Evaluation of the energy consumption in different mobility scenarios to meet the goal of a 2000-watt society

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Abstract

Greenhouse gas emissions related to energy production is the main cause of climate change. Transportation accounts for 30% of the total energy consumption, and a reduction in the energy used for mobility is necessary. The 2000-watt society is an environmental concept that fixes a sustainable limit to the energy consumption in different sectors, including mobility. This paper evaluates the energy consumption in several mobility scenarios, and it assesses whether the goal suggested by the 2000-watt society is achievable. We investigate the social characteristics and mobility habits of the population living in a case study area. Then, we calculate the modal shift induced by transportation policies such as car-sharing, car-pooling and car-free district. We evaluate the resulting energy consumption, and we compare it with the 2000-watt society limit. We conclude that only a set of measures combining car usage reduction, increase in walking and cycling, and reduction in the total travel distance can achieve the needed energy reduction.

1 Introduction

Climate change is a great risk for the environment, society and economy (Solomon, 2007). The primary cause of climate change is the emission of greenhouse gases (GHG) by combustion of fossil fuel related to energy production for human activities (Pachauri *et al.*, 2014). The transportation sector is responsible for 30% of the total energy consumption and 20% of total GHG emission in the European Union (EC, 2013). Transport policies have direct effects on energy consumption and GHG emission (Poudenx, 2008), and they can lead to a modal shift up to 5% toward more energy efficient modes of transport such as public transport, walking and cycling (Ogilvie *et al.*, 2004). Several public institutions have planned reduction in terms of energy consumption and GHG emission for 2050 (EC, 2011).

A possible goal for energy consumption reduction is given by the concept of 2000-Watt society (2000W-society) (Notter *et al.*, 2013). Two thousand watts (W) is the continuous energy usage calculated as primary energy for transportation, personal activities, nutrition, household, infrastructure and other common consumption of the society divided by the population. Two thousand watts is the average energy usage of the entire world, and it is considered an environmentally sustainable consumption (Bretschger *et al.*, 2013). Citizens of industrialized nations consume between 5,000 and 12,000 watts, while, in developing countries, only a fraction is used. The 2000W-society aims to balance this difference without reducing the standard of living in industrialized nations. The energy consumption of some nations is visualized in Figure 1(a), while, Figure 1(b) shows the breakdown of the total energy consumption in Switzerland.

In this paper, we investigate the energy consumption related to mobility and discuss whether it is possible to reach the objective set by the 2000W-society. We analyze the current mobility patterns and energy consumption of the population living in a case study area. We evaluate if existing transport policies, such as car-sharing, car-pooling and car-free district, could induce a modal shift capable

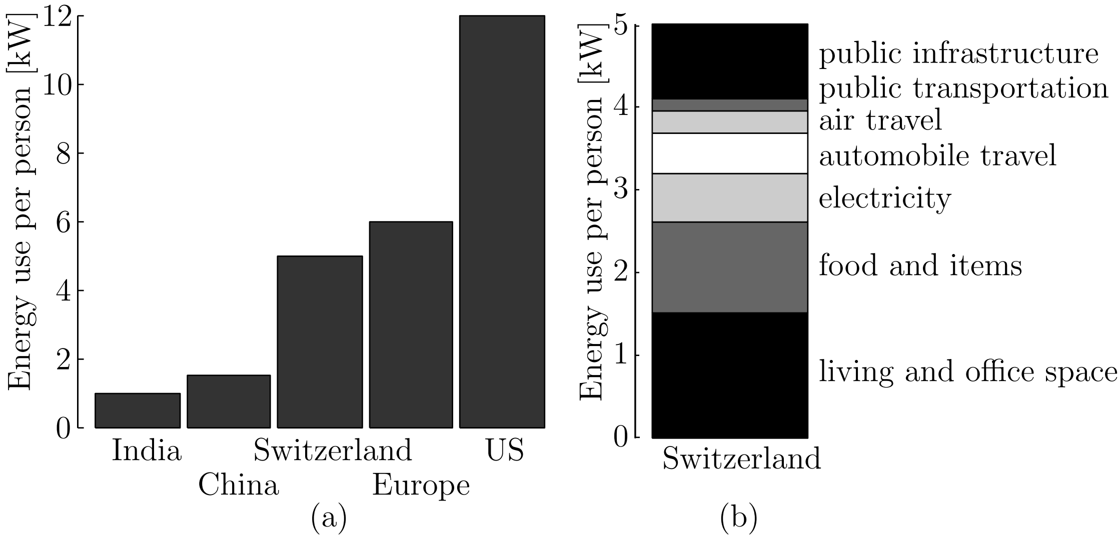


Figure 1: (a) energy consumption in different nations, and (b) detail of energy consumption in Switzerland . Adapted from Notter *et al.* (2013) and Stulz (2011).

of meeting the energy objective.

We use an area in the city of Fribourg, Switzerland, as the case study. This city has been chosen because it is the test case for the Swiss participation to the Solar Decathlon (SD) competition (DoE, 2016). The SD competition aims to design a solar-powered building that incites a sustainable use of energy and resources. Among the different aspects, transportation and mobility are considered.

The Swiss SD team proposes the idea of a network of solar-powered buildings, referred to as pavilions (EPFL, 2016). These pavilions are catalyst for improving sustainable live styles, including sustainable mobility, of the population living in their proximity. They are multifunctional buildings providing several services and information. We define the study area as the surrounding of the main pavilion, and we refer to this area as the SD district.

We use the following methodology to evaluate whether the adoption of transport policies to the case study area could reduce the energy consumption for mobility and meet the goal of the 2000W-society. First, we define the boundary of the SD district, we analyze the inhabitants and their mobility patterns using data from the Swiss Federal Statistical Office (FSO, 2016). Secondly, we quantify the objective of the 2000W-society for mobility, and we compare them to the current energy use. We calculate the possible modal shift when the transport policies are applied in different scenarios. The impact on the mobility is estimated using data of ex-post evaluations of these policies in other cases. Finally, we discuss if the energy consumption goal is reached and what measures should be adopted.

We make a series of assumptions to investigate this aspect.

(a) We do not consider technological advance that could improve the efficiency of transportation systems in the future. Therefore, the reduction in energy consumption is achievable only by modifying the modal share or reducing the mobility.

(b) We ignore the way in which the energy is produced and the resulting GHG emission. For example, in the present work, we do not evaluate the different impact and sustainability of electricity produced by fossil fuel or using solar photovoltaic cells.

(c) We evaluate the best possible scenarios for each transport policy. The modal shift induced by transportation policies is influenced by many aspects. However, we simply apply the reduction factors found in the literature to the SD district. This allow us to evaluate a sort of best case scenario. We are indeed interested to know whether it is possible to reach the objective of the 2000W-society in the best possible case.

(d) The mobility of the inhabitants of the SD district is based on the available information. We do not perform any data collection campaign. If statistics are present only for a larger area, we assume that these statistics are representative of the SD district.

Several researchers have investigated the topic of energy consumption linked to mobility, the effects of transport policies, and the possible impacts that they can have on travel behavior and greenhouse gas emissions (see Section 2). Differently from the previous research in the literature, this paper directly compares the effects of transport policies to the goal set by the 2000W-society. This is done evaluating the impacts of these policies in a specific case study, i.e. the SD district. The main contribution of the present work is to show if the reduction in energy consumption induced by transport policies is enough to achieve the sustainable level indicated by the 2000W-society.

The remaining of the paper is structured as follows. A review of transport policies and their impacts on the energy consumption is reported in Section 2. Section 3 identifies the boundary of the case study, and presents the characteristics of the population and the current mobility patterns. In Section 4, we calculate the energy consumption objective of the 2000W-society, we evaluate different mobility scenarios, and we quantify the induced mobility changes inside the SD district. We compare the resulting energy consumption with the 2000W-society goal to understand whether this objective is achievable. The paper finishes with the main conclusions in Section 5.

2 Review of transport policies

The impact of transport on the energy consumption and greenhouse gases emission is considerable (EC, 2013), and numerous transport policies have been implemented to reduce it. In this section, we report examples of studies evaluating the effects of implemented policies for road transport.

Two main methodologies to assess energy reduction can be identified. The first is based on modeling, and it provides quantitative results on the possible reductions induced by each intervention in simulated scenarios (Schade and Schade, 2005). The second is based on the evaluation of the transport policies with a before-after implementation comparison, also known as *ex-post* evaluation. This methodology gives empirical indications, however, it is extremely difficult to separate the effects of the transport policy under evaluation from general trends such as economic situations, technological improvements, urbanistic transformations, complementary policies and other macroscopic changes in the study area (Gudmundsson *et al.*, 2005).

Several studies and research projects evaluate the effects of transport policies. Fujii *et al.* (2001) classify the policies into *structural*, i.e. interventions that modify the physical or legislative transport supply (e.g. road closures, bus priority lanes, road pricing (Saleh, 2007; Green and Stone, 2004)), and *psychological*, i.e. interventions aimed to change the attitudes toward transportation systems and to induce voluntary changes (e.g. information campaigns, environmental awareness, travel advice, car-sharing, car-pooling, teleworking and teleshopping, eco-driving (Fujii and Taniguchi, 2005; Gross *et al.*, 2009)). Santos *et al.* (2010) classify the policies into three categories: *physical*, *soft* and *knowledge* policies. While the first two categories are similar to the ones identified by Fujii *et al.* (2001), the third category emphasizes the importance of research and development for sustainable mobility. Cairns *et al.* (2008) analyze several studies and estimate a possible reduction in CO_2 between 4% and 11% by applying soft measures only. Möser and Bamberg (2008) conduct a meta-analysis on more than 100 studies evaluating soft policy implementations. They point out that often the studies are not conducted in a rigorous manner, and the findings are based on limited statistical analyses. The project Thematic Network Benchmarking European Sustainable Transport (BEST, 2001) evaluates the impacts of transport policies, such as transport infrastructures capacity utilization, time delays, price/performance relationships, metropolitan transport planning, quality of planning processes, cycling policies, integrated transport policies, transport road safety, and carbon dioxide reduction strategies. The project investigates the effectiveness of these policies implemented in several programs by different institutions, such as the Dutch Ministry of Transport, Federal Department of Transportation (USA), NATCYP National Cycling Policy Benchmarking Program, CfITUK Commission for Integrated Transport (UK), BOB Road Benchmarking of Benchmarking, ECN Study by the Energy Research Centre Netherlands (BEST, 2001). Another review paper by Graham-Rowe *et al.* (2011) evaluates the impact of several car-use reduction interventions. The authors review 77 studies, founding contrasting methodologies and indexes of performance among the evaluations.

Policies related to information and increase in awareness indicate promising results. Cairns *et al.* (2004) and Parker *et al.* (2007) indicate that information policies, such as personalized travel planning, can lead to a reduction of the travel distance by car between 2 km and 3 km per day per person. Also Garvill *et al.* (2003) show that increasing awareness can have positive effects, in particular on individuals with strong driving habits. Examples of another information action known as eco-driving, i.e. campaigns aimed to increase the driving efficiency, also show reductions close to 10% in CO_2 emission (Santos *et al.*, 2010). Contrary to the previous research, Eriksson *et al.* (2008) found no clear evidence of the effectiveness of these measures.

An increase in use of public transport can reduce environmental impacts (Whiteing and Stantchev, 2008; Santos *et al.*, 2010). It is estimated that the use of private vehicles roughly consumes three to five times more energy than the use of public transport (BVI, 2002). Therefore, a strong reduction in emission can be achieved incentivizing the modal shift from private to public transport (Aßmann and Sieber, 2005). Bamberg (2006) shows that a test group of individuals provided with public transport use information and incentives decreases the travel distance by car by 12% in comparison with a control group. However, other similar interventions show no significant improvement (Fujii and Kitamura, 2003).

Another common measure to increase the efficiency of car usage is car-sharing. Cervero *et al.* (2002) evaluate the impact of car-sharing in San Francisco. They find that the average daily travel distance by car decreases by 10% more in a test group in comparison with a control group. Shaheen *et al.* (2006) report that car-sharing reduces the car travel distance between 28% and 45% due to the change in mobility habits and the modal switch to public transport. Ledbury (2007) estimates that if car-sharing would reach 15% penetration rate in UK, this could lead to a reduction of 6.4% of the global transport emission. However, Gross *et al.* (2009) report that the level of the environmental impact reduction related to the introduction of car-sharing and car-pooling has not been measured with enough precision in the literature.

Given the low occupation rate of 1.6 persons per vehicle in average in Europe (Hu and Reuscher, 2004), increasing the number of passengers in each car with car-pooling can contribute to reducing car travel distance and energy consumption. Jacobson and King (2009) suggest that adding a passenger every ten vehicles could lead to a reduction of 5.4% in fuel consumption. Common practices to incite car-pooling are limiting parking possibilities, increasing road tolls and introducing high occupancy vehicle (HOV) lanes on motorways. However, the impacts of these measures, especially HOV lanes, is still debated (Menendez and Daganzo, 2007).

Often, individual policies are not effective, and an integration among interventions is needed. Schade and Schade (2005) show that with a combination of policies, including increase of fuel tax, increase of road pricing, improvements in emission regulation, expansion of railway infrastructure and land-use measures, could be possible to obtain a CO_2 emission reduction of 72% in 30 years in Germany. Santos *et al.* (2010) report evidence that a combination of transport policies with taxes and permits control together with an integration with urbanistic transformations can lead to a sustainable transport system. When several policies designed to reduce car usage are integrated in a specific district of a city, this area is often referred to as a car-free district. Lange (2003), Nobis (2003) and Coates (2013) describe the car-free districts of Vauban in the city of Freiburg, Germany. Another example is analyzed by Ornetzeder *et al.* (2008) in the district of Floridsdorf, Vienna, Austria.

Among other measures, we mention that financial disincentives can lead to a decrease of travel distance between 3% and 7% (Jakobsson *et al.*, 2002), and, improvement in inspection and maintenance policies can reduce GHG emission by 3% to 7% (Aßmann and Sieber, 2005).

Transport policies in countries with a strong economic growth have different effects than in industrialized countries. For example, China has implemented policies to limit the increment of GHG emission promoting gas vehicles and fuel economy standard in 19 regions and cities (Wang *et al.*, 2007). The implementation of these policies could bring to a reduction of energy consumption up to 50% in comparison with the uncontrolled scenario (Yan and Crookes, 2009). Aßmann and Sieber (2005) show that the use of rapid bus services can have strong impacts in developing countries. Furthermore, the authors identify two- and three-wheelers as a major problem in many Asian towns, especially for emission related to two-stroke engines. Santos *et al.* (2010) suggest that the key to provide sustainable transport systems in developing countries is the integration of transport and land-use policies.

In addition to transport policies, technological improvements can lead to strong reductions in environmental impacts. Aßmann and Sieber (2005) report that a decline of 16% in GHG can be observed in Europe from 1980s thanks to technical improvements in the vehicle engine efficiency, and a larger share of diesel engines in the vehicle fleet. Further improvements can be accomplished with the introduction of hybrid vehicles, which, combining petrol and electric engines, have an higher energy efficiency (Fontaras *et al.*, 2008). Graham-Rowe *et al.* (2011) suggest that thanks to technological developments, it may be possible to achieve 80% reduction in CO_2 in the future. However, studies indicate that these developments may be too slow to prevent critical environmental impacts (Shell, 2008). For this reason, transport policies that induce changes in travel behavior play a crucial role (Cambridge Systematics Inc, 2009).

From this review, we can conclude that transport policies can affect the energy consumption related to mobility, however the impacts of various measures are not easy to quantify (Yan and Crookes, 2009). It is not straightforward to measure and compare transport policies in order to establish clear references, and the policies are not directly comparable across different contexts (Gudmundsson *et al.*, 2005). As mentioned by Graham-Rowe *et al.* (2011) "the lack of a standardized approach to measuring car-use reduction makes it difficult to compare effectiveness across interventions", and, as a consequence, this limits the possibility to estimate the impacts of the introduction of specific policies (Niemeier, 2010). These difficulties arise mainly due to a lack of robust data (DfT, 2009). Given the high uncertainty in the induced effects and the aim of this paper to evaluate an upper bound on energy reduction, we assume that the transport policies applied in our case study, i.e. the SD district, have the maximum possible positive impacts. Among the different policy evaluations, we use the results of successful examples applied in case studies geographically close to the city of Fribourg. We decide not to use results from simulation studies, but only from empirical ex-post evaluations.

3 Solar Decathlon district

In the following, we specify the study area, the population characteristics and their mobility habits.

Study area

The study area is defined as the area of influence of the main pavilion within the city of Fribourg. The pavilion is situated in the residential area of Beaumont, on a parking slot, see Figure 2. The neighborhood is a dense housing area characterized by high residential towers, 12-14 stories. The distance of the pavilion to the main train station is around 1 km, and 2 km to the city center.

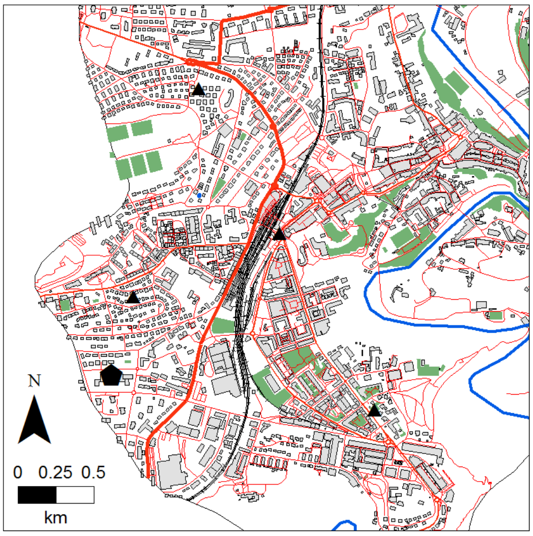
As mentioned, the concept developed by the Swiss SD team includes the idea of a network of interconnected pavilions. The location of the secondary pavilions is not decided yet. However, to define the area of influence of the main pavilion, we assume the location of the secondary pavilions following simple criteria. The pavilions are placed in crucial locations of the city, e.g. in the center of housing areas and transportation hubs. It should be possible to cover the distance between two pavilions by walking or cycling. Therefore, the inter-pavilion distance should not be more than 1 km. Following these criteria, the resulting locations of the secondary pavilions surrounding the main pavilion are presented in Figure 2.

Based on the location of the pavilions, we can define the area of influence by proximity. The area of influence is defined as the area closest, in distance, to each pavilion, as visible in Figure 2(b). We can consider that distance is directly proportional to travel time, because we assume that the inhabitants reach the pavilion by walking or cycling, which is rarely influenced by congestion. Figure 2(c) and Figure 2(d) show the resulting boundary of the SD district. We define it following the lines of equi-distance between pavilions and physical boundaries such as existing roads and the municipality border. The west boundary follows the municipality border, which is also a natural border due to the high difference in height at this location. The north boundary also follows the difference in height and an existing road. The east boundary follows a cantonal road. Beyond this road, it is present the industrial area of "Les Daillettes et Cardinal" without residential buildings, therefore, it is not considered in the SD district.

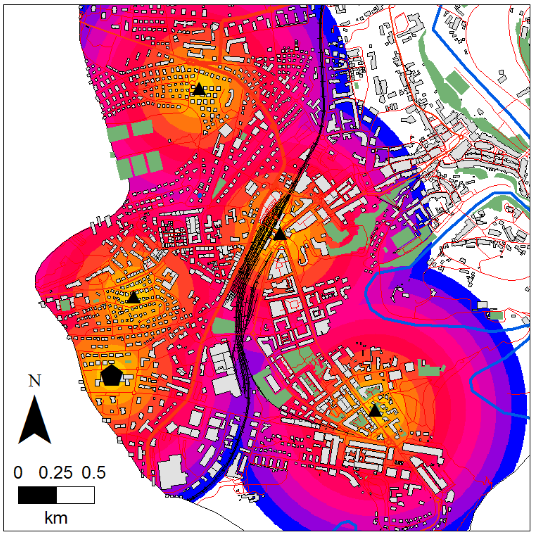
Population

Based on the defined SD district and demographic data (FSO, 2015), it is possible to investigate the characteristics of the population in the case study area.

The estimated population living in the SD district is 4,000 inhabitants, and the age distribution in comparison with the entire municipality is shown in Figure 3. The SD district presents a younger population than the city of Fribourg. There are less inhabitants with an age between 5 and 20 years, more between 20 and 40 years, and again less between 40 and 60 years. The mean age in the district is 38.9 years, lower than the canton of Fribourg (39.6 years) and Switzerland (41.9 years) (FSO, 2015).



(a)



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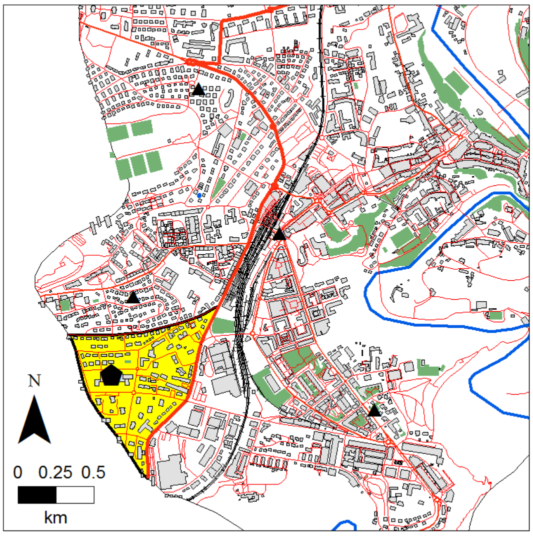

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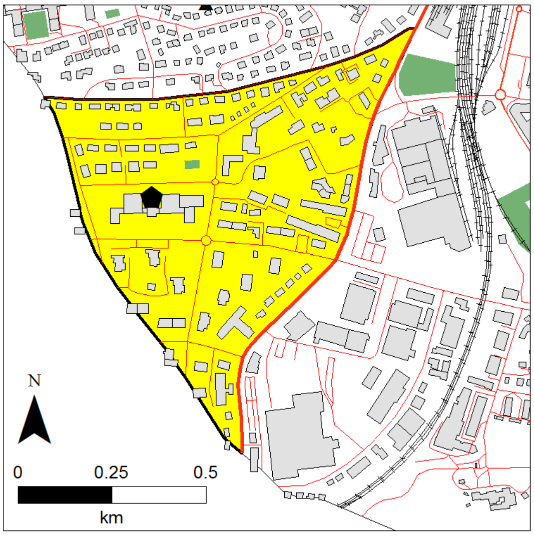

(d)

Figure 2: Case study area with the main and secondary pavilions identified by a pentagon and triangles respectively. (a) Section of the city of Fribourg in proximity of the main pavilion. (b) Area of influence of each pavilion identified by the distance map. (c) and (d) SD district boundary.

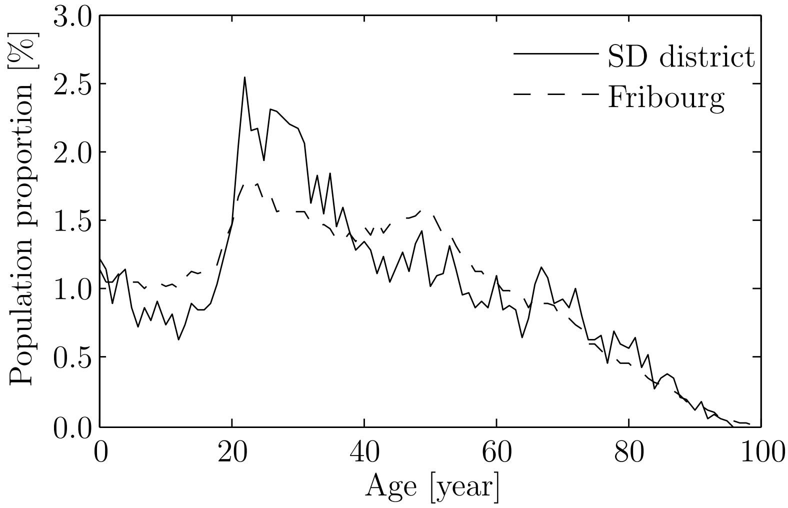

Figure 3: Population age distribution in the SD district and the city of Fribourg.

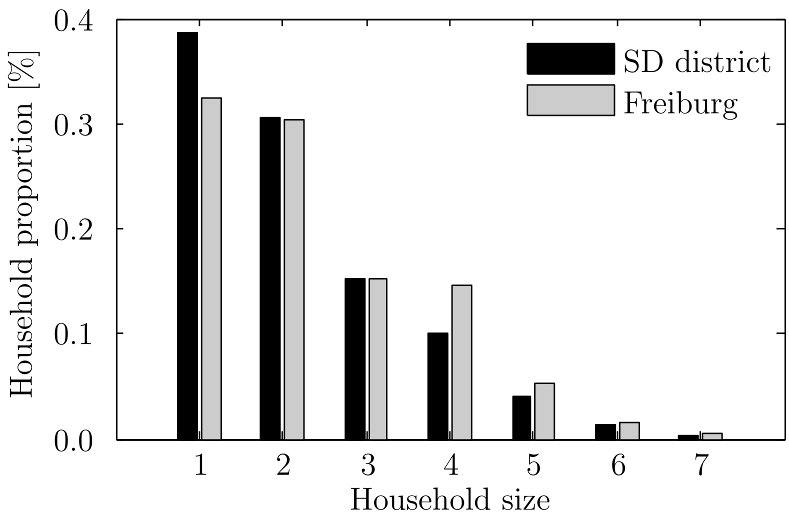

Figure 4: Household size in the SD district and the city of Fribourg.

Figure 4 shows the household configuration in the SD district and in Fribourg. In the SD district, more single people household are present in comparison with Fribourg, while there are more four people to seven people households in the rest of the municipality.

The distribution of education levels across the inhabitants relative to the age is presented in Figure 5. It is visible that the bulk of the population between 25 and 44 years old has a university degree, while the rest of the active population in the 45-64 age group is uniformly distributed among the education levels.

The data indicate that the population living in the SD district has a large component of young adults mostly living in households of one to three people. In other terms, single persons, couples and young families with a child. The education level distribution indicates that there is a large share of inhabitants with a university degree. These considerations are also supported by the presence of the University of Fribourg. The population of Fribourg is approximately of

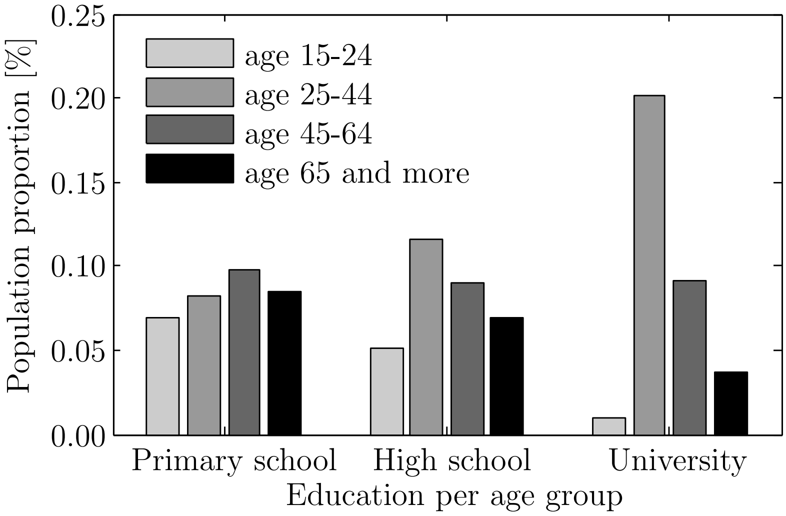

Figure 5: Education levels relative to age groups.

37'000 (FSO, 2015), and the university has 10'000 students. Even though not all students live in Fribourg, it is possible to assume that a large share of the population of Fribourg is composed by university students.

These considerations are useful to identify the types of actions aimed to promote sustainable mobility, and the types of services that the SD pavilion should offer to the population.

Mobility

The mobility of the population living inside the SD district is described based on the mobility data extracted from the "Microcensus on mobility and transport 2010" (FSO, 2010), a detailed large-scale survey of the mobility habits of the Swiss population directed by the Swiss Federal Statistical Office (FSO, 2016).

The travel distance for each mode of transport and trip purpose are reported in Table 1 and visualized in Figure 6. The predominance of the private transportation for most of the purposes is immediately visible, with a share of 68%. The leisure trips by car present the highest travel distance, being almost twice the travel distance by car for work. Public transport (PT) has a share of 25%, and "slow modes" (walking and cycling) have a share of 7%, mostly covered by walking. Moreover, the Microcensus data also give information on the proportion of the distance traveled inside the city of Fribourg for each mode of transport and trip purpose. The data report that more than 60% of the distances are done inside the city, and slow modes are almost never used for trips outside the city.

The occupation rate, defined by o, is the average amount of people per car for a trip. This information allows us to differentiate between the distance traveled by a person, defined by d_p, and the "effective" distance traveled by a car, denoted by d_c. We define d_c as follows:

$$d_c = \frac{d_p}{o}, \tag{1}$$

Table 1: Average travel distance for each mode of transport and trip purpose [km]

	Car	PT	Walking	Cycling
Work	5.75	2.43	0.25	0.18
Education	0.44	1.14	0.46	0.04
Shopping	3.01	1.00	0.25	0.02
Leisure	10.50	3.04	1.06	0.28
Others	4.80	1.40	0.00	0.00
Total	24.50	9.00	2.00	0.40
Share [%]	68	25	6	1

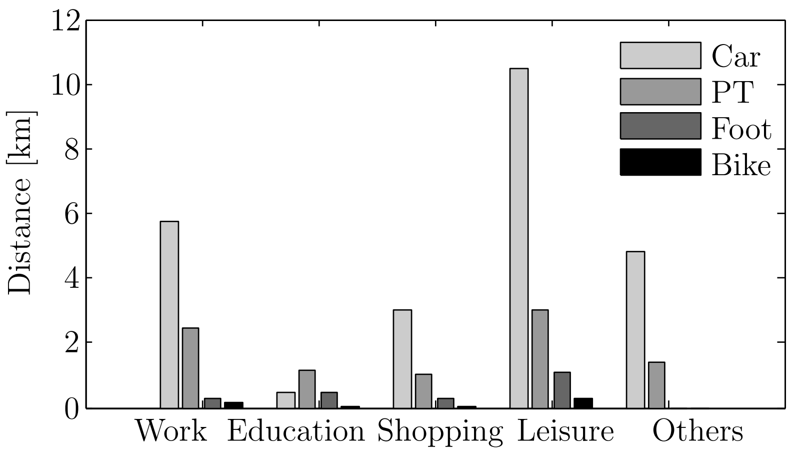

Figure 6: Average travel distance per mode of transport and trip purpose.

Table 2: Person-distance d_p [km], occupation rate o [passengers/car] and effective car-distance d_c [km] for car trip

	d_p	o	d_c
Work	5.7	1.08	5.3
Education	0.4	1.10	0.4
Shopping	3.0	1.79	1.7
Leisure	10.5	1.79	5.9
Others	4.8	1.92	2.5
Total	24.5	1.55	15.8

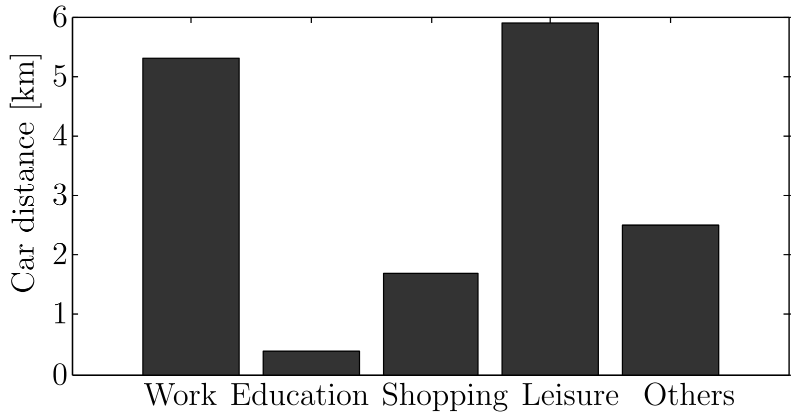

Figure 7: Effective travel distance by car per trip purposes.

where we assume a constant occupation rate for the entire trip of the car. The occupation rate for car trips for the different trip purposes and the corresponding effective car-distance are reported in Table 2 and visualized in Figure 7. The effective car-distance traveled is similarly distributed between work and leisure purposes, in comparison with the person-distance reported in Figure 6 that presents leisure as the main component. This is due to the higher occupation rate of leisure trips in comparison with work related journeys. Focusing on the energy consumption, this implies that if a car has a higher occupation rate, it has less energy consumption per person with the same person-distance traveled.

Similarly to the population analysis, these considerations are useful to identify the mobility patterns that should be reduced. As visible from the data, the services offered by the SD district should principally focus on the trips related to work and leisure activities within the city boundary.

4 Mobility scenarios

In this section, we evaluate the effect on energy consumption of different hypothetical mobility scenarios, and we compare the results with the 2000W-society energy objective.

The energy objective related to mobility of the 2000W-society is defined based on the research of Notter *et al.* (2013). The authors study a sample of the Swiss population that already lives around the threshold of 2000 W, and they determine the amount of energy consumed by the different transportation modes. Following this study, the objectives for the 2000W-society are reported in Table 3. We

Table 3: Current energy consumption and 2000W-society objective

	Current situation [W]	2000W-society objective [W]
Car	1375	235
Public transportation	159	83
Airplanes	240	20
Slow modes	0	0
Total mobility	1774	338
Total	6300	2000

assume that slow modes do not consume energy; therefore, travel distance can always be covered by slow modes without increasing the total energy consumption. Airplane transportation is not taken into account in the present study, because we assume that transportation policies at the district level cannot influence the use of airplanes. Table 3 also reports the current energy consumption in the SD district, which we consider as the reference scenario. It is visible that the current total consumption is more than three times the objective, and the mobility consumption of 1774 is five times higher than the limit of 338 W.

We compare five scenarios to see what would happen to the energy consumption in different situations, and to identify whether it is possible to achieve the energy objectives. We start with two extreme cases, namely *PT transition* and *Imposed*, and subsequently, we evaluate the effect of three transport policies aimed to incite car-sharing, car-pooling and car-free district. The following is a summary of the five scenarios evaluated:

1. *PT transition*. In this scenario, we evaluate the energy consumption if all the travel distance currently done by car is covered by public transport.

2. *Imposed*. In this scenario, we evaluate the energy consumption if only a minimum share of travel distance is done by car. The rest of the daily trips are split between PT and slow modes. The split is chosen such that the total energy consumption respects the limit set by the 2000W-society.

3. *Car-sharing*. In this scenario, we evaluate the energy consumption if a car-sharing system is introduced in the SD district.

4. *Car-pooling*. In this scenario, we evaluate the energy consumption if a car-pooling system is introduced in the SD district. In addition, we evaluate the consequences if all car trips are made with a maximum occupation rate of four passengers per car.

5. *Car-free*. In this scenario, we evaluate the energy consumption if the SD district becomes a car-free district. We analyze two cases of induced modal shift.

The results for all scenarios in terms of travel distance and energy consumption are reported in Table 4 and visualized in Figure 8. The scenarios are ordered from the most energy consuming to the least one. In the following, we discuss each scenario individually.

PT transition

In this extreme scenario, we impose a full PT transition. Because car trips are the largest in terms of travel distance, and the car is the most energy demanding mode of transport, we calculate what would happen if we transfer all the car travel distance to other less energy consuming transport modes. We consider a complete shift to public transportation, being PT 2.5 times more energy efficient than private cars (UIPT, 2015). We assume that the travel distance by car is completely traveled by PT, and we calculate the resulting energy consumption in this case. From the results, it is visible that even though public transportation consumes less energy than cars for the same distance, the total energy consumption related to mobility is 596 W, still larger than the 318 W objective imposed by the 2000W-society.

Imposed

The scenario of a full PT transition is an extreme case, and a complete elimination of car mobility is not realizable. In the *Imposed* scenario we limit the travel distance by car to the minimum, and we impose a constraint to the travel distance by PT in order to reach the objective of the 2000W-society. This constraint is necessary, because, from the previous scenario, we know that a full PT transition is not enough to reach the objective. Notter *et al.* (2013) report that people already living under 2000 W travel 82.4% less by car than the average population. Following this consideration, we reduce the travel distance by car by 82.4%, leaving only 17.6% of the total car distance. We split the rest of the daily travel distance between PT and slow modes in order to reach the imposed energy objective. We remind that slow modes are assumed to have zero energy consumption independently from the travel distance. The result shows that it is possible to achieve the 2000W-society objective only with a daily travel distance by walking and cycling equal to 27.7 km per person. In the following, we discuss the feasibility of this distance to be covered by slow modes.

Car-sharing

In this scenario, we consider the introduction of a car-sharing system. To evaluate the consequences of this system, we assume that the same effects identified in the literature can be assumed in the SD district. Domon (2015) describes the change in

Table 4: Travel distance and energy consumption in the different mobility scenarios

Distance [km]

	Current situation	Car-free 2	Car-sharing	Car-pooling	PT transition	Imposed	2000W-society	Car-free 1
Car	24.9	18.8	14.4	24.9	0	4.4	-	3.6
Public transportation	9.1	10.2	22.7	9.1	34	4.3	-	4.4
Slow modes	2.4	7.4	3.2	2.4	2.4	27.7	-	28.4
Total	36.4	36.4	40.3	36.4	36.4	36.4	-	36.4

Energy consumption [W]

	Current situation	Car-free 2	Car-sharing	Car-pooling	PT transition	Imposed	2000W-society	Car-free 1
Car	1375	1038	798	646	0	242	235	197
Public transportation	159	179	398	159	596	76	83	76
Slow modes	0	0	0	0	0	0	0	0
Total	1534	1217	1195	805	596	318	318	274

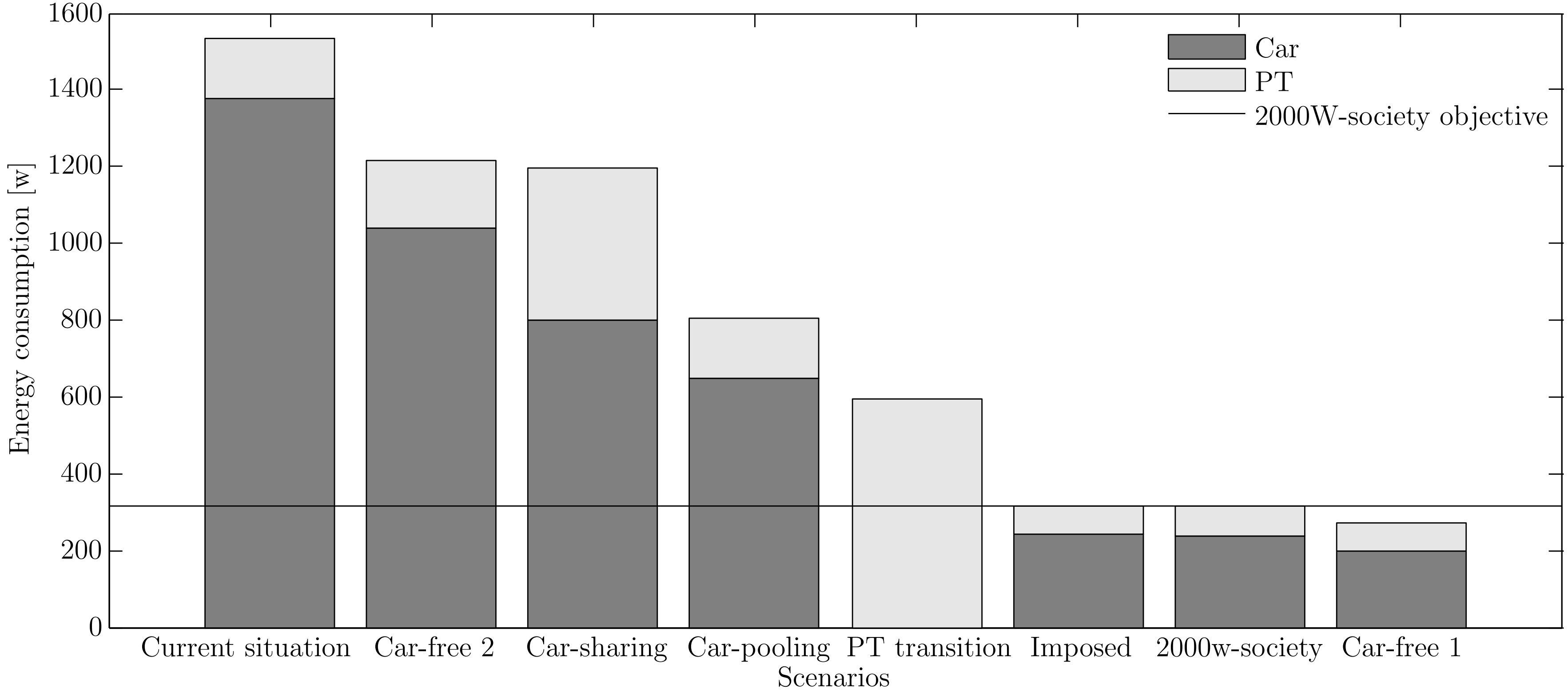

Figure 8: Energy consumption in the evaluated mobility scenarios and 2000W-society objective.

Table 5: Modal share in percentage of car-sharing users and private car users

	Car	PT	Slow modes	Other
Car-sharing users [%]	41	46	10	3
Private car users [%]	74	18	6	2

mobility habits for car-sharing users in Switzerland in terms of kilometers traveled for each mode of transport. Table 5 reports the main findings of this study. People using the car-sharing system tend to travel less by car and more by public transport. In average, a car-sharing user travels 42% less distance by car, 150% more by public transportation and 33% more with slow modes. A negative effect is that their overall mobility increases by 2.6%. Applying these percentage changes to the mobility habits of the inhabitants of the SD district, we can calculate the modification in terms of energy consumption when the car-sharing system is introduced. From the results in Table 4 and Figure 8, we see that car-sharing is not sufficient to achieve the 2000W-society energy objective. The total energy consumption is reduced from 1534 W of the current situation to 1195 W, however this reduction is far from being sufficient to reach the maximum 318 W limit.

Car-pooling

The car-pooling system directly affects the occupation rate of car trips. Cici *et al.* (2014) assess the potential of a successful car-pooling service. They report a reduction in car traffic that can be related to an increase in the occupation rate. The occupation rate after the implementation of the service ranges between 2 and 3.36 passengers per car, higher than the current occupation rate in the SD district reported in Table 2. Assuming that similar effects can be achieved in the SD district introducing a car-pooling system, we apply the best scenario of occupation rate equal to 3.36 to the current situation, and we calculate the car-distance travel using Equation 1. We see that the resulting energy consumption related to car travel is 646 W, greater than the 2000W-society objective of 235. This happens even if we increase the occupation ratio to a maximum of 4 passengers/car. The energy consumption related to car is 534w in this case. We conclude that although car-pooling reduces the effective car-distance, it is not sufficient to reach the needed energy reduction.

Car-free

There are several examples of districts where the use of private cars is strongly dissuaded (Topp and Pharoah, 1994). A well documented example is the district of Vauban, Freiburg, Germany (DE) (Nobis, 2003; Lange, 2003; Coates, 2013). To avoid confusion between the city of Fribourg, Switzerland, and the city of Freiburg, Germany, we refer to the latter as Freiburg-DE. The district has no parking spaces, the speed limit for vehicular traffic is 30km/h in main roads, it is connected to the city center with a tram line, and several services are present within the district to reduce the need of mobility, such as shopping facilities, green areas,

Table 6: Modal share in the SD district, Vauban and Freiburg-DE

	Car	PT	Walking	Cycling
SD district [%]	68	25	6	1
Vauban [%]	10	12	30	48
Freiburg-DE [%]	25	16	30	29

Table 7: Modal share induced by the introduction of the *Car-free 2* district measure in the SD district

	Car	PT	Walking	Cycling
Car-free 2 SD district [%]	52	25	8	12

nurseries, primary schools and a neighborhood center with social and cultural activities. Coates (2013) and Lange (2003) report accurate figures on the modal share of car, public transport, cycling and walking in Vauban. Table 6 reports a comparison among the modal share in the SD district, Vauban and the entire city of Freiburg-DE. The population of Vauban uses bikes as the main transportation mode and uses less public transportation than the population of Freiburg-DE. In the scenario *Car-free 1*, we directly apply the modal share present in Vauban to the SD district using the current total travel distance. We see that this scenario is able to achieve the 2000W-society energy objective, with a reduction in energy consumption from 1534 W to 274 W, value lower than the 2000W-society objective of 318 W. However, considering the current SD district total travel distance, the distance covered by slow modes is 28.1 km per day.

The modification to the modal share induced by the introduction of a car-free district should be somehow related to the original modal share of the area where this measure is established. In Table 6, we see that the current situation in the SD district is different from the one in the city of Freiburg-DE, which presents a greater modal split towards walking and cycling. Meanwhile, the modal share in Vauban is not as different from the one in the entire city of Freiburg-DE. The fact that Freiburg-DE is a different starting point should be taken into account while considering the potential modification induced by a car-free district. To quantify this modification, we calculate the difference in modal share between Vauban and Freiburg-DE, and we apply this proportion to the SD district modal share. Table 7 reports the modal share that we could expect in the SD district if the car-free district measure is introduced taking into account the original starting point reported in Table 1. We refer to this scenario as *Car-free 2*. This scenario presents a limited reduction in energy consumption, with a total of 1217 W.

Discussion

From the analysis of these scenarios, we notice that it is possible to achieve the energy objective only with a distance covered by slow modes greater than 27 km per day (we refer again to Table 4 and Figure 8 for a summary of the results for all scenarios). Different studies discuss the maximum daily distance covered by slow modes (Sa and Gouveia, 2011; Perez and Rey, 2013). For example, Choi *et al.* (2007) report that people are willing to walking or cycling continuously a maximum of 30 minutes for one trip. The data from the Microcensus (FSO, 2010) report an average walking speed of 5 km/h and cycling speed of 12 km/h in the SD district, speeds in agreement with values from the scientific literature (Browning *et al.*, 2006; Mohler *et al.*, 2007). Following these values, we can estimate a maximum walking distance of 2.5 km/trip and cycling distance of 6 km/trip. The average number of trips per day done by slow modes in the SD district is 2.6 (FSO, 2010). Therefore, assuming that the people maintain the same number of trips per day, the maximum distance covered by slow modes ranges from 6.5 km to 15.6 km, depending if covered by walking or cycling. Therefore, the scenarios reaching the energy consumption goal cannot be considered reasonable, requiring a distance greater than 27 km/day to be covered by slow modes.

A solution is to reduce the need for mobility, so people have a lower total travel distance per day. Using the *Imposed* scenario as a reference and the maximum distance covered by slow modes as a limit, we can calculate the percentage reduction in the total travel distance. In case the slow mode distance is covered by walking only, a reduction of 57% is needed to respect the walking limit of 6.5 km per day, resulting in a total travel distance of 15.6 km/day including all modes of transport instead of the current 36.4 km/day. While, a reduction of 32% is needed if the 15.6 km limit of slow mode distance is covered by cycling, resulting in a total distance of 24.8 km/day.

The analyses on the scenarios are based on a series of assumptions listed in Section 1. In particular, the assumptions (a) and (b), which assume the absence of technological advance capable of improving the efficiency of transportation systems, and the absence of more efficient ways to produced energy and reducing GHG emission, appear restrictive. As shown by Aßmann and Sieber (2005), Fontaras *et al.* (2008) and Graham-Rowe *et al.* (2011), significant improvements of the transport sector toward sustainability have been induced by technological changes rather than political actions. Therefore, we can conclude that technological improvement, in both vehicle efficiency and energy production, can allow reaching the 2000W-society objective requiring a less drastic change in mobility habits than the one showed in the analyzed scenarios. Moreover, innovative transport modes, such as personal rapid transit systems (Cottrell, 2005), urban cable cars (Brand and Dvila, 2011) and moving walkways (Scarinci *et al.*, 2016), could play a crucial role in the future.

Assumption (c) states that we evaluate the "best-case scenario" if the transport policies are applied to the SD district. This means that there is a low probability that the presented effects are achieved by introducing the policies in the area. Moreover, the possibility to implement the scenarios in the study area is subject to legal, political and practical limitations that go beyond the scope of this paper. Thus, we expect that individual policies, although effective, are not enough to reach the 2000W-society reduction, but only a integrated transport strategy can induce the needed changes in mobility habits.

From this analysis, we can summarize that the current situation is far above the limit proposed by the 2000W-society. None of the individual policies, such as car-sharing and car-pooling induces a large enough reduction in energy consumption. Interesting, neither a full transition to public transport achieves the goal. The scenario *PT transition* shows that a complete shift to public transport alone is not enough, resulting in an energy consumption of 596 W. We see that only an integrated policy like the car-free district, which incorporates several strategies, can reach the energy consumption limit.

5 Conclusions

In this work, we investigate the energy consumption related to mobility in different scenarios. First, we identify the study area as the zone of influence of the Solar Decathlon pavilion, and we study the characteristics of the population living in the district and their mobility patterns. Then, we evaluate whether the energy consumption in the scenarios meets the objective set by the 2000W-society of 318 watts per person.

We conclude that reaching the goal of a 2000W-society requires drastic changes in the mobility behavior. These changes can be achieved only with an integrated intervention such as the car-free policy, which is the only presented scenario that has the potential to respect the energy objective. In this scenario, the energy consumption is 274 W, in the best case; although this result strongly depends on the initial mobility situation. Only a combine increase in walking and cycling, with a share greater than 76%, and reduction in car usage below 10% can achieve the energy goal. However, the resulting modal share requires that a distance greater than 27 km is covered by cycling or walking every day. This distance is larger than an indicative maximum daily distance covered by slow modes, which is of 15.6 km. This indicates that the overall mobility needs to be reduced between 30% and 60% in order to have feasible mobility patterns.

A way to reduce the mobility need is providing services within the district focusing on the most energy consuming trips. From the population mobility analysis, we can conclude that the SD pavilion should offer services to decrease the mobility related to work and leisure activities within the city boundary. This can be done diversifying the urbanistic structure of the neighborhood by adding, for instance, offices, shops, restaurants and recreational centers. The population of the district is young and highly educated, and these factors could be favorable to a change in habits. Services and information campaigns specific for this population should be developed.

It is clear that no measure independently can achieve the goal of the 2000W-society. Only a set of coordinated measures could have a strong effect in modifying the mobility habits of the people (Dill, 2009; Harms *et al.*, 2016; Nobis, 2003). These measures should incorporate mobility policies, town planning design, connection of public spaces and services. This set of measures can be promoted with the concept of a car-free district, which has the potential to improve the cycling and walking modal share (Coates, 2013; Lange, 2003; Nobis, 2003).

The current mobility habits are centered on private cars, however in order to achieve a sustainable mobility, we must change the paradigm towards mobility. Mobility with a reduced use of private cars has been implemented in several districts (Coates, 2013; Lange, 2003; Nobis, 2003). However, this transition requires well-designed infrastructures that make walking, cycling and public transportation competitive (Harms *et al.*, 2016). This change in paradigm is particularly challenging in an existing district. In the majority of the cases, people living in car-free districts move there voluntarily and they are fully aware of the mobility limitations imposed by the car-free concept. In Fribourg, we investigate the transformation of an already built district in a car-free district.

Future work should focus on the definition of the measures to be implemented in the district able to promote the needed change in mobility patterns. These measures range from an increase of infrastructure specific for slow modes (e.g. creation of on-road bike lanes, separated lanes for bikes, separated sidewalks for pedestrians and safe crossroads) (Saelens and Handy, 2008; Dill, 2009; Harms *et al.*, 2016; Jones, 2012), introduction of bike-sharing and car-sharing systems (Garcia-Palomares *et al.*, 2012), the creation of on-line shops and delivery systems that could reduce the mobility need for shopping and the use of private vehicles, financial advantages to promote the use of public transportation (e.g. reduction on PT subscription card, car-sharing and bike-sharing services), and reduction of on-street parking and re-use of the space. Moreover, the pavilion should be a reference point for information and a catalyst for social identity. Access to information on an environmentally sustainable live style can incite the energy saving, and social identity and cohesion promoted through common spaces can help develop changes in mobility habits (Ornetzeder *et al.*, 2008).

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