures is called the rebound effect. It is important to distinguish energy use effects that should not be assigned to the rebound effect, e.g. increases in fuel demand due to economic growth (Saunders, 2000).

Three levels of rebound effects are generally distinguished: direct effects, indirect effects and macro-level effects (Berkhout et al., 2000). These shall be presented in the following paragraphs.

The direct rebound effect (DRE) is also called own price effect. It is a first-order effect which stands for increased demand for the same service, e.g. because the service has become cheaper (Berkhout et al., 2000; de Haan et al., 2007). The service that is more resource-conserving because of increased energy-efficiency is being demanded more than when less efficient technology was used. The DRE can be computed simply as the difference between calculated savings and actual savings. The calculated savings are determined by the jump in energy efficiency due to new technology and would be generated applying the *ceteris paribus* assumption, i.e., assuming that service demand remains the same (de Haan, Mueller et al., 2006). The actual savings can be obtained by measurement or observation.

The indirect rebound effect, also called secondary rebound effect, can occur due to more money (i.e. purchasing power) or more time becoming available through the use of higher-efficiency energy technologies (de Haan et al., 2007). When demand for other fuel-consuming services increases due to the increased efficiency, one speaks of an indirect rebound effect.

The macro-level rebound effect, also called economy-wide or tertiary rebound effect is a structural effect on larger parts of the economy due to changed demand, production and distribution patterns (de Haan et al., 2007). The first- and second-order effects (direct and indirect rebound effects) induce a shift of individual household and company spending patterns which in turn alter the pattern of sales in the production sector. This large-scale structure effect has consequences for energy demand resulting in either positive or negative net energy use (Berkhout et al., 2000). Looking at macro-level effects in neo-classical growth terms, the source of rebound is twofold. First, a fuel efficiency gain increases the attractiveness of fuel relative to other production factors needed for production (capital, labor) which leads to the increased substitution of the latter by the use of fuel. Second, fuel efficiency gains can be assumed to increase overall economic output. This increased economic activity then drags up fuel use, because economic growth

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and fuel use are very closely linked in today's economies (Saunders, 2000). The macro-level rebound effect is almost impossible to quantify (de Haan, Mueller et al., 2006).

types of increased demand ↓	causal mechanisms for rebound →		economic rebound	socio-psychological rebound	regulatory rebound
	Saunders 2000	Sorrel 2007	§	Ψ	§
direct rebound	direct rebound (income/output eff.)		increased demand for the same good or service (Saunders 2000) income/output effects (Sorrel 2007)		
indirect rebound	direct rebound (substitution eff.)		increased demand for other goods/services (Saunders 2000) substitution effect (Sorrel 2007)		
macro-level rebound	indirect rebound		adaptation of production system to new demand patterns (Saunders 2000) secondary and grey energy effects (Sorrel 2007)		
<i>Holds for resource rebound effects in general, in special for energy rebound (increased demand due to increased energy-efficiency) and time rebound (increased demand due to increased time-efficiency)</i>					

Table 1. Differentiation of total observable rebound effect according to different types of increased demand, both in the Saunders (2000) and Sorrel (2007) categorizations, and according to different causal mechanisms.

2.2 Research questions

The following three direct rebound effects are conceivable when more fuel-efficient cars enter the market (de Haan, Mueller et al., 2006; de Haan et al., 2007).

Increase in car size (DRE1). Households purchasing the new fuel-efficient vehicle may substitute a smaller lighter car for a larger hybrid car because its operational costs will be comparable to cars which are smaller in size and weight. This purchasing behavior would constitute a direct rebound effect to the potential fuel-savings associated with hybrid power train technology. It is only considered rebound if it exceeds the current market trend behavior of buying ever larger cars.

Increase in average household vehicle ownership (DRE2). The (cost-saving) advantages of the HEV may encourage a household to increase its vehicle fleet by buying the hybrid vehicle. In this case the HEV has caused more vehicles to be produced, than if the hybrid had not entered the market. Every vehicle accounts for energy use in its production. An increase in vehicle ownership in a household would therefore constitute the occurrence of the second possible rebound effect.

Increase in kilometers traveled (DRE3). Due to its more efficient power train, the operational costs of an HEV are lower compared to another car of comparable weight and power. The most intuitive rebound effect therefore is the increased use of the hybrid vehicle compared to its precursor. I.e. more kilometers may be driven in the hybrid car, than with a similar car without hybrid technology. This would constitute the third possible rebound effect: an increase in kilometers traveled.

DRE 1 through 3 could occur due to a variety of possible rebound drivers. These include cost saving, time saving and socio-psychological cost of ownership (see de Haan, Mueller et al. (2006) for a detailed introduction, especially regarding DRE1 and DRE2). A discussion of possible drivers for DRE3 follows hereafter.

One of the goals of this report is to establish whether a direct vehicle kilometer rebound effect (DRE₃) is measurable for the RX400h vehicles and for the complete household vehicle fleets, comparing Swiss RX400h owners with the control group consisting of Swiss Lexus RX300 purchasers. In case a DRE₃ can be identified, it shall be quantified as a percentage of rebound. Furthermore, a more comprehensive test of a CO₂ rebound in all household vehicle fleets shall follow any occurrence of DRE₃ found. It is conceivable that a rebound for the RX400h or even for the household fleet can occur without the total CO₂ emissions increasing, because the HEV might be used more in place of other less fuel-efficient cars in the household.

The rebound effect has been studied in the field of energy economics for decades. The principle goal is to improve the economic models to better describe what rebound effects will take place on the introduction of any new energy- or resource-saving technology. Being able to predict the rebound effects that will occur would be especially useful in supporting economic policy decisions; case in point being possible tax cuts or other subsidies for hybrid vehicles. Policy measures that aim at lowering energy use could be made more effective by knowing in detail where to best implement such policies, viz. by subsidizing technologies which are expected to show the lowest degree of rebound. The rebound effect has a sound theoretical basis; however, its magnitude and importance for any specific technology and application are an empirical question (Saunders, 2000). A number of factors need to be better constrained, e.g. the substitution and fuel elasticity (Binswanger, 2001). Empirical results in a wide range of applications are needed to better understand the rebound effect and to better predict its occurrence for any specific technology introduction.

It has been suggested, based on theoretical and semi-empirical econometric studies on the subject, that a rebound effect will be present in the transport sector (Binswanger, 2001; Greening et al., 2000). Binswanger (2001) cites various studies that have established vehicle kilometer rebound effects (DRE₃) ranging from 5% to 51% based on regression models that use time series of energy prices and estimated constant price elasticities of service demand to derive rebound intensity. These results must be viewed with care, though, as they don't arise from direct observation. A number of recent studies (Altorfer et al., 2006; de Haan, Mueller et al., 2006; Minder, 2006) have investigated various direct rebound effects for two hybrid vehicles in the Swiss market: Toyota Prius 2 and the Lexus RX400h. The results of these studies are all similar. Neither the first nor the second direct rebound effect (DRE₁ and DRE₂) could be detected in either of the two hybrid vehicles investigated. In fact, for both the Prius 2 and Lexus RX400h vehicles, the average increase in vehicle curb weight was slightly (not significantly) lower for the hybrid vehicle buyers than for the respective control groups representing similar vehicles with conventional ICEs. I.e. on average, hybrid car buyers seem not to switch from small, already fuel-efficient cars to new larger hybrid cars and they seem not to expand their household vehicle fleets by adding the new hybrid vehicles (but instead replace an old car with the new hybrid vehicle).

Qualitative studies by Kurani (2008) have established that households display a shift from other household vehicles to the HEV, i.e. the HEV is used more while other vehicles in the households are used less; this behavior would manifest itself as a DRE₃ for the HEV. Yet to date, no quantitative empirical research is known to have been carried out on the third direct rebound effect (DRE₃). The reason is probably to be found in the complexity and detail involved in acquiring the necessary data (de Haan, Peters et al., 2006). This study aims to provide the first empirical research results for this possible effect accompanying the market introduction of hybrid vehicles: the vehicle kilometer rebound effect (DRE₃).

There are various conceivable drivers for the DRE₃. The first possible driver is that of lower operating costs, i.e. because the hybrid technology reduces fuel use and its costs, the owners of hybrid cars might use the car in situations they may not have otherwise. Additionally, RX400h owners may want to "earn back" the price premium paid for the hybrid technology (CHF 6'650), which can only be achieved by driving the car a substantial amount (see section 5.8). The evaluation of the first mail-out survey had established that the owners of the RX400h were quite aware of its fuel saving nature and indicated that this fact was vital in choosing this hybrid automobile: Among 12 possible purchasing criteria, fuel usage ranked first among RX400h purchasers, whereas it ranked last among RX300 purchasers (Altorfer et

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al., 2006). Therefore an important precondition for the rebound driver of lower operating cost is indeed met, viz. the awareness of fuel and cost saving property of the hybrid vehicle. The above stated awareness of RX400h owners could however simply encourage them to substitute driving the RX400h for more fuel consuming cars, as observed by Kurani (2008), yet this would not lead to a rebound on the household level.

Altorfer et al. (2006) also determined, however, that owners of the RX400h did not intend to drive more on average in the 12 months after purchase than the RX300 owners, despite their explicit awareness of the fuel saving advantages of the hybrid vehicle. According to this data, the possible rebound driver of lower operating costs is not in effect. The reason for this may be found in the income class of RX400h customers: The 'crossover' vehicle RX400h with a purchase price of CHF 85'900 is almost in the class of luxury vehicles. Therefore, saving money can be assumed not to be a high priority for these customers. But as mentioned above, there are further possible drivers for the DRE3.

As postulated by de Haan et al. (2007), a direct rebound effect should be expected for the RX400h in particular (as opposed to other hybrid vehicles) because of the possibly large decrease in the socio-psychological cost of ownership. This suggested driver emanates from the assumption that big, highly fuel-consuming cars (a.k.a. 'gas guzzlers') attract disapproval from surrounding friends, family and neighbors. The case studies of Heffner (2007) provide some anecdotal evidence for this assumption. Altorfer et al. (2006) point out that the cars owned previously to the RX400h were of similar size: large heavy vehicles. The hybrid technology may significantly increase outside approval of these large cars, despite its fuel use still being higher than the average car owned in Switzerland. Because of the strong social disapproval of the RX400h vehicle class to begin with, the relative difference in social perception between the non-hybrid and hybrid vehicles will be biggest for this vehicle class, i.e. the decrease in socio-psychological cost of ownership can be assumed to be large for this vehicle.

The decrease in socio-psychological cost of ownership may not have been foreseen by the respondents when they filled out the first survey stating that they did not intend to drive the RX400h more than previous cars. This rebound driver may only have its effect after the owners of the hybrid vehicle experience their peers' (positive) reactions over time. Further, as mentioned earlier, the driver of lower operating costs only has rational justification for large amounts of annual vehicle kilometers (see section 5.8). Therefore we postulate that if a rebound effect is found, it is due to the socio-psychological effect mentioned earlier. Relating to this assumption I shall further explore the relationship of intended vehicle kilometers and the previous year's vehicle kilometers (indicated in the 2006 survey) with actual kilometeric performance of the respective RX vehicle owners.

There is another reason, however, why a rebound may not occur despite the rebound driver introduced above. Each model of the RX400h is equipped with a real-time display which shows the person driving in real-time how energy is being allocated, where it is coming from and when energy is being used or regained. It also provides a quick overview of how much fuel was consumed and whether the driving style was fuel-efficient or not. The heightened awareness of RX400h owners for the resource use associated with driving mustn't be underestimated and may counteract the psychological rebound driver mentioned earlier. In fact, this driver could even lead to a reduction in the number of vehicle kilometers driven for all vehicles in the household. We also investigate how many years it takes an average RX400h owner to save as much money in fuel savings as was spent extra at purchase compared to the RX300.

3 Hybrid electric vehicles and the Lexus RX400h

HEVs can be classified into three categories according to their degree of hybridization: stop-start HEV, mild HEV and full HEV (Bitsche et al., 2004). The battery in stop-start HEVs, with some potential to regain energy by regenerative braking, is only used to supply the necessary power while the ICE is shut off (when not needed, e.g. at a traffic light); the only source of propulsion power is the ICE. In a mild hybrid vehicle, the electric system is expanded by an electric motor (42V) running in parallel with the ICE during acceleration of the vehicle. Full HEVs allow for total flexibility in battery power allocation in order to run the parallel ICE-HEV system most efficiently at all times. The battery in full HEV (300V) is capable of powering the car's propulsion on its own.

Compared to conventional ICE vehicles, full HEVs effectively save energy and substantially reduce fuel consumption in a number of ways (Brahma et al., 2000; Chau et al., 2002):

- No engine idling: When the vehicle does not need propulsion energy the engine is always turned off. It can be turned on instantaneously when needed.
- Recuperation of braking energy: When the vehicle brakes to slow down, the kinetic energy of the vehicle is used as a power source to load the batteries, thus recycling energy that would otherwise be lost as heat in the brake pads. This makes HEVs especially efficient in stop-and-go traffic.
- Additional degree of freedom: The power demand of the driver can be satisfied by splitting between thermal and electrical paths to always be the most energy efficient.
- Maximization of engine operation in its peak efficiency area: In many driving situations the engine can be run at RPM and torque values that are most fuel efficient while the electrical motors take over the rest of the power needed, or load the battery with excess power, depending on the given situation. Furthermore, small fluctuations in acceleration are handled by the electrical motor, letting the ICE run smoothly and constantly to conserve fuel.
- Smaller ICE: The size and power of the ICE is generally determined by the acceleration power that customers demand. Because the electric drive system provides a large amount of power to accelerate the car, the ICE can be substantially downsized, reducing inefficiencies from underutilization of the engine.
- Efficiency of the electric system: Electric motors and batteries operate with very high efficiency.

The Lexus RX vehicle line was first introduced in 1997 with the RX300, while the RX400h has been on the market since 2005. The RX400h and the Lexus RX300 use the same body design of a crossover SUV and have many of the same specifications. The main difference lies in the drive train: The RX300 uses only a V6 gasoline ICE with 150 kW (204 hp), while the full hybrid RX400h has an all-wheel 'Lexus Hybrid Drive' drive train which combines a similar V6 gasoline ICE with 2 electrical motors (for front and rear wheels), achieving a total combined power of 200 kW (272 hp). The RX400h uses the display of the GPS system to show the driver real-time details on the operation of the hybrid technology, such as direction of energy flow, motors running, battery charge and fuel usage (mileage) for each trip. Both vehicles have been re-launched in the meantime as new versions: The RX350, released in 2007, and the RX450h, which will be released in the US in 2009 (Evans, 2008). See Table 1 for more details on the differences of these vehicle's specifications.

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Table 2. Comparison of Lexus RX300 and RX400h specifications (Lexus, 2005a, 2005b). *CVT = electronically controlled continuously variable transmission. **See text for methodology used to compare purchasing prices of RX300 and RX400h.

specifications	Lexus RX300	Lexus RX400h
Motor	V6 Gasoline ICE	V6 Gasoline ICE & 2 electric motors
transmission	4-wheel drive automatic	dynamic 2- and 4-wheel E-CVT*
motor power	150 kW (204 hp)	200kW (272 hp) total
fuel consumption	12.2 l/100km	8.1 l/100km
CO₂ emissions	288 g CO ₂ /km	192 g CO ₂ /km
vehicle weight	1835 kg	2000 kg
acceleration 0-100 km/h	9.0 sec	7.6 sec
sales price**	CHF 79'250	CHF 85'900

The RX400h was sold in 2006 with far fewer options than the RX300. The purchase price of the RX300 therefore was corrected for the various components that were included in every RX400h but were optional in the RX300. We started with the specifications of the basic RX400h model and listed every included component quoted on the sales brochure of the RX400h (Lexus, 2005b). We then compared this list with the sales brochure of the RX300 and added the prices of all optional components that came as standard with the RX400h to the price of the RX300 (Lexus, 2005a). The analogous version of the RX300 had the following setup: Lexus RX300 class 'edition' with the optional components 'Power-Package' and 'GPS navigation system'. The RX400h cost CHF 85'900, while the RX300 with analogous components had a price of CHF 79'250. The price difference between comparable versions of the RX400h and RX300 therefore amounted to CHF 6'650.

4 Survey

4.1 Design of the mail-back surveys

The data needed for the purpose of these investigations were obtained with two mail-back surveys, conducted in collaboration with Lexus Switzerland who supplied and managed the addresses of Lexus customers. The first comprehensive survey was sent out in April 2006 to two groups of Lexus customers in German and French speaking Switzerland: those who bought the hybrid Lexus RX400h (the experimental group) and purchasers of the Lexus RX300 (the control group). The Italian speaking part of Switzerland was omitted from these surveys for cost-benefit reasons: the resulting sample size would have been too small. 746 surveys were sent out with a return rate of 43%, i.e. the sample consisted of 195 (RX400h) and 123 (RX300) cases (Altorfer et al., 2006). This survey covered many areas of interest including car usage, purchasing decision criteria, sociodemographic data, traffic behavior and more. As part of this first survey, the odometer readings of all the cars owned by the survey participants were recorded. To take a look at the full questionnaire, see Altorfer et al. (2006).

Roughly 15 months later, in July 2007, a one-page follow-up survey was sent out to the Lexus customers who had agreed to participate in a follow-up survey (RX400h: 181, RX300: 106). 205 of the total 287 follow-up surveys sent out were filled out and sent back, yielding an exceptional return rate of 71% (see Table 3 for more details). This follow-up survey allowed for the collection of odometer readings for all the cars in the respective households for the successive year. By using a unique code for each household participating in the two surveys, we gathered two odometer readings of the same cars in the same households in two consecutive years. Final odometer readings of cars disposed of and original odometer readings of new cars acquired since the first survey were also recorded. This data forms the basis for the investigation of the occurrence of the third possible DRE: the vehicle kilometer rebound effect. Notice that all odometer data is recorded for a time frame of approx. 15 months (between April 2006 and July 2007). The complete follow-up survey questionnaire can be viewed in the Appendix.

Table 3 Sample of 2007 follow-up survey

RX400h	Sent out	Returned	Return rate
RX400h total	181	143	79%
RX300 total	106	62	58%
Overall total	287	205	71%

4.2 Characterization of RX400h owners

Altorfer et al. (2006) provide us with some information about the purchasers of these two Lexus vehicles in Switzerland. See Table 4 for an overview of the differences in RX purchasers' characteristics and behavior. Considering age, education and gender the differences that can be found between purchasers of the RX400h and RX300 are marginal. However RX400h owners do earn a slightly higher income on average, as can easily be explained by the higher cost of the Lexus RX400h. Further, RX400h owners attribute higher importance to fuel usage than do owners of the RX300 and they indicate fuel cost to be an important factor in their purchasing decision, but they do not intend to drive significantly more kilometers than RX300 owners. The most striking difference between the two groups of Lexus owners is found in their willingness to adopt new technologies as described by Rogers (2003). Most owners of the RX400h can be assigned to the category of 'early adopters' with a few even belonging to the 'innovators'. Owners of the RX300 belong to the 'late majority' or 'laggards', i.e. they are among the last 10% to buy a car with new technology (Altorfer et al., 2006).

Table 4 The owners of the Lexus RX series in Switzerland in April 2006.

	Lexus RX300	Lexus RX400h
Characteristics		
Gender	86.6% male	88.2% male
Average age	53.8 years	55.6 years
Education	Vocational education, Technical college, University	Mostly university degree
Monthly income	50% over CHF 14'000	>60% above CHF 14'000
Behavior		
Intended use for RX	Mostly leisure	Mostly leisure
Selling point	Security	Fuel usage
Technology adoption category	Late majority, laggards	Early adopters, innovators

4.3 Statistical testing

We have two groups of samples, the experimental group consisting of RX400h customers and the control group consisting of RX300 customers. To detect a rebound in vehicle kilometers in RX400h purchasers, their average kilometric performance is compared to a control group with similar characteristics, namely RX300 purchasers. I assume, therefore, that a lack of rebound for the hybrid technology in the RX400h would express itself as an identical average of vehicle kilometers driven in both sample groups, while a significantly differing average would point to the occurrence of the DRE3. By using a control group which is very similar in characteristics to the experimental group, we avoid many possible external effects (apart from differing power train technology) arising from differences in vehicle class, design and price. To statistically test the differences in average kilometric performance, T tests for two independent samples are conducted. If they yield significant results (i.e. if the null hypotheses mentioned in section 2.2 can be discarded), a DRE3 is prevalent or vice versa. These tests are performed (1) for the RX vehicle only, (2) for the complete vehicle household fleet and (3) for the household vehicle fleet excl. the Lexus RX vehicles.

Further testing with the T test shall be conducted with various subgroups of the sample according to income and the amount of household vehicles owned. To investigate on the motivators for more or less kilometers driven with the

RX400h, the amount of kilometers RX owners intend to drive (indicated in the 2006 survey) shall be compared to the actual kilometric performance of the respective RX vehicles, differentiating between the owners of the RX300 and RX400h. For this purpose, the observed kilometric performances must be adapted from a 15 month to a 12 month time frame by multiplying them by a factor of 0.8.

With this method and the sample sizes given for the various statistical tests conducted, a DRE₃ that occurs in reality can only be determined in the sample groups if it is of large enough magnitude, i.e. if the averages in the sample groups differ by a large enough margin. Using the program G*Power, it is possible to investigate how large the rebound effect would have to be in reality, for a significant result to appear in the test setups used for the various statistical tests (Faul et al., 2007). This enables an estimation of the range in which the rebound effect truly lies, even if results of the T tests are non-significant. A statistical power ($1 - \beta$ error) of 0.8 was used for these G*Power analyses.

4.4 Testing survey data with SPSS

Data preparation, data quality assurance, data manipulation, and statistical examinations of survey data were all conducted using the statistics software SPSS version 16 for Mac. The digital data originated from the two surveys described earlier (see section 4.1). Two principal assumptions were applied for quality assurance: (1) the odometer readings from the 2007 survey have to be larger than the odometer readings of the same car in the 2006 survey and (2) very small (<5000 km) and very large (>50'000 km) values for kilometers traveled are unlikely. Questionable kilometer values were double-checked by manually referring to the original questionnaire sheets.

To calculate kilometric performances of the RX vehicles and all other vehicles in the household fleet, the odometer readings of all cars in the 2006 survey were simply subtracted from the odometer readings of the 2007 survey. For vehicles that had been disposed of, the last odometer reading before disposal was used. For vehicles acquired between the two surveys, the odometer reading at time of purchase was subtracted from the respective odometer reading at the time of the second survey. Total household kilometric performances were calculated by adding up the kilometric performances of all cars in every household. The calculation of the cumulated kilometric performance of all secondary vehicles (excluding the RX) was done analogously. To test for the occurrence of DRE₃ in RX owners, the SPSS function 'Independent Samples T test' was used to compare the means of the two sample groups made up of households owning an RX300 and households owning an RX400h, respectively. When testing kilometric performances of the RX vehicles, as well as when testing kilometric performances of all secondary household vehicles (other than the RX), all cases were excluded where the RX vehicle was already disposed of again before the 2007 follow-up survey. When testing household kilometric performances of all household vehicles two cases were excluded where the odometer readings specified by the survey respondents were not realistic. One case was dropped (for all tests) because it did not represent a private household. Table 5 lists the circumstances under which cases were dropped when the statistical tests were conducted. Note that for numerous cases multiple of the circumstances listed apply.

Table 5 Cases that were dropped for statistical testing (with overlap)

Circumstance	No. of Cases	Cases dropped when testing
Not a private household	1	All tests
Lexus sold before follow-up survey (2007)	13	RX vehicles, secondary vehicles
Missing values for RX vehicle	5	RX vehicles
Values unfeasible	2	Household fleet, secondary vehicles

4. Survey

5 Results

5.1 DRE1: Car size rebound effect

In this section we analyze the difference in car size from the previously owned car (that has been, according to the respondents, replaced by the Lexus RX vehicle) to the Lexus RX. If hybrid car buyers previously owned smaller cars than the control group did, this would be an indication of a direct rebound effect, i.e. the hybrid powertrain might have served as socio-psychological justification for an increase in car size that is larger than in the case of a new non-hybrid vehicle. As proxies for car size, we regard curb weight (empty vehicle weight). We also test for vehicle length and the volume of the smallest box the vehicle would fit into. The RX400h and control group's RX300 are identical with regard to car size, with the exception of curb weight: Due to the hybrid drive train, especially the battery pack, the RX400h has a surplus weight of 165 kg (Table 2). We will also analyze whether the decrease in rated CO₂ emissions that can be observed for the RX400h group is smaller than, or larger than, the theoretically expected decrease due to the differences between RX400h and RX300. Two-sided Student's T tests for independent samples were used for all these metric parameters.

Curb weight as proxy for car size

Differences in curb weight were significant, $t(285) = 3.144$, $p = 0.002$ (Table 7). However, the difference in weight increase is 95 kg (Table 6) which is below the difference of 165 kg that is caused by the hybrid powertrain. So while the buyers of the control group, by purchasing the Lexus RX, increased the car weight owned by 233 kg, the hybrid buyers group increased car weight by 163 kg (plus 165 kg for the hybrid powertrain), i.e. they exhibited a below-average increase in car size.

	Purchased car model	N	Mean	Std. Deviation	Std. Error Mean
DiffLGEW	Lexus RX 400h	180	328.0222	249.61378	18.60511
	Lexus RX 300	107	233.6729	239.37638	23.14139

Table 6. Descriptive statistics for differences in curb weight between previously owned vehicle and new Lexus RX.

		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% C.I. of the Difference	
									Lower	Upper
DiffLGEW	Equal variances assumed	.003	.959	3.144	285	.002	94.34933	30.01191	35.27621	153.42244
	Equal var. not assumed			3.177	230.332	.002	94.34933	29.69300	35.84472	152.85393

Table 7. Test results for differences in curb weight between previously owned vehicle and new Lexus RX (T test for independent samples).

Car length as proxy for car size

No significance emerges for differences in length in millimeters, $t(286) = 0.030$, $p = 0.976$ (Table 9), with both groups showing an increase in vehicle length of approx. 11.5 cm (Table 8).

	Purchased car model	N	Mean	Std. Deviation	Std. Error Mean
DIFF_LEN	Lexus RX 400h	181	115.1547	236.92926	17.61081
	Lexus RX 300	107	116.0000	213.88738	20.67727

Table 8. Descriptive statistics for differences in vehicle length (in millimeters) between previously owned vehicle and new Lexus RX.

		Levene's Test for Equality of Variances		t-test for Equality of Means					95% C.I. of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
DIFF_LEN	Equal variances assumed	.169	.681	.030	286	.976	.8453	27.88404	-54.0387	55.72927
	Equal var. not assumed			.031	240.909	.975	.8453	27.16046	-52.6570	54.34760

Table 9. Test results for differences in vehicle length (in millimeters) between previously owned vehicle and new Lexus RX (T test for independent samples).

Car cubic volume as proxy for car size

No significance results emerge for differences in cubic volume (vehicle length times width times height), with $t(285) = 0.047$, $p = 0.963$ (Table 11). An average, both groups increased the cubic volume (in the definition used here) by approx. 1.65 m³.

	Purchased car model	N	Mean	Std. Deviation	Std. Error Mean
DIFF_KUB	Lexus RX 400h	181	1.6482	1.67198	.12428
	Lexus RX 300	106	1.6579	1.75225	.17019

Table 10. Descriptive statistics for differences in cubic volume (car length times car width times car height, in cubic meters) between previously owned vehicle and new Lexus RX.

		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% C.I. of the Difference	
									Lower	Upper
DIFF_KUB	Equal variances assumed	.023	.879	.047	285	.963	.0097	.20816	-.40004	.41943
	Equal var. not assumed			.046	211.714	.963	.0097	.21074	-.40572	.42511

Table 11. Test results for differences in cubic volume (car length times car width times car height, in cubic meters) between previously owned vehicle and new Lexus RX (T test for independent samples).

Differences in rated CO₂ emissions

As had to be expected, differences between groups for the differences in rated CO₂ emissions between previously owned and newly purchased Lexus RX vehicle are highly significant (Table 13), $t(285) = 18.019$, $p = 0.000$. The RX300 has rated CO₂ emissions of 288 g CO₂/km, the RX400h of 192 g CO₂/km; a difference of 96 g CO₂/km. The observed difference between previously owned and newly bought Lexus RX vehicle increases by 23 g CO₂/km for the control group, but decreases by -87 g CO₂/km for the hybrid group. The difference between the averages for the two groups hence is -109.85 g CO₂/km, which exceeds the theoretically expected decrease (due to the hybrid powertrain) of -87 g CO₂/km by over 20%.

	Purchased car model	N	Mean	Std. Deviation	Std. Error Mean
DiffCO ₂	Lexus RX 400h	180	-86.6332	50.90111	3.79395
	Lexus RX 300	107	+23.2184	48.27460	4.66688

Table 12. Descriptive statistics for differences in rated CO₂ emissions (g CO₂/veh-km) between previously owned vehicle and new Lexus RX.

		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% C.I. of the Difference	
									Lower	Upper
DIFF_CO ₂	Equal variances assumed	.277	.599	18.019	285	.000	109.85160	6.09628	97.85216	121.85104
	Equal var. not assumed			18.265	232.318	.000	109.85160	6.01447	98.00173	121.70147

Table 13. Test results for differences in rated CO₂ emissions (g CO₂/veh-km) between previously owned vehicle and new Lexus RX (T test for independent samples).

Overall conclusion on DRE1 (potential direct rebound effect manifested as increased car size)

In none of the different proxies used for car “size”, the hybrid group showed an increase in car size with respect to the control group. On the contrary, the increase in car weight in the hybrid group is lower than theoretically expected: In the hybrid group car weight increase was only 95 kg higher than in the control group, although the surplus weight of the hybrid power train is 165 kg. The similar (inverted) picture becomes visible for rated CO₂ emissions, where the decrease in the hybrid group exceeds the theoretical expectation: While the difference in rated CO₂ emissions between conventional RX300 and hybrid RX400h is -96 g CO₂/km, in the hybrid group the CO₂ emissions on average drop by -110 g CO₂/km compared to the control group. No differences can be seen regarding changes in average car length or car cubic volume. Hence overall, the hybrid group did not buy a larger vehicle (regarding the proxies length or cubic volume) only because of the hybrid power train, but changes in car weight and rated CO₂ emissions even exceeded the theoretical expectation.

5.2 DRE2: Increase in car ownership

Changes in car ownership are tested for regarding two aspects: First, by analyzing the share of new cars that truly replaced a previously owned car versus the share of new cars that increased household car ownership (first-ever car owned by the household, or car is added to car fleet). Second, by analyzing the distribution of the number of cars in the household fleets. Both a Mann-Whitney test and a Students’ T-Test have been performed, as the variable “previously owned car has been sold or scrapped” can be interpreted either as an ordinal or as a metric variable. Both types of test yielded similar results: The Mann-Whitney test shows no significance, Mann-Whitney-U = 9828.000, p = 0.442 (Table 14, Table 15), nor does the T test, t (289) = -0.768, p = 0.443 (Table 16, Table 17).

	Purchased car model	N	Average rank	Rank sum
Previously owned car sold or scrapped	Lexus RX 400h	183	145.70	26664.00
	Lexus RX 300	108	146.50	15822.00
	Total	291		

Table 14. Mann-Whitney test: Rank statistics for replacement of previously owned vehicle.

	Previously owned car sold or scrapped
Mann-Whitney-U	9828.000
Wilcoxon-W	26664.000
Z	-.768
Asymptotic significance (2-sided)	.442

Table 15. Test statistics for Mann-Whitney U test for replacement of previously owned vehicle.

	Purchased car model	N	Mean	Std. Deviation	Std. Error Mean
Previously owned car sold or scrapped	Lexus RX 400h	183	.99	.074	.005
	Lexus RX 300	108	1.00	.000	.000

Table 16. Descriptive statistics for replacement of previously owned vehicle.

		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% C.I. of the Difference	
									Lower	Upper
Prev. owned car sold/scrapped	Equal variances assumed	2.383	.124	-.768	289	.443	-.005	.007	-.019	.009

Table 17. Test results for differences share of previously owned vehicle that has been sold or scrapped (T test for independent samples).

Regarding the frequency distribution of the size of the household car fleet (number of cars owned by the household), also no significant differences could be found.

	Purchased car model	N	Average rank	Rank sum
Number of household vehicles apart from Lexus RX	Lexus RX 400h	193	166.70	32174.00
	Lexus RX 300	122	144.23	17596.00
	Total	315		

Table 18. Mann-Whitney test: Rank statistics for replacement of previously owned vehicle.

		Number of household vehicles apart from Lexus RX
Mann-Whitney-U		10093.000
Wilcoxon-W		17596.000
Z		-2.334
Asymptotic significance (2-sided)		.020

Table 19. Test statistics for Mann-Whitney U test for replacement of previously owned vehicle.

	Purchased car model	N	Mean	Std. Deviation	Std. Error Mean
Number of household vehicles apart from Lexus RX	Lexus RX 400h	193	1.26	1.064	.077
	Lexus RX 300	122	.98	.918	.083

Table 20. Descriptive statistics for frequency distribution of number of household vehicles apart from Lexus RX.

		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% C.I. of the Difference	
# hh veh. apart from RX	Equal variances assumed	2.986	.085	2.402	313	.017	.281	.117	Lower	Upper
									.051	.511

Table 21. Test results for frequency distribution of number of household vehicles apart from Lexus RX. (T test for independent samples).

In conclusion, there are no significant differences in car transaction behavior and car ownership between the hybrid group and the control group, hence the hybrid power train does not seem to give rise to a tendency to own more vehicles for the reason of hybrid power trains having entered the market.

5.3 DRE3: Vehicle kilometer rebound effect

The mean difference in kilometric performance between owners of the RX400h and RX300 vehicles is a mere 597 km (RX400h: 21'630 km p.a., RX300: 21'034 km p.a.), i.e. the RX300 is driven a little bit less in our sample than the RX400h. While this might allude to a diminutive rebound, it is not a significant result to refute the null hypothesis of equal means. Therefore, no significant rebound can be found for the Lexus RX400h, $t(185) = 0.377, p = 0.707(0.05), n(\text{RX400h}) = 135, n(\text{RX300}) = 52$. G*Power analysis reveals that the true rebound would have to be larger than 22% for it to be significant in this test ($\sigma \approx 10'000$ km, stat. power = 0.8). On the household level we see the opposite of a rebound for owners of the RX400h: Households owning a Lexus RX400h drive an average of 1'367 km less per year with all household vehicles (RX400h: 33'230 km p.a., RX300: 34'597 km p.a.). These results are not significant, $t(86.325) = -0.410, p = 0.683(0.05), n(\text{RX400h}) = 142, n(\text{RX300}) = 58$. According to G*Power analysis, rebound would have to be larger than 25.5% for a significant result to appear ($\sigma \approx 20'000$ km, stat. power = 0.8). See Table 4 for an overview of the factors that caused the different sample sizes in the two tests above. The T test for the secondary household vehicles (household vehicles excluding the Lexus RX) brought forth another non-significant result: $t(135) = 0.020, p = 0.984(0.05), n(\text{RX400h}) = 100, n(\text{RX300}) = 37$. The difference in average kilometric performance of all secondary vehicles results in a mere 58 km (RX400h: 16'667 km, RX300: 16'609 km). Rebound would have to be larger than 49% for this test to yield significant results ($\sigma \approx 15'000$ km, stat. power = 0.8).

5.4 Testing Kurani's 'household shift' observation

To investigate further on Kurani's observations of a 'household shift' from secondary vehicles to the hybrid vehicle, I repeated the three tests for all households owning multiple vehicles, and the first test for all households owning only one vehicle:

Multiple-vehicle households

In the sample of households owning multiple cars the following results are attained. The RX is driven 776 km less in households owning the hybrid version (RX400h: 21'727 km, RX300: 22'503 km). The result is non-significant, $t(133) = -0.421, p = 0.674(0.05), n(\text{RX400h}) = 99, n(\text{RX300}) = 36$. For this test a rebound would have to be larger than 24.5% to ($\sigma \approx 10'000$ km, stat. power = 0.8). The complete household fleet is driven 1'007 km less (RX400h: 38'372 km, RX300: 39'379 km) in households owning a hybrid vehicle. Results are non-significant, $t(133) = -0.279, p = 0.781(0.05), n(\text{RX400h}) = 99, n(\text{RX300}) = 36$. Only a rebound larger than 28% would yield a significant result in this test ($\sigma \approx 20'000$ km, stat. power = 0.8).

Secondary vehicles are driven 221 km less (RX400h: 16'655 km, RX300: 16'876 km) in households owning a hybrid vehicle. This result is non-significant, $t(133) = -0.075$, $p = 0.94(0.05)$, $n(\text{RX400h}) = 99$, $n(\text{RX300}) = 36$. This test can only yield significant results for a rebound above 48.5% ($\sigma \approx 15'000$ km, stat. power = 0.8).

One-vehicle households

Regarding households with one vehicle only, namely the respective Lexus RX vehicle, we see a hint of rebound, albeit non-significant: The mean difference in kilometric performance amounts to 3'228 km (RX400h: 21'004 km, RX300: 17'776 km), $t(48) = 1.018$, $p = 0.314(0.05)$, $n(\text{RX400h}) = 35$, $n(\text{RX300}) = 15$. In this test, the rebound would have to be larger than 49.5% ($\sigma \approx 10'000$ km, stat. power = 0.8) for a significant result to emerge.

Table 22 Overview of results (MVHH: multiple-vehicle households; OVHH: one-vehicle households)

Vehicles considered	Mean difference [km]	t	p	n(RX400h)	n(RX300)	Theoretically detectable rebound ¹
RX	597	0.377	0.707	135	52	22%
Household fleet	-1'367	-0.41	0.683	142	58	25.5%
Secondary vehicles	58	0.02	0.984	100	37	49%
RX (MVHH)	-776	-0.421	0.674	99	36	24.5%
Household fleet (MVHH)	-1'007	0.279	0.781	99	36	28%
Secondary vehicles (MVHH)	-221	-0.075	0.94	99	36	48.5%
RX (OVHH)	3'228	1.018	0.314	35	15	49.5%

5.5 Analysis of income groups

Various tests were conducted investigating the question whether a rebound can be found for certain income groups while not for others. Some differences could be found, e.g. regarding the income group with a salary of between CHF 12'000 and CHF 14'000 a significant rebound was detected ($p=0.043$). But due to small sample sizes for these salary sub-groups these results are considered inconclusive. A larger sample size and higher ranging income groups (going beyond CHF 14'000 per month) would be necessary to investigate this question in more detail.

5.6 Analysis of intended vehicle kilometers

Owners of the RX400h expect to drive an average of 1'300 km more (RX400h: 18'392 km, RX300: 17'092 km) with their car than RX300 owners as indicated by the respondents in the first survey (2006) but this result is non-significant, $t(284) = 1.115$, $p = 0.266$, $n(\text{RX400h}) = 177$, $n(\text{RX300}) = 109$. When comparing the amount of kilometers intended to be driven in the coming year with the amount driven according to odometer readings gathered in the second survey (2007), we get the following results. On average, RX400h owners drive 937 km less than expected while RX300 owners drive 491 km more than expected, yielding a non-significant difference of 1'427 km between the two groups, $t(181) = -1.245$, $p = 0.215(0.05)$, $n(\text{RX400h}) = 131$, $n(\text{RX300}) = 52$.

¹ Statistical power ($1 - \beta$) of 0.8 was used to conduct these sensitivity analyses with G*Power.

5.7 Comparison of kilometric performance with the previous year

Both sample groups drive less km p.a. than they indicated to have driven with the precursor vehicle: RX300h owners drive 2'354 km less, RX300 owners drive 1'873 km less, on average, with a non-significant mean difference of 481 km, $t(173) = -0.214$, $p = 0.831(0.05)$, $n(\text{RX400h}) = 128$, $n(\text{RX300}) = 47$. These results must be taken with care, since the data on the previous cars' kilometric performances were supplied by estimation. Nevertheless, these results do confirm the RX owners' intention not to drive more with the new car (RX) than with the old car (Altorfer et al., 2006).

5.8 Analysis of payback time for surplus purchasing price of the RX400h

The following formula is used to estimate the amount of years (t) that the RX400h would have to be driven to compensate for the initial surplus in the purchasing price of CHF 6'650 compared to the RX300.

$$f = \frac{x \cdot \nabla n \cdot b^{\text{gas}}}{\nabla b}$$

ΔP (price difference between RX vehicles) = CHF 6'650.

x (average yearly distance driven by RX400h owners in first year of ownership) = 17'120 km p.a.

P_{gas} (average price of gasoline from April 2006 to April 2007) = CHF 1.69 per liter.

Δu (average difference in fuel usage between the two vehicles) = 4.1 l per 100km = 0.041 l per km.

x is derived from survey data, P_{gas} is derived from the Zurich Bureau of Statistics (2008) and Δu is derived from the Lexus RX sales brochures (Lexus, 2005a, 2005b).

Time to payback (assuming constant kilometers traveled annually) results to 5.6 years, assuming constant fuel price and annual kilometric performance and disregarding maintenance costs. The annual fuel cost savings, given identical assumptions, amount to CHF 1'186 per year. The initial premium price of CHF 6'650 paid at purchase of the RX400h therefore can be realistically earned back with fuel savings due to the hybrid technology, assuming fuel prices and annual kilometric performances don't drop significantly. We must consider however, that although a pay-back time of 5.6 years is short enough for a rational consumer, real-world purchasers mostly consider initial vehicle price differences (Diamond, 2009) and the first few years of fuel savings (Greene et al., 2005).

6 Discussion

The principle aim of this study was to investigate the presence of a DRE3 in our sample of Lexus RX400h owners in Switzerland by comparing the average kilometer performances of RX400h owners with owners of the RX300 in statistical tests. The results indicate that neither of the first two null hypotheses can be rejected. Therefore, our main result for this research paper is the following: No statistically significant vehicle kilometer rebound (DRE3) can be found for the RX400h, neither on the level of the RX vehicle alone, nor on the level of all household vehicles. When including considerations of statistical power, our results imply more precisely that no rebound above roughly 25% occurs in the sample of RX400h owners in Switzerland. To test for smaller degrees of rebound our sample size would have to be augmented considerably (for more details see the end of this chapter).

When we take a separate look at the kilometer performances of the RX vehicle in households with multiple vehicles and households that own only the Lexus RX vehicle, we see an indication of differing driving behavior in these two groups. While in multiple vehicle households (anywhere from 2 to 5 vehicles) the RX400h seems to be driven less kilometers compared to the control group (RX300), the RX400h was driven for substantially more kilometers in single-vehicle households. The latter test for households owning only a single vehicle has a small sample size (RX400h: 35; RX300: 15) and produces a non-significant result ($p = 0.314$); still it seems to hint at a rebound somewhere below 50% (due to considerations of statistical power). To investigate this more precisely, the kilometer performances of experimental and control groups would have to be compared separately for the number of people in the household who drive. Due to time constraints this was not done. Further tests were conducted in order to investigate Kurani's 'household shift' observation from secondary vehicles to the hybrid vehicle in the household. The direct comparison of the results of all three tests (RX vehicle, all household vehicles and secondary vehicles) required a smaller sample size which remained constant for all three tests with $n(\text{RX400h}) = 99$ and $n(\text{RX300}) = 36$. The results do not substantiate Kurani's observation of a 'household shift'. We see that the RX400h accounts for the bulk of the difference in kilometer performances (-776 km) between RX400h and RX300 owners on the household level, while the secondary vehicles accounts for a smaller fraction (-221 km). This means we see no evidence for the Lexus RX400h being used more while the other vehicles in the household are driven less. Instead, the RX400h group drives all cars slightly less, on average, than the control group (in multi-vehicle households).

In section 2.2 two potential drivers were presented that might play a role in generating rebound: low operating costs and the drop in socio-psychological cost of ownership. It was argued that the first driver might not affect customers in this high-income market segment, while the second potential driver would have particular importance for this type of vehicle due to its high fuel consumption and disfavor in society (de Haan et al., 2007). Reviewing these considerations with the results at hand leads to the conclusion that the potential rebound driver of socio-psychological cost of ownership is also not strong enough to create a remarkable rebound effect (though as noted above, the test at hand is not strong enough to determine a rebound below approx. 25%). The investigation of intended vehicle kilometers as given by respondents in the 2006 survey (see section 5.6) suggests that RX400h owners end up driving less than they first intended, while RX300 owners drive slightly more than anticipated. Therefore a psychological driver may truly be in effect that leads owners of the RX400h to drive fewer kilometers. This is further supported by the fact that even the secondary vehicles are driven slightly less in households owning an RX400h. One possible reason for this could be heightened awareness of their fuel-use due to fuel efficiency data provided by the vehicle's multi-function display.

Interestingly, both groups of Lexus owners drove less than they indicated to have driven with the precursor vehicle. Previous theoretical and semi-empirical studies predicted a rebound effect for the transport sector ranging from 5% to 51% (see section 2.2). The results of the present research were not able to substantiate a rebound effect in kilometeric performance for the Lexus RX400h, neither for the hybrid vehicle itself nor when regarding all cars in the respective household fleets. Naturally, the previous theoretical results may not be correct, but also we must be aware of the fact that a generalization based on the results for the Lexus RX400h must be done with caution for a number of reasons.

The market segment investigated in this study earns a very high income which reduces some potential for rebound. We must expect differing behavior from other market segments, especially such with monthly incomes closer to average. The high fuel elasticity of substitution otherwise to be expected in Switzerland due to an excellent and inexpensive (state-subsidized) public transportation network cannot be observed in high-income groups because the price does not matter to them (Saunders, 2000). The cost-saving due to more fuel-efficiency might have a larger effect on lower-income consumer segments that use public transportation more often; they may be enticed to switch more often from public transport to using the car. That said, the result of this study can be taken as representative for the high income market, i.e. for cars in the luxury segments. It would be interesting to conduct similar research with a low-cost hybrid vehicle which would be more representative for the whole market of hybrid vehicles including future models. This would perhaps allow more generalized conclusions about the rebound to be expected with such vehicles.

As described in Binswanger (2001) the price of energy and the energy price trend can also be significant for the rebound to be expected because they influence energy-price elasticities. The period in which the surveys were conducted saw an average fuel cost of CHF 1.69 and overall rising energy prices (Zurich Bureau of Statistics, 2008). Had this research been done at a different time under different circumstances, the results may have varied. The literature on rebound differentiates between a short- and long-term rebound effect (Greening et al., 2000). The time-frame of this study only allows for the investigation of rebound during the first year after purchase. While it is possible that research over a longer period might reveal new results, I consider it improbable that the drivers for a direct rebound effect would change considerably over longer periods of time. The consideration of long-term rebound effects is more appropriate for more complex indirect and macro-level rebound effects.

Using a control group to discern rebound behavior, as was done in this study, is a simple and effective method to measure rebound. It is important that the two groups are as similar to each other as possible and to consider any external effects that might distort the findings. As shown in Altorfer (2006), the sociodemographic differences between the two groups of Lexus purchasers are marginal. The only statistically significant difference between the two groups of Lexus purchasers can be found in the income with RX400h purchasers earning a slightly higher salary, on average. This can easily be explained by the higher cost of the Lexus RX400h, even though according to a simple estimation (section 5.8) the premium in initial cost is indeed saved again over the time of vehicle use. Further, the surveyed Lexus customers did not differ significantly in their answers to the intended purpose of their RX vehicle or the expected amount of kilometers to travel with their car (Altorfer et al., 2006). Therefore we can eliminate the possibility that a substantial amount of RX400h purchasers bought this vehicle specifically to drive more kilometers with it.

To my knowledge this study is the first to empirically investigate the vehicle kilometer rebound effect. Keeping the considerations above in mind, further research would be advantageous to help constrain the results and allow for a generalization for the whole hybrid market, at least in Switzerland. Future research should ideally reach a higher sample size to make possible the detection of smaller amounts of rebound: E.g. according to G*Power estimations, the sample size would have to be around 700 to significantly determine a rebound of as small as 10% (assuming a standard deviation of 8'000 km, mean annual performance of 17'000 km and statistical power of 0.8). A more middle-class hybrid model would be advantageous as the object of investigation for any future survey as it would enable a generalization of its results.

7 Conclusions

Previous research established that the low fuel consumption of hybrid vehicles does not motivate people to switch to larger vehicles or to buy additional vehicles (Altorfer et al., 2006; de Haan, Peters et al., 2006). This study presents evidence that owners of a Lexus RX400h hybrid electric vehicle in Switzerland exhibit no significant vehicle kilometer rebound behavior, thereby adding to the evidence that hybrid electric technology does not lead to any substantial direct rebound effects; at least for 'innovator' and 'early adaptor' consumer groups to which the majority of RX400h owners belong (Altorfer et al., 2006).

Overall, we conclude that no direct rebound effects are to be expected to counteract the fuel saving and CO₂ emissions reduction potential of the hybrid vehicle technology. Therefore hybrid cars indeed are suited to play a role in energy conservation measures aiming at reducing CO₂ emissions from individual road transport, such as state-sponsored cash rewards, sales tax exemption or tax rebates for hybrid vehicles. The double dividend offered by hybrid technology saving both costs and energy and the abatement costs per ton CO₂, which are comparable to other carbon reduction measures in the road transport field makes this technology politically favorable (de Haan et al., 2007). Having ruled out the occurrence of a direct rebound effect, the suitability of a specific state-subsidized incentive for a given situation must be closely examined before implementation, paying particular attention to current gas prices and expected gas price evolution, which can easily crowd out any modest effects from incentives or gasoline taxes (Diamond, 2009).

Further studies with other hybrid vehicles and other market segments would be desirable to help constrain the results and allow for a generalization for the whole hybrid vehicle market. The upcoming 3rd generation Toyota Prius which is to come into the market towards the end of 2009 offers a good opportunity for a subsequent survey with a more middle-class vehicle. We propose conducting a two-part mail-in survey of purchasers of the 3rd generation Prius which is more or less analogous to the survey conducted for the Lexus RX400h. As a control group a similar Toyota car would have to be chosen, as was done in de Haan, Peters et al. (2006) and data collected in the survey would help to check for similar demographics and especially driving behavior.

According to the considerations made in section 2.2 and our current results with the RX400h, a large-scale rebound effect should not be expected for the Prius. Compromising for practicability we suggest trying to achieve a sample size of at least 320 for a survey with the Prius, which would allow for the detection of a rebound of 15% and above (assuming kilometric performance of 17'000km and standard deviation of 8'000km). It must be expected that a substantially higher number of these middle-class Toyota vehicles will be sold compared to the high-end Lexus RX vehicles, which would enable a future survey to reach the sample size proposed.

7. Conclusions

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Appendix

The original questionnaires sent out to German and French speaking owners of the RX400h during the follow-up survey in July 2007 are displayed on the following six pages.

[Herr/Frau]
[Vorname] [Name]
[Adresse]
[PLZ Ort]

[Datum]

Umfrage zum Lexus RX 400h

[Anrede] [Herr/Frau] [Name]

Sie haben letztes Jahr einen Lexus RX erworben. Die ETH Zürich hat im Juni 2006 eine wissenschaftliche Befragung unter Lexus RX-Käufern durchgeführt. Sie haben den Fragebogen ausgefüllt und der ETH die Erlaubnis zu einer Nachbefragung gegeben.

Die ETH Zürich verspricht sich von Ihren Angaben neue Erkenntnisse darüber, wie innovative und neuartige Fahrzeuge konzipiert werden sollen, damit sie von einem breiteren Publikum gekauft werden.

Lexus hat sich zur Mithilfe bereit erklärt und versendet deshalb diesen Fragebogen. Ihr Name und Ihre Adresse werden der ETH Zürich nicht bekanntgegeben. Ihre Antworten bleiben damit anonym.

Wir bitten Sie höflich, den beiliegenden Fragebogen auszufüllen und mit dem beigelegten Antwort-Couvert an die ETH Zürich zu senden.

Herzlichen Dank für Ihre Mithilfe!

Mit freundlichen Grüßen

Lexus Schweiz

ETH Zürich, IED-NSSI



Christian Wellauer
Director of Marketing Communication



Prof. Dr. R. W. Scholz



Dr. P. de Haan



Eidgenössische Technische Hochschule Zürich
Ecole polytechnique fédérale de Zurich
Politecnico federale di Zurigo

Institute for Environmental Decisions (IED)
Natural and Social Science Interface (NSSI)
Universitätstrasse 22, CHN J73.2, 8092 Zürich

1

Nachbefragung zum Lexus RX

Liebe Teilnehmerin, lieber Teilnehmer an unserer Untersuchung

Herzlichen Dank, dass Ihr Haushalt letztes Jahr an unserer Lexus-Befragung teilgenommen und sich bereit erklärt hat, an einer Vertiefung der Befragung teilzunehmen!

Bitte senden Sie uns Ihre Antworten wenn möglich bis zum **16. Juli** zurück mit beiliegendem Antwortkuvert.

Herzlichen Dank für Ihre Mithilfe bei unserer Forschung!

Ihre ETH Zürich, Dr. Peter de Haan van der Weg & Katrin Häni

Informationen zum Datenschutz

Ihre Daten werden absolut vertraulich behandelt und nur für die wissenschaftliche, nicht-kommerzielle Forschung und Lehre verwendet. Die ETH garantiert Ihnen den vollumfänglichen Schutz Ihrer persönlichen Daten.

Die von der ETH erstellten Auswertungen und Statistiken erlauben keine Rückschlüsse auf Einzelpersonen.

Die **Nummer in der rechten oberen Ecke dieses Fragebogens** benötigen wir ausschliesslich, um die Daten mit denen der ersten Befragung vom Sommer 2006 zu verknüpfen. Ihre Antworten werden nicht mit Ihrem Namen und Ihrer Adresse in Verbindung gebracht.

bitte wenden

Änderungen beim Autobesitz Ihres Haushaltes

1. Im Juni 2006 haben Sie uns auf die Frage nach allen Autos Ihres Haushaltes folgende Fahrzeuge genannt.
 → Bitte geben Sie uns für jedes Fahrzeug an, ob es noch im Haushalt vorhanden ist oder nicht.
 → Bitte geben Sie ausserdem den *heutigen Stand des Kilometerzählers* dieser Fahrzeuge an
 (falls das Fahrzeug nicht mehr vorhanden ist, so geben Sie bitte den *letzten Km-Stand* an).

	Marke und Modell, Baujahr [RX: bestellt oder geliefert]	Km-Stand Juni 2006	Noch im Besitz des Haushalts?	Km-Stand heute*
Auto-Nr. 1	Lexus RX400h, ausgeliefert Apr. 2006	400	[] ja [] nein	_____
Auto-Nr. 2	Mercedes-Benz A-Klasse, Baujahr 2001	47'500	[] ja [] nein	_____

* falls das Fahrzeug verkauft/weitergegeben/verschrottet wurde, bitte den letzten Km-Stand angeben.

2. Sind in Ihrem Haushalt seither (seit Juni 2006) **weitere Autos** dazugekommen? nein ja, und zwar:
 (Alle Personen, die in derselben Wohnung leben, bilden einen gemeinsamen Haushalt.).

Auto A, das seit Juni 2006 dazugekommen ist:

Marke	Modell	Motogrösse (in Liter)	Treibstoff	Schaltung	Baujahr/ Jahrgang	Wann gekauft? Monat/Jahr
			<input type="checkbox"/> Benzin	<input type="checkbox"/> handgeschaltet		
			<input type="checkbox"/> Diesel	<input type="checkbox"/> automatik		
			<input type="checkbox"/> anderer	<input type="checkbox"/> variomat/tiptronic		
a)	_____	_____			_____	_____ / _____
b)	Km-Stand bei Kauf/Übernahme: _____		Km-Stand heute: _____			
c)	Hat dieses Auto ein Vorgängerauto ersetzt?		<input type="checkbox"/> nein <input type="checkbox"/> ja, und zwar aus obiger Liste Auto-Nr. _____			

Auto B, das seit Juni 2006 dazugekommen ist:

Marke	Modell	Motogrösse (in Liter)	Treibstoff	Schaltung	Baujahr/ Jahrgang	Wann gekauft? Monat/Jahr
			<input type="checkbox"/> Benzin	<input type="checkbox"/> handgeschaltet		
			<input type="checkbox"/> Diesel	<input type="checkbox"/> automatik		
			<input type="checkbox"/> anderer	<input type="checkbox"/> variomat/tiptronic		
a)	_____	_____			_____	_____ / _____
b)	Km-Stand bei Kauf/Übernahme: _____		Km-Stand heute: _____			
c)	Hat dieses Auto ein Vorgängerauto ersetzt?		<input type="checkbox"/> nein <input type="checkbox"/> ja, und zwar aus obiger Liste Auto-Nr. _____			

Anmerkungen: _____

Herzlichen Dank für das Ausfüllen des Fragebogens!

[Monsieur/Madame]
 [Vorname] [Name]
 [Adresse]
 [PLZ Ort]

[date]

Sondage concernant la Lexus RX 400h

[Anrede] [Monsieur/Madame] [Name]

L'année dernière, vous avez acquis une Lexus RX. En juin 2006, l'Ecole Polytechnique Fédérale (ETH) de Zurich a effectué un sondage scientifique parmi des acheteurs d'une Lexus RX. Vous avez rempli ce questionnaire et vous avez consenti de recevoir l'enquête suivante.

L'Ecole polytechnique fédérale de Zurich espère que vos indications lui permettront de tirer des conclusions en ce qui concerne la façon de concevoir de nouveaux véhicules innovants, pour qu'ils soient achetés par un large public.

Disposée à collaborer, Lexus vous envoie ce questionnaire. Vos nom et adresse ne seront pas communiqués à l'ETH de Zurich, vos réponses demeureront donc anonymes.

Nous vous prions de bien vouloir remplir le questionnaire ci-inclus et de le retourner à l'ETH de Zurich au moyen de l'enveloppe-réponse ci-jointe.

Merci de votre coopération!

Avec nos salutations les meilleures

Lexus Schweiz

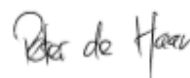
ETH Zurich, IED-NSSI



Christian Wellauer
 Director of Marketing Communication



Prof. Dr. R. W. Scholz



Dr. P. de Haan

ETH	«CODE»
Eidgenössische Technische Hochschule Zürich Ecole polytechnique fédérale de Zurich Politecnico federale di Zurigo	Institute for Environmental Decisions (IED) Natural and Social Science Interface (NSSI) Universitätstrasse 22, CHN J73-2, 8092 Zürich
Deuxième sondage concernant la Lexus RX	
Chère participante, cher participant de notre sondage,	
Nous remercions cordialement votre ménage d'avoir participé au sondage „Lexus RX ” de juin 2006, et d'avoir accepté de participer également à ce deuxième sondage.	
Veuillez s.v.p. nous retourner vos réponses d'ici si possible jusqu'au 16 juillet au moyen de l'enveloppe-réponse ci-incluse.	
Nous vous remercions cordialement de votre participation à notre recherche!	
<i>Votre EPF Zurich, Dr. Peter de Haan van der Weg & Katrin Häni</i>	
Informations concernant la protection des données	
Vos données feront l'objet d'un traitement strictement confidentiel et elles ne seront utilisées que pour la recherche et l'enseignement scientifiques et non commerciaux. L'EPF vous garantit une protection totale de vos données personnelles.	
Les statistiques et analyses de l'EPF Zurich ne permettent pas de tirer de conclusions concernant des individus.	
Le numéro figurant dans le coin droit en haut du questionnaire a uniquement pour but de nous permettre d'établir un lien avec les données du premier sondage de l'été 2006. Vos réponses <u>ne seront pas</u> reliées à votre nom et à votre adresse.	
tourner la page s.v.p.	

Changements au niveau de la possession des voitures par votre ménage

1. L'année passée, vous avez cité comme faisant partie de votre ménage les véhicules suivants.
 → Veuillez s.v.p. nous indiquer si chacun de ces véhicules existe encore dans votre ménage ou non.
 → Veuillez s.v.p. aussi indiquer *les kilomètres actuellement au compteur* de ces véhicules.
 (si le véhicule n'est plus en possession par votre ménage, veuillez indiquer les kilomètres au compteur à la fin).

	Marque et modèle, année de construction [RX: commandée ou livrée]	Kilomètres au compteur juin 2006	Encore en possession du ménage?	Kilomètres actuels au compteur*
voiture no. 1	Lexus RX400h, livrée janv. 2006	10'000	[] oui [] non	_____
voiture no. 2	Mercedes-Benz C-Klasse, construit 1998	200'000	[] oui [] non	_____
voiture no. 3	Renault Trafic, construit 2006	12'000	[] oui [] non	_____

* si le véhicule a été vendu/transmis/cassé, veuillez indiquer les kilomètres au compteur à la fin.

2. Des **autres voitures** sont-elles venues s'y ajouter (depuis juin 2006)? non oui, à savoir:
 (Toutes les personnes habitant dans la même unité d'habitation forment un ménage commun.).

Voiture A qui est venue s'ajouter depuis juin 2006:

Marque	Modèle	Taille moteur (en litres)	Carbu- rant	Boîte à vitesses	Année de construction	Date d'achat: Mois/année
a) _____	_____	_____	<input type="checkbox"/> essence <input type="checkbox"/> diesel <input type="checkbox"/> autre	<input type="checkbox"/> levier manuel <input type="checkbox"/> automatique <input type="checkbox"/> variomat/tiptronic	_____	_____/_____
b) Kilomètres au compteur au début: _____		Kilomètres actuellement au compteur: _____				
c) Ce véhicule a-t-il remplacé un véhicule précédent?		<input type="checkbox"/> non <input type="checkbox"/> oui, voiture no. _____ de la liste ci-dessus.				

Voiture B qui est venue s'ajouter depuis juin 2006:

Marque	Modèle	Taille moteur (en litres)	Carbu- rant	Boîte à vitesses	Année de construction	Date d'achat: Mois/année
a) _____	_____	_____	<input type="checkbox"/> essence <input type="checkbox"/> diesel <input type="checkbox"/> autre	<input type="checkbox"/> levier manuel <input type="checkbox"/> automatique <input type="checkbox"/> variomat/tiptronic	_____	_____/_____
b) Kilomètres au compteur au début: _____		Kilomètres actuellement au compteur: _____				
c) Ce véhicule a-t-il remplacé un véhicule précédent?		<input type="checkbox"/> non <input type="checkbox"/> oui, voiture no. _____ de la liste ci-dessus.				

Si vous avez des remarques à faire, veuillez s.v.p. les noter ci-dessous:

.....

.....

.....

Merci d'avoir rempli ce questionnaire!

ETH Zurich
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