A Tool to Optimize the Initial Distribution of Hydrogen Filling Stations

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Abstract
An important barrier towards the introduction of fuel cell vehicles (FCVs) running on hydrogen is the lack of widespread refueling infrastructure. The niche of buses for public transport, taxis and deliverers with a local application area might not be large enough to generate the reductions of FCV costs that are necessary for a general technology switch. Thus, fuel availability at trunk roads probably plays a crucial role in generating demand for FCVs also from private consumers. In this paper we assume that consumers are more likely to consider buying a FCV the more frequently they are exposed to hydrogen refueling opportunities on long distant trips. We introduce a tool to test different small scale initial distributions of hydrogen outlets within the German trunk road system for their potential success to generate a large scale adoption of FCVs. The tool makes use of agent based trip modeling and Geographic Information System (GIS) supported spatial modeling. We demonstrate its potentials by testing a ring shaped distribution of hydrogen outlets at highway filling stations. We find that the structure of an optimized initial distribution of filling stations depends on what drivers consider a sufficiently small distance between refueling opportunities.

Keywords: Agent based modeling; Alternative fueled vehicles; Hydrogen; Fuel Cells

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1 Introduction

Fuel Cell Vehicles (FCVs) running on hydrogen are a medium to long term option to reduce externalities related to individual transport. There are basically no local emissions from driving but water and the noise level is low (compared to internal combustion drive trains). Greenhouse gas emissions can be decreased, depending on the energy mix that is used for the generation of hydrogen. Moreover, displacing oil as the main transport fuel reduces costs associated with supply security due to the uneven distribution of oil reserves worldwide (Ogden et al., 2004). There has been long experience with hydrogen production and pipeline or tank vehicle distribution even at larger scales, because hydrogen is a widely applied industrial gas. On the vehicle side, several major car producers handed over small series of FCVs to end consumers for testing in everyday life. Former technological problems related especially to high pressure hydrogen refueling, on board hydrogen storage or cold start of the fuel cell system seem to be resolved. Current research is mainly focused on size and weight of the fuel cell and the reduction of material inputs, especially noble metals like Platinum and Ruthenium (depending on the fuel cell type). So there is a general shift of attention from technological issues towards economic ones.

To launch FCVs at the market at reasonably competitive prices would require setting up production lines to achieve cost reductions from fuel cell mass production. But car producers are probably reluctant to do so as long as a sufficient initial hydrogen infrastructure does not exist, because demand for such cars crucially depends on fuel availability. On the other hand, filing station operators are not willing to make major infrastructure investments as long as there are hardly any FCVs on the road. Ignoring this start up problem, which is also termed the "chicken and egg problem of H_2 and FCVs", the majority of economic studies that focus on estimating the costs and/or the environmental benefits of pathways into an "H_2-economy" are basically best-case scenarios of a successful system switch. The standard approach is to assume a certain number of FCVs and estimate the necessary infrastructure investments to supply them or alternatively to take certain infrastructure developments as given and derive the number of FCVs that can be supplied (see, e.g., Schneider et al. (2004), Thomas et al. (1998), Moore and Raman (1998), Ogden (1999, 2002), Stromberger (2003), Mercuri et al. (2002), Sørensen et al. (2004), Oi and Wada (2004), Hart (2005)).

In this study, we suggest a tool for filling station operators to test the potentials of initial small scale distributions of hydrogen filling stations. The idea is that to overcome the “chicken and egg problem” initial infrastructure investments should be low, but at the same time sufficient to generate a general notion of fuel availability for potential FCV buyers. Explicit models on the dynamics of the early stages of a H_2-infrastructure system and FCV driving are absent with the exception of one by Stephan and Sullivan (2004), who suggest an agent-based model, in which drivers tend to buy a FCV, if they are frequently exposed to H_2 filling stations on their usual trips. Conversely, filling station owners add an H_2-pump if they observe sufficient FCV traffic. They test these behavioral assumptions in an artificial urban area with surroundings covering 160x160km. Within this area, commuters drive regularly to a specific business district and some other attractors. In this study, we integrate Stephan and Sullivan's behavioral model into the real German trunk road system combining features from geographic information systems (GIS) and agent-based trip modeling. In doing so, we provide a tool that decision makers can apply to test the potential of different initial distributions of H_2-pumps at trunk road filling stations to initiate a successful transition of the road fuel system. We demonstrate the functionality of the approach by analyzing different initial distributions as, e.g., the "HyWay-ring" suggested by Hart (2005). The placement of H_2-pumps on trunk road filling stations will connect initial urban hydrogen filling stations, which are already set up or planned as demonstration projects. Trunk road refueling is therefore crucial for generating a private demand for FCVs and letting them step out of the niche of buses for public transport, taxis or local deliverers. Given today's statements of car producers and energy suppliers, this step could be made in the middle of the next decade.

Our results suggest that a carefully located small amount of H_2-pumps on trunk road filling stations can initiate a transition. Moreover, knowledge about what potential FCV buyers consider a sufficiently short distance between H_2 filling stations changes the structure of the initial placement that performs best. However, if there is uncertainty about this distance, filling station operators should not overstate the assumed distance, in order to prevent complete failure of the distribution.

The paper is organized as follows: The next section describes all parts of the model, i.e. the road network used, the set up of the gravity trip model and the behavior of agents. It also provides information on the data used for calibration. Section 3 demonstrates the functionality of the model by applying it to the "HyWay-ring" and Section 4 shows how the model can be used to optimize initial H_2 filling station distributions. Section 5 concludes with a summary of the main results and points out some weaknesses of the current model.

2 The model

The graphs in Figure 1 show the German trunk road network as used in the model, where the bold blue roads are expressways ("Autobahnen") and the red ones are highways ("Bundesstraßen"). All drivers are assumed to reside in one of about 200 cities with populations larger than 50,000 including a few bordering cities like Basel (Switzerland) or Strasbourg (France). The focus is on cities, because initial H_2-stations (this term is used from now on to refer to an existing filling station that adds an H_2-pump) are likely to be set up in larger urban areas, e.g., to supply buses in public transport or taxis. The labeled cities are the 15 largest German cities with respect to population and they are split in up to 8 city parts. In contrast to Stephan and Sullivan, long distance trips are modeled. The reason is that with current H_2 tank capacity, a range of more than 400km is no problem. This is enough for trips within a city. Thus, a few H_2-stations at arterial roads seem to be sufficient. However, a major benefit from car ownership is the flexibility to do spontaneous long distance trips. This is what people are believed to have in mind, when they state that they would buy an alternative fuel car if they were able to refuel it "everywhere".

2.1 Gravity trip modeling

To get a first approximation of long distance traveling behavior, a gravity model of travel is used (see, e.g., Sheppard, 1978, Erlander and Stewart, 1990, Roy and Thill, 2004). For each city as an origin of a trip it generates for each city as a potential destination a probability that a trip is made between them. The gravity model implies that traffic between two cities increases with the size of the cities but decreases with distance. We estimate the gravity model by applying the maximum entropy approach that goes back to Wilson (1967) and has been applied to regional science by Anas (1983). The maximum entropy concept defines the most probable distribution as the one that has the highest micro level uncertainty (maximum entropy) but generates the observable macro level patterns. In other words, given that the actual individual trip making behavior is unobservable, no restrictions should be made on the individual level, given that aggregated inflow and outflow data emerge. The standard notation of the maximum entropy approach is

$$\max_{t_{i,j}} \; E = -\sum_{i,j} t_{ij} \log t_{ij} \tag{1}$$

$$\text{s.t.} \qquad \sum_j t_{ij} = outflow_i \qquad i = 1, \ldots, I$$

$$\sum_i t_{ij} = inflow_j \qquad j = 1, \ldots, J$$

$$C = \sum_{i,j} c_{ij} t_{ij} \; ,$$

where t_{ij} is the probability that a trip is made from origin i to destination j. The sum of all trips starting at origin i must be equal to the (observable) $outflow_i$ and the sum of all trips ending at a destination j must be equal to the (observable) $inflow_j$. The third restriction limits total trip costs to a constant C. The costs of a trip c_{ij} are assumed to be proportional to distance, thus C can be represented by the total amount of kilometers traveled. The required data are optained from the German Federal Statistical Office (FSO-GOR) for inflow/outflow of commuters and tourist arrivals;[1] total kilometers traveled are derived from GFMTBH (2005). We depart from the standard entropy approach by including additional constrains that make sure that the generated trip probabilities match with traffic count data from Lensing (2003).

2.2 Behavior of drivers

Drivers make randomized trips according to the probabilities of the gravity model. During their trips they recognize the distance between H_2-stations on their way, no matter whether they drive a FCV or a conventional car. As long as this "H_2-distance" is lower then a certain "don't worry distance" (*DWD*), e.g., 50km, they perceive this as sufficient coverage. For greater distances drivers get worried about refueling and the total worry for one trip is then computed as the squared sum of H_2-distances exceeding the *DWD*, so that

$$Worry_{trip} = \alpha \sum_n (H_2distance_n - DWD)^2 , \tag{2}$$

where α is a parameter and $H_2distance_n$ is the distance between the n^{th} and the $(n+1)^{th}$ H_2-station that actually exceeds the *DWD*. When a driver makes a decision to buy a new car he first of all checks whether H_2 is available at his home city and if so, he buys a FCV only if

$$\text{Indiv. Benefits + Soc. Benefits + Tax Exemp.} > \text{FCcosts} + \sum_{trip} Worry_{trip} \ . \tag{3}$$

Individual benefits are add-on benefits of driving a FCV, as, e.g. being a technological precursor or showing environmental awareness by driving a "zero emission car". Social benefits are derived from group pressure and other network externalities associated with the increased use of the new technology, like the number of garages specialized on fuel cells. These impacts are approximated with the share of people driving FCVs in the home city. Moreover, tax exemptions are assumed to be granted for "zero emission cars". These positive effects of driving a FCV must outweigh the additional costs of the fuel cell system (FCcosts) compared to an internal combustion engine. Costs decline with the number of FCVs sold due to learning by doing, but are extremely high at the beginning. The benefits must also

[1] Since the values are correlated with population, missing data are approximated using population figures.

compensate the "refueling worry" associated with driving a hydrogen vehicle, which is computed by summation over the trips during the last six month.[2]

To calibrate the buying decision we compute the relative benefit of driving a FCV compared to an advanced internal combustion engine vehicle (ICEV) with hybrid electric transmission, automatic gear box and complex end-of-the-pipe emission reduction. When first offered to the public, we assume that replacing the engine with a fuel cell increases costs per kilowatt by a factor of five. Costs then decline with a learning rate of 10%[3]. Given that drive train costs amount for roughly one fifth of total costs, a FCV would initially cost twice as much as a comparable ICEV. We use a tax exemption of 25% of the end price and assume that individual benefits are correlated with income. Thus, we let the distribution of individual benefits follow the (right skewed) German income distribution.[4] We have to jointly calibrate individual benefits and refueling worries to get the initial amount of potential FCV buyers.[5] Figure 2 shows the share of people who would buy an FCV, given the underlying distribution of individual benefits and a *DWD* of 50km for different densities of the H_2-station distribution and cumulated numbers of FCVs produced. A diffusion process would start with combinations in the down right corner with long distances between H_2-stations and low cumulated numbers of FCVs produced. Here, between 0.5% and 1% of the buyers would actually buy a FCV. This share of "enthusiasts" is actually far below the share of people with a taxable income of more than 100,000€ per year, and therefore could also represent people who buy a second car and are therefore less dependent on refueling. A successful diffusion would then lower the distance between H_2-stations and increase the cumulated number of FCVs produced so that we would "climb up the hill" towards the top left corner.

The actual amount of buying decisions and therefore of newly registered cars and replaced old ones are fitted against data from the Federal Bureau of Motor Vehicles and Drivers (FBMVD, 2005a, 2005b). Driving behavior, i.e. the number of long distance trips people tend to do is derived from the German Mobility Panel (GFMTBH, 2005).

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[2] We implement the *DWD* as if it was independent of drivers. In reality, though, drivers differ in their *DWD* and therefore, all else being equal, potential buyers could be ranked according to their individual *DWD*. However, during our experiments we are interested in the relationship between the (average) *DWD* and the geographic distribution of H_2-stations, and these qualitative insights are not affected by our simplifying assumption.

[3] A learning rate of 10% means that costs decline by 10% each time cumulative production doubles.

[4] Data of German income distribution can be obtained at e.g. at http://www.sachverstaendigenrat-wirtschaft.de.

[5] Social benefits increase linearly with the share of FCVs but are negligibly low at the very beginning. Later on, they stop increasing after a share of 10% of newly registered cars has been reached.

2.3 Behavior of filling station owners

As in Stephan and Sullivan, filling station owners add an H_2-pump, if they observe sufficient demand for H_2 as implied by the number of FCVs at their road. Stephan and Sullivan are unclear about the threshold they use. We assume that on average one potential customer per hour observed over a period of six month (with more weight on recent months) is enough for a start, given that a filling station owner would from then on expect increasing demand. In reality, filling station owners cannot observe the traffic on their road.[6] But they do know where their customers come from (e.g., from asking them for their zip code) and they can combine this information with the sales figures of FCVs in these areas. The new H_2-pump is kept at least six months. After the initial six month, the H_2-pump is shut down, if actual FCV traffic (i.e. H_2 demand) is below half of the expected. Thus, we implicitly assume that operation and maintenance costs of the new pump technology together with H_2 transport costs to a remote filling station are considerable, so that shutting down the pump, which can be done at no costs, might be a reasonable option.

A basic H_2 coverage within a city (i.e., H_2-stations at selected arterial roads) is set up, if the number of potential FCV buyers, who would have bought a FCV, but didn't, because of the lack of H_2 in their home city exceeds 1% per quarter. Given usual sales frequencies, this implies roughly 50 potential buyers within a year for an urban area with 50,000 inhabitants – a number of vehicles served per station well in line with other scenarios (Bevilacqua Knight, 2001; SINTEF, 2005). Depending on the actual number of FCVs in the city later on, this basic H_2 coverage might also be shut down. Again, in reality the necessary information for filling station operators to decide on adding H_2-pumps is not directly observable. What they do observe, though, are constructions of H_2-stations at surrounding trunk roads and therefore likely increases in the number of potential FCV buyers.

The thresholds to set up H_2-pumps cannot be validated with empirical observations, because future investment costs for an H_2-pump are not clear and neither are future revenues from selling hydrogen to end consumers. However, these values can be influenced by governmental decisions, e.g. by granting loans with low interest rates and tax exemptions for hydrogen. The general success of the diffusion process modeled is highly dependent on the thresholds used.

[6] Future traffic control and toll systems could actually provide such information.

But comparing the success of different geographic placements of H_2-pumps, as it is done below, is independent of the thresholds.[7]

3 Testing an existing infrastructure scenario

The upper left graph of Figure 1 shows an initial distribution of H_2-stations (blue "H") at trunk roads following the "HyWay-ring" suggested by Hart (2005) in a study for *Linde AG*. This ring connects major German car production clusters and cities with H_2-station demonstration projects. The distance between the stations does not exceed 50km. In all the model runs presented in the paper, the connected cities (Berlin, Leipzig, Nürnberg (Nuremberg) and so on) are assumed to have a basic H_2 coverage at year 0, which is supposed to be somewhere between 2010 and 2015.

Figure 1 shows the resulting development of H_2-stations, given the initial "Linde scenario" distribution after 5, 10 and 15 years for a *DWD* of 100km, implying that refueling worries are extremely low. After 5 years, some H_2-stations particularly in the West and in the East have been deconstructed due to insufficient demand; while particularly in the South there has been a small increase in H_2-stations. Note that even after 15 years parts of the initial ring remain empty, while the connection between the two largest cities Berlin and Hamburg has been established. This indicates that the suggested initial ring distribution might be suboptimal.

Figure 3 displays the corresponding numbers of urban areas with basic H_2 coverage, trunk road H_2-stations and the cumulated number of FCVs sold. In Figure 4, results are shown for a lower *DWD* of 50km, representing a higher concern about refueling that seems to be more realistic. Here, the system is severely hit after the first 4 years, implying that the initial coverage was insufficient. In this scenario, given the initial H_2 coverage, FCVs would not enter the mass market for at least another 20 years.

4 Optimizing an initial H_2-station distribution

Given the number of potential initial locations of H_2-stations it is impossible to search for the optimal distribution.[8] Nonetheless, results from the simulations presented above provide useful information to improve distributions substantially. For example, H_2-stations that are

[7] Due to the straightforward impact of varying the thresholds, we refrain from showing the results from sensitivity analyses with respect to them.

[8] Even if we were able to reduce the number of potential initial locations to 50, there would be more than 10 billion theoretical combinations of placing 40 initial H_2-stations. There are methods like genetic algorithms to search combinations for a (local) optimum. Each search step requires evaluation of one combination (i.e. running the simulation with that combination), which takes about an hour on a Pentium IV. However, the size of the problem would probably require at least a few thousand search steps.

shut down after the initial four years period should rather be located at roads with high FCV traffic. Figure 5 shows results from using two different improved initial distributions, one derived from the *DWD* = 50km and the other one from the *DWD* = 100km case above. With the same amount of initial trunk road filling stations as before, the improved initial distribution derived from the *DWD* = 50km case (solid lines) starts up a slow but steady infrastructure build-up that outperforms the situation in Figure 4. The new initial distribution is superior, and should be applied instead of Hart's "HyWay-ring".

Figure 5 also shows the performance of an initial distribution that is fitted to a *DWD* of 100km overstating the actual *DWD*. This refers to a situation in which filling station operators have been too optimistic with respect to refueling worries of drivers when setting up the initial distribution. In consequence, the transition fails.

The impact of fitting the initial distribution to the actual *DWD* rather than a low one can be seen from Figure 6. Here, the actual *DWD* is indeed 100km and the accordingly fitted initial distribution performs better than the one fitted to the in this case too pessimistic *DWD* of 50km. But differences are rather small; the transition is successful in both cases. So putting together the information of Figure 5 and Figure 6 leads to the conclusion that in order to avoid the transition to fail, filling station operators should rather err on the conservative side if there are uncertain about the actual refueling worries of drivers; that is, a low DWD should be assumed.

5 Conclusion

There must be at least some initial H_2-stations to overcome the chicken and egg problem associated with H_2 and FCVs (or with alternative fuels in general). To keep upfront infrastructure investments as low as possible, the initial distribution should include just as many H_2-stations as necessary to be self sustained, i.e. to "survive" until vehicle costs go down sufficiently, such that large scale demand for FCVs and H_2 arises. Such an initial H_2-stations system requires careful design, because inappropriate placement can lead to a collapse of major parts of the system due to the lack of hydrogen demand, endangering the whole introduction of the new technology.

In this paper we introduce a tool to test different initial distributions for their potential success. The tool combines spatial modeling with GIS support and agent based trip modeling. It is applied to the German trunk road system. For demonstration purpose we implement the

"HyWay-ring" distribution suggested by Hart (2005). The ring is originally motivated as a connection of major German car production clusters and cities with H_2-station demonstration projects. Results suggest that this ring can only be a promising starting point if the distance between H_2-stations that drivers consider sufficient (“don’t worry distance”) is rather large. But with small refinements in the initial distribution a transition is possible even if drivers are more sensitive with respect to refueling. In general, the optimal placement of initial H_2-stations depends on the assumed “don’t worry distance”. However, if filling station operators are uncertain about the refueling worries of drivers, their assumptions should be rather conservative in order to prevent failure of transition.

Given the magnitude of infrastructure investments required to implement an alternative fuel system, savings from an optimized initial distribution should be significant. This calls for further research into this issue to overcome limitations of the current model: First of all, the trip distributions generated by the gravity model are "most likely distributions", but do not necessarily reflect real travel behavior, which is often characterized by specific habits or work requirements. Moreover, holiday trips to specific sights at the seaside or the Alps are not included and the same holds for trips abroad in general. Thus, a more complex travel model, perhaps on a European level would be preferable. Furthermore, the - to some extent - ad hoc parameterization of the agent behavior restricts the model to qualitative results from comparing different initial conditions. Finally, it would be desirable to increase the overall resolution of the model to also account for optimal H_2-station distributions within the cities.

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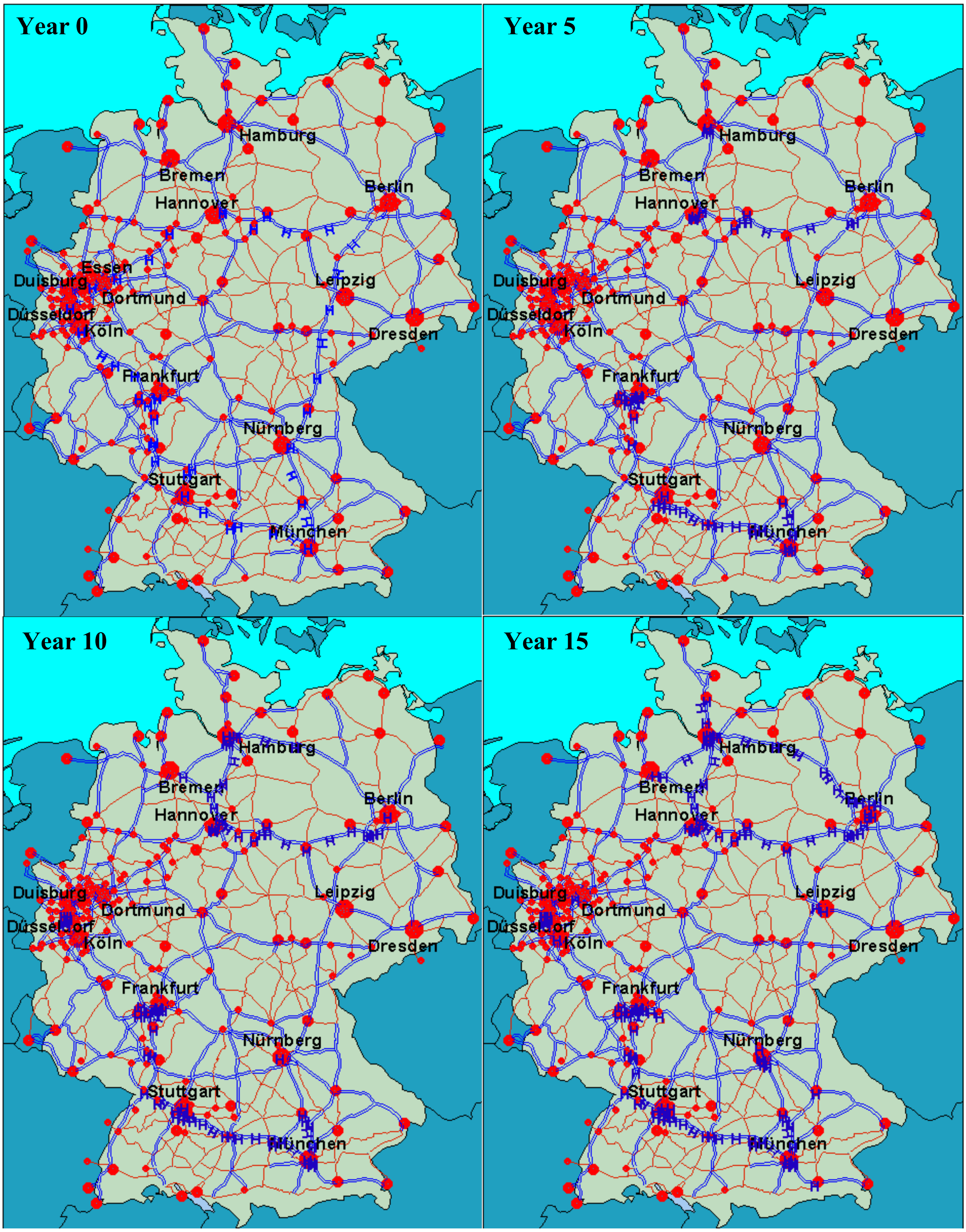

Figure 1: H_2 trunk road station development for Linde Scenario (DWD = *100*km)

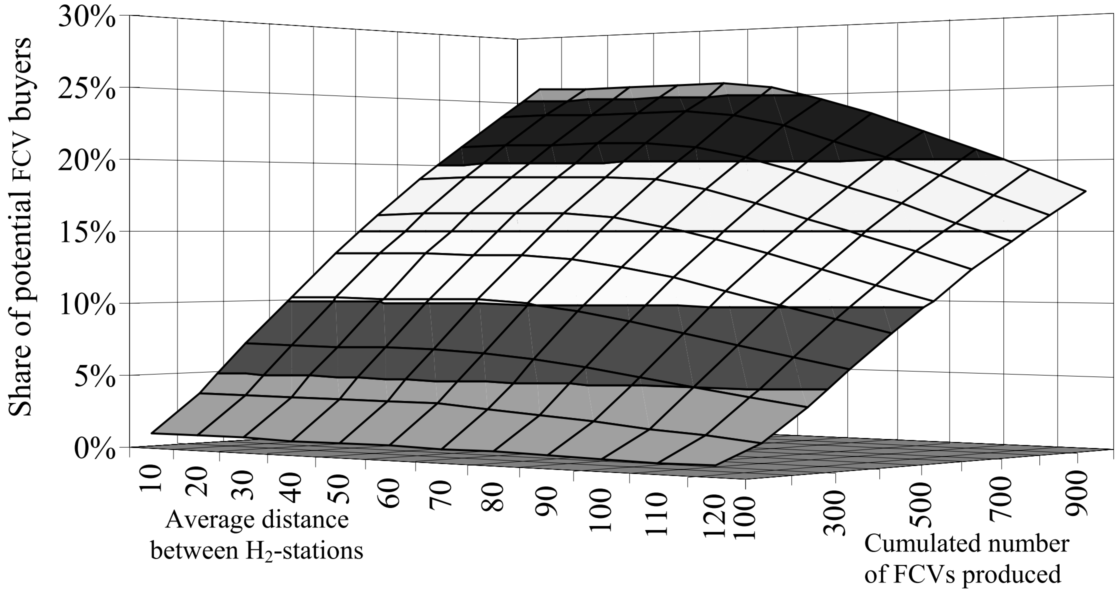

Figure 2: FCV demand implied by H_2-station density and cumulated production

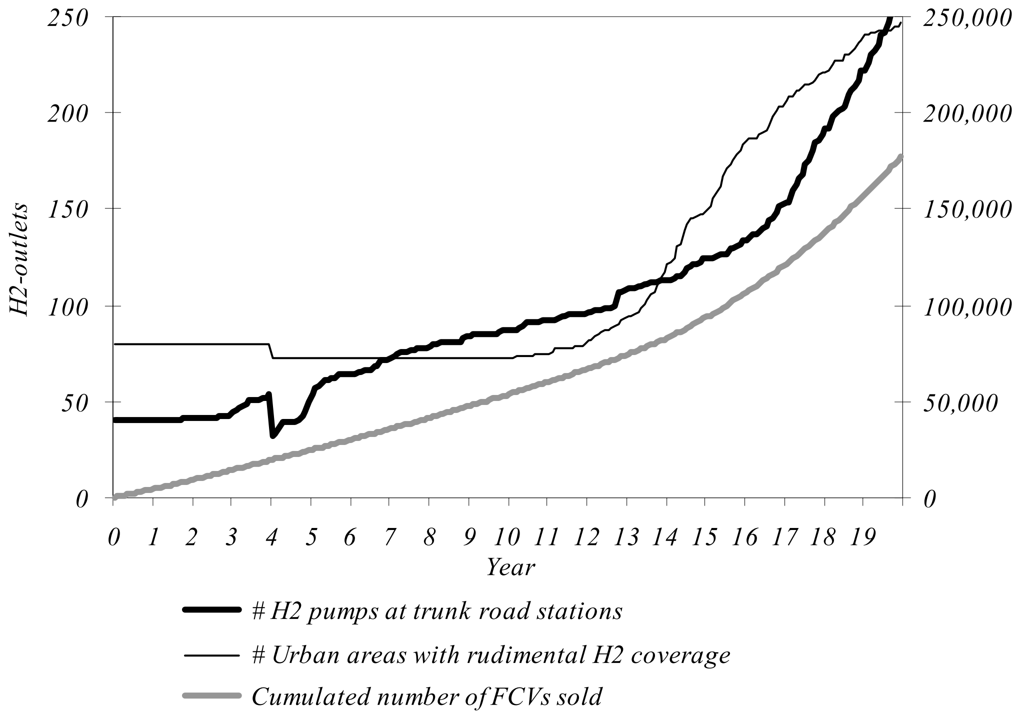

Figure 3: Infrastructure development and vehicle adoption of Linde Scenario (*DWD* = 100km)

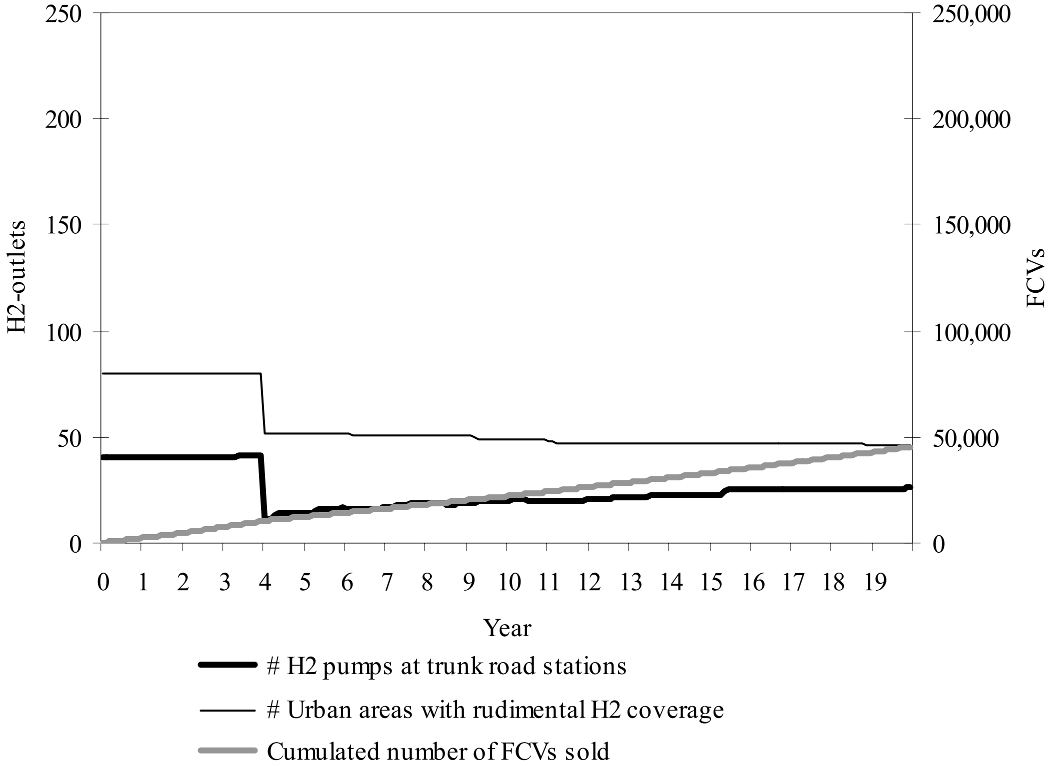

Figure 4: Infrastructure development and vehicle adoption of Linde Scenario (*DWD* = 50km)

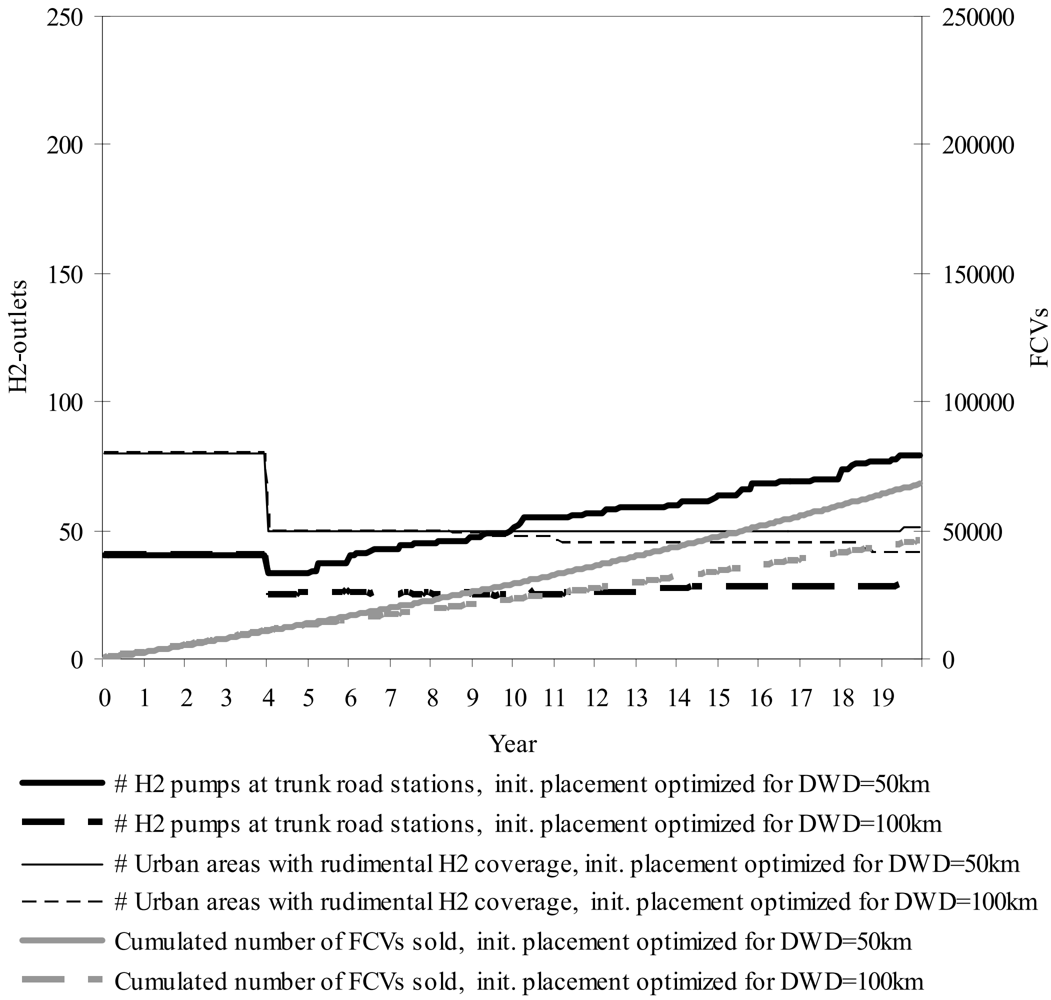

Figure 5: Infrastructure development and vehicle adoption if actual *DWD* turns out to be 50km (high refueling worries)

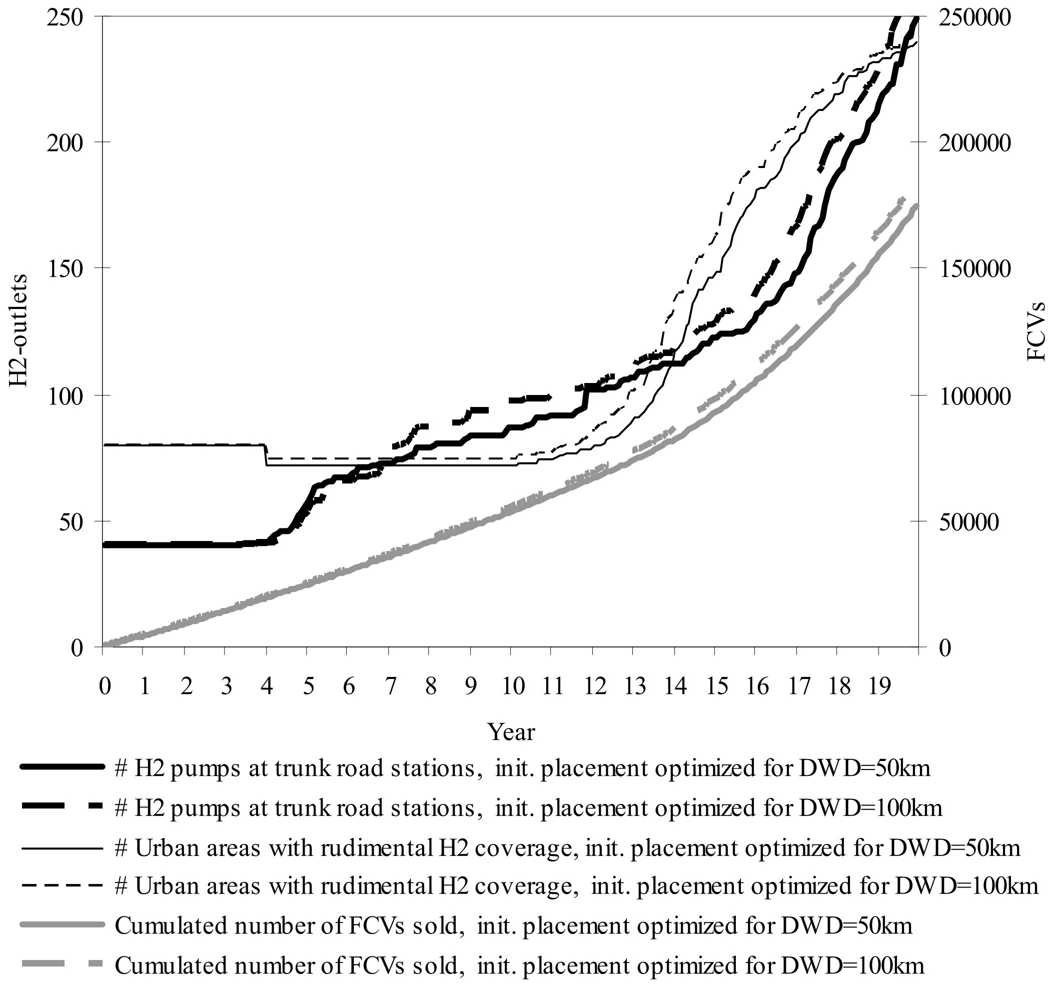

Figure 6: Infrastructure development and vehicle adoption if actual *DWD* turns out to be 100km (low refueling worries)

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