ABSTRACT

A transition to a personal transportation system based on hydrogen rather than petroleum will entail major changes in the supporting infrastructure and in the driving habits of consumers. Early-adopting consumers will be put to some inconvenience in making trips, as they will likely have to plan ahead to determine if there will be hydrogen stations available when and where they need to refuel. While this and other potential drawbacks to an individual’s decision to purchase and drive a hydrogen vehicle operate on a very personal level, the benefits of doing so are almost exclusively societal in nature (that is, reduction in both the worldwide demand for petroleum and the emission of carbon dioxide). It will be critical to build up the hydrogen support infrastructure in a way that minimizes the hardship to the consumer and creates as strong an incentive as possible for robust early growth of the system. In this paper we examine the growth of a hydrogen infrastructure in a simple agent-based model consisting of a city center, a metropolitan region, suburbs, and a surrounding rural area. Previous studies have shown that a successful transition to a self-sustaining system depends on cost of ownership, community member influence, and vehicle and station densities, and that the growth and ultimate penetration of the hydrogen system may be strongly dependent on the initial distribution of stations and drivers. In this paper, we extend the investigation to consider other factors, such as effects of driver preference for refueling near home and the effects of changing subsidies.

Keywords: drivers, hydrogen, infrastructure, transportation

INTRODUCTION

Energy security and carbon emission concerns have stimulated a renewed interest in shifting world energy consumption away from fossil fuels and replacing them with alternative energy resources. One approach advocates a transition to hydrogen as a fuel, in particular for use in the transportation sector. A number of researchers have addressed this question, some from a strategy point of view and others from an infrastructure and vehicle point of view. All cost-related studies conclude that the development of a hydrogen vehicle and fuel infrastructure, i.e. a hydrogen transportation system, will be very expensive. Ogden, et al. (2004) found that most advanced vehicle/fuel options, including hydrogen fuel cell vehicles, would not be cost competitive with conventional vehicles without internalizing externalities associated with air pollution, climate change and energy security. They go on to say that even when such fuel/vehicle systems are available, it would take decades before a meaningful impact on the above-cited issues could be made and that this technology should not be pursued to the exclusion of...
of work on advanced conventional technologies (hybrids, diesel, advanced spark ignited). Mintz, et al (2002) have estimated the cost of hydrogen generated from natural gas using three different production systems, namely, resource-centered, market-centered, and decentralized hydrogen production. Hydrogen unit costs range between $18 to $23 per GJ, much higher than today's gasoline cost, which is about $7/GJ and not likely to ever exceed $10/GJ (Mintz, et al., 2002). This cost differential is formidable. But perhaps, developing a hydrogen fuel infrastructure in some other way could help reduce this differential. For example, Farrell, et al. (2003) argue that selecting a transportation mode like shipping, which represents a few large operating units that move along comparatively few routes, might reduce the cost of introducing and developing a hydrogen infrastructure.

As useful as they are, the above cited studies and others in the literature base their analyses on some combination of exogenous economic factors about conventional and hydrogen transportation system costs with the inclusion of hitherto unaccounted for externalities (climate change, etc.). Unfortunately, these studies make neither attempt to account for the evolution of a market for such a system nor to elucidate the factors that could emerge that would either impede or spur its growth. Agent based modeling (ABM) can be used for such a purpose, and if done successfully could provide valuable insight into this important question. Because market supply and demand behaviors including cost emerge endogenously in such models, ABM results potentially offer a realistic representation of the evolution of the hydrogen infrastructure.

ABM has been extensively used in traffic modeling simulations. For a sampling of that work, the reader is directed to a recent journal issue (Transportation Research, 2002) devoted to applications of ABM in transportation. With the exception of our previous paper (Stephan, et al., 2003), to the authors’ knowledge ABM has not been applied to the evolution of any alternative fuel market, let alone hydrogen. It would be misleading to suggest that all one needs to address such an important economic and societal question is to build an ABM. We recognize that Agent Based Modeling is a nascent field. Nevertheless, insights into human and social behavior have already been gleaned from ABM results (Axelrod, et al., 1999; Computational Social Science, 2000), including interpretation of organizational behavior. It is even being applied to long term policy analysis (Lempert, et al., 2003). Indeed, Ford's interest in ABM is broader than the hydrogen transportation system evolution question addressed here. For example, the climatic and supply issues cited above concerning fossil fuel use portend changes in world energy use patterns. What form they will take is not known, but they are likely to cause a shift in market preferences, including that for transportation. Anticipating potential shifts in both magnitude and timing has obvious business implications, but it requires more than a casual acquaintance with understanding causes and magnitudes of social trends. Again, ABM could help illuminate discussions around such questions.

MODEL

The transition from a petroleum to a hydrogen-based personal transportation system promises to be a difficult and complex one. The technical problems of building hydrogen-fueled vehicles and the infrastructure to support them are formidable in and of themselves. However, a further challenge that must be faced is how such a system can grow from what must of economic necessity be a small beginning to one comparable in extent to the present petroleum-based one. It is a classic “chicken and egg” problem in that fuel suppliers will be reluctant to invest in hydrogen production, distribution and fueling facilities until they are assured of a sufficient
customer base, and drivers will not purchase vehicles unless there exists a number of hydrogen stations sufficient to ensure they need not worry about refueling. To maximize the chances of a successful transition, it will be vital to have a good understanding of how the various agents involved in a hydrogen-based transportation system – vehicle owners, vehicle manufacturers, hydrogen producers, distributors, and retailers, and government bodies – will interact as the system grows.

We have taken a first step towards that understanding by considering a simple system involving just two types of agents, vehicle owners and hydrogen retailers. They interact on a grid representing a central metropolitan area, suburbs, and rural area. This region is shown in Figure 1, a screen capture of the display from the RePast/Java ABM modeling framework in which the simulation was developed. The grid consists of a 100 by 100 array of cells, and is considered to represent an area about 100 miles on a side. A number of expressways, shown as light grey lines, crisscross the grid and form a ring around the boundary. Local roads are considered to be ubiquitous and are not shown explicitly on the display. The population of drivers (blue circles) is distributed randomly, but weighted so that density is highest in the metropolitan and suburb areas, and zero in the central city district. In the simulations, a driver population of 800 was used, and thus agents can be considered “markers” for a much larger population living in the 10,000 square mile area. At the beginning of a simulation, most drivers drive conventionally-powered vehicles (open circles) but a small percentage have hydrogen-powered ones (solid circles). The grid also contains a number of locations (representing jobs, schools, etc., shown as black squares) to which the drivers commute on a daily basis. Each driver is associated with a single such location. The drivers also make less frequent (“weekend”) trips to other locations on the grid. The destination for each such trip is picked randomly, but certain cells on the grid representing “attractions” (sports stadiums, parks, etc., shown as one or more large magenta squares) are weighted to be favored destinations. In driving to a given destination, a driver agent follows a protocol of driving on local roads to the nearest entrance of the first North-South expressway in the direction of his destination, following that expressway to the East-West expressway closest to (but not past) his destination, in turn following that expressway to the appropriate exit and finally once more taking local roads to the destination. A typical route is shown in the figure. (Entrances and exits to expressways are located at intersections and on each expressway at the midpoint between two intersecting expressways.)

Fuel retailers comprise the second type of agent in the simulation. Conventional fuel stations are considered to be ubiquitous and are not shown explicitly on the display. At the beginning of the simulation a small number of cells (open red squares) are chosen to contain hydrogen fueling facilities. These locations can either be chosen randomly (though always at expressway intersections) or placed as desired. As the simulation proceeds, these stations monitor their hydrogen fuel sales and if the sales are insufficient they will close their facilities. Every cell on the grid is a candidate location for a new hydrogen fuel station, and if the expected sales volume is high enough a new station will open. Once opened, a hydrogen station will remain open for at least six months, but then may close again if the actual sales volume is less than a second, lower, threshold. Depending upon its location, a station can have one or two types of sales. Studies of consumer behavior have found that drivers prefer to fuel their cars at stations near their home or work (Kitamura, et al., 1987). Reflecting this, our driver agents purchase all their fuel for local trips (commuting and the portions of random trips that are within 50 miles of home) from

* http://repast.sourceforge.net/
stations within a specified radius of either home or work, distributing their purchases equally among all such stations. A station located in a cell containing an expressway (i.e., a station that is within one half mile of the expressway), sells fuel to both local drivers and to non-local drivers using the expressway. It is expected that two stations located in close proximity to each other on an expressway (e.g., on adjacent cells) will compete for business from such drivers, while one that is relatively isolated will service all passing drivers needing fuel. To account for this, we incorporate a local “proximity factor” that reflects the competition that an expressway station faces from nearby stations. For example, a station with a competitor on an adjacent cell has its sales reduced by one third compared to what they would be otherwise, and the two stations together sum to 4/3 “effective” stations. When an agent makes a non-local trip, he divides his fuel purchases among all hydrogen stations passed on the trip on the basis of their effective ratings. (While an individual driver would obviously not divide his purchases this way, the procedure reflects the marker nature of the agents.)

Figure 1 Screen capture of the model region showing a central city (outlined by the smaller red square at center), surrounding metropolitan region (larger red square), three suburbs, and rural area. Expressways are shown as grey lines. Hydrogen fueling stations (open red squares) have been placed randomly at expressway intersections. A small fraction of the driver agents (blue circles) have hydrogen vehicles (solid circles). “Jobs” are shown as solid black squares. An “attraction” (large solid magenta square) has been placed in the upper left of the region. The green line traces the route of one hydrogen vehicle driver making a trip to the attraction.

During each time step of the simulation (one step representing a time period of approximately one month) the actual or potential fuel sales for each cell on the grid during that

* A cell is considered to have either zero or one hydrogen fuel station. While in reality there could be more than one station in the cell’s one square mile area, we assume that drivers will treat all such stations equivalently in terms of their location so that their sales can be combined to represent one “superstation”.
period are calculated. The sum of sales from all preceding months is multiplied by a factor chosen to exponentially decay and normalize the historical record to reflect a characteristic time period of about one year, weighted towards more recent months. For off-expressway locations sales are local only, whereas expressway locations add the local and expressway sales. If the sum for an empty cell exceeds a threshold, the cell will add a hydrogen station. If the sum for a cell with an existing hydrogen station (which has been in operation for a minimum of six months) falls below a lower threshold, the station will close.

Drivers buy new cars on a regular basis, keeping them for a randomly-assigned length of time. When the next purchase time arrives, a driver chooses either a conventional or a hydrogen vehicle on the basis of a “utility function” that takes into account a number of factors. The first is the difference in fixed costs of a hydrogen vehicle vs. a conventional one. This factor includes not only the purchase price of the vehicle but such intangibles as a desire to be “environmentally friendly” or “high tech”. The hydrogen vehicle is assumed to have a lower fixed cost, yielding a positive “fixed benefit” in the utility function. Likewise there is assumed to be a positive “variable benefit”, proportional to the distance driven, for a hydrogen vehicle. This also includes benefits that are both tangible (fuel and other operating costs) and intangible (dispensation for unrestricted travel in HOV lanes, for example). In addition, the agent’s purchase decision may be influenced by the purchase decisions of his friends and neighbors and the public at large. Also, we expect that the cost of hydrogen vehicles will drop as volume grows. Counteracting this, there may be a purchase price government subsidy (such as is presently the case for hybrid vehicles) which could decrease as sales of hydrogen vehicles increased. In the present simulation, we incorporate these three factors into a single volume-dependent term, namely the percentage of all drivers who own hydrogen vehicles. Depending upon its sign, this term can add an element of either positive or negative feedback.

Offsetting these assumed benefits are the two drawbacks of possible lack of convenient hydrogen stations near home or work, and worries about running out of fuel on non-local trips. The first factor is expressed mathematically as:

\[
Inconvenience = \left[ 8(0.25 + N_{\text{Home}})(0.5 + N_{\text{Work}}) \right]^{-1}
\]

where \( N_{\text{Home}} \) and \( N_{\text{Work}} \) are the number of hydrogen stations within a 3-cell distance of the agent’s home and job, respectively. Values for different numbers of home and work stations are shown in Table 1. The term is 1 for no stations at either location and rapidly approaches zero as the number of stations increases. The different additive terms for home and work reflect most people’s preference to refuel near home rather than work. (In both this expression and the one to follow, both the form of the equation and the numeric values of the parameters are clearly arbitrary. We have chosen them only as approximations reflecting our limited understanding of consumer behavior.)
We include a “worry factor” to account for possibly uncomfortably or prohibitively long distances between successive hydrogen stations on extended trips. Drivers (both hydrogen and conventional) monitor the locations of hydrogen facilities that they pass along their random trips. If the stations are spaced closely enough together, a driver’s worries about running out of fuel are diminished. A “worry factor” is calculated as the square of the distances between successive fuel stations passed when the distances exceed a threshold.

\[ WorryFactor = \sum_{\text{All trips}} (\text{distance between successive hydrogen stations} - \text{comfort zone})^2 \quad (2) \]

(The power of two reflects the simple observation that one’s worry about being stranded increases in a more than linear fashion as the fuel gauge approaches empty.) Note that for drivers of hydrogen vehicles, Inconvenience and Worry are actual; for conventional vehicle drivers they are potential. All these factors are summarized in the statement of the driver utility function \( U \):

\[ U = \text{FixedBenefitFactor} + \text{VariableBenefitFactor} \cdot \text{DistanceTraveled} + \text{VolumeFactor} - \text{InconvenienceFactor} - \text{WorryFactor} \quad (3) \]

Each term can be weighted as appropriate. For example, the weights of coefficients multiplying InconvenienceFactor and WorryFactor would reflect the relative weights of inconvenience and worry in a driver’s purchase decision. The utility function differs from driver to driver depending upon his location and travel distance from month to month. If the utility function is positive at the time when a driver is ready to purchase a new car, he buys a hydrogen vehicle; otherwise he purchases a conventional one.

The model used in this study differs in some significant ways from the one used for results reported in our earlier paper (Stephan, et al., 2004). We have extended the previous model to include suburb regions of high population and job density, and have been more precise in specifying to what fuel stations a hydrogen vehicle driver’s fuel budget is distributed. In the earlier model hydrogen fuel stations were restricted to expressway cell locations (i.e., within 0.5 miles of an expressway), and no distinction was made between sales made to vehicles being used for commuting and ones being used for “random” trips. A hydrogen fuel station, or potential hydrogen fuel station, was credited with a fuel purchase every time a driver of a hydrogen vehicle passed his station. These purchases were discounted based on the proximity of competitor stations in the same way they are here. The actual amount of fuel sold by a given hydrogen station in one time step (one month) was:

<table>
<thead>
<tr>
<th>Number of stations near home (( N_{\text{Home}} ))</th>
<th>Number of stations near work (( N_{\text{Work}} ))</th>
<th>Inconvenience</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0.33</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0.20</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>0.07</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>0.02</td>
</tr>
</tbody>
</table>
\[ \text{Fuel Sold} = \frac{\text{Total H}_2\text{Vehicle Miles}}{\text{Total Passes by all H}_2\text{ Drivers of All H}_2\text{ Fuel Stations}} \times \text{Eff. Passes} \]  

where “Eff.” (effective) denotes that passes were discounted for local competition.

In contrast, in this model a hydrogen fuel station can be located anywhere on the grid, though to participate in sales to vehicles on “random” trips the station must be located within 0.5 miles of an expressway. Commuting drivers buy their fuel only at fuel stations near their home or work, not en route. Purchases of fuel in a “random” trip are distributed equally among all stations (outside the home neighborhood) passed en route. The expressway fuel sold by a given station is:

\[ \text{Fuel Sold} = \sum_{\text{All H}_2\text{Drivers}} \sum_{\text{All trips of a given H}_2\text{ Driver past Station}} \frac{\text{Total Distance of Trip}}{\text{Eff. # H}_2\text{ Fuel Stations Passed on Trip}} \]  

The result is to take into account more precisely the effect of non-local competition. A driver following a route with many hydrogen fuel stations (even if spaced far enough apart that there is no local competition) will purchase less fuel at each station than if the route were sparsely populated with hydrogen stations.

**RESULTS**

Figures 2 and 3 show the initial display of Figure 1 after one month (one step), three years and 15 years of a transition where the net benefits of driving a hydrogen vehicle are substantially positive. Note that while hydrogen fuel stations can be located anywhere, in this case they have all chosen to locate on expressways to take advantage of non-commuter traffic. There is a particular concentration along the approach roads to the attraction, which is the destination for 5% of random trips. Figure 4 shows the time dependence of the percentage of drivers who have switched to hydrogen vehicles, the number of hydrogen fueling stations, and the fuel sales per station. The transition is substantially complete after about 10 years, with about 70% of drivers having switched to hydrogen and the number of hydrogen stations having grown from a starting value of 11 to 60. There is still slight growth for another 10 years. Note that the sales volume per station has remained relatively steady. This is because in most cases when the sales volume of a station in a given cell (indicated by the size of the square) rises much above average, competitor stations spring up in nearby cells to share the business. An exception example is the station at the intersection due east of the attraction. A competitor locating north of that station would not get any business from the majority of drivers coming from the south.
Figure 2  The distribution shown in Figure 1 after the first step of the simulation. The areas where there is a potential for hydrogen fuel sales are shown in green, darker shades indicating higher potential.

Figure 3  The distribution after 3 years and after 15 years.

Figure 5 shows the average Fixed and Variable Benefits, Worry, and Inconvenience for all drivers and for hydrogen vehicle drivers. Notice that, as expected, the negative factors decrease over the years as more hydrogen stations are built, and that they are smaller for hydrogen vehicle drivers than for overall drivers. The latter is particularly true for Inconvenience, which has been weighted in this example to be the dominant consideration for drivers.
Figure 6 contrasts the growth of hydrogen vehicles shown in Figure 4 with that resulting when conditions are changed in two ways. In “Lower Benefits” the benefits to the driver are cut by about 40% (e.g., through lower subsidy of vehicle and fuel purchase costs). Not surprisingly, the ultimate penetration of hydrogen vehicles is lower (60% vs. 74% after 20 years). Additionally, though, the growth rate is much slower at the beginning: after 10 years, penetration in the second case is less than half that of the first. In the “Judicious Placement” case we have again cut the benefits but this time attempted to place the initial stock of 11 hydrogen fuel stations in a “judicious” (though probably not optimum) fashion based on observing their placement at the end of the previous runs. With this procedure, the ultimate penetration recovers to 70% and the initial growth rate is much higher than before. Indeed, under some circumstances the initial growth rate can be than that for a system with ultimately higher penetration. Correct initial placement of hydrogen fuel stations thus appears key to a successful hydrogen transition.

In this and all following figures (except Figures 5 and 8) the same ordinate scale represents percentage of hydrogen drivers, absolute number of hydrogen stations, and arbitrary units for fuel sales/station.
Figures 7 and 8 show a simulation run identical to that of Figures 4 and 5, but with the Worry weighting coefficient increased and the Inconvenience coefficient decreased to make Worry the dominant consideration. In contrast to the previous case, the transition is complete – virtually all drivers have hydrogen vehicles at the end of 15 years. However, in this case the results are very sensitive to the positive benefit factors. Whereas before a 40% cut in benefits slowed the transition and reduced penetration by 74% to 60%, here a 5% cut reduces it from 100% to 20% (Figure 9). Why should this be? In the former case the decision to switch to hydrogen depended markedly on the driver’s location. If there happened to be a hydrogen station near him, his Inconvenience was low; otherwise it was high. In the present case a driver’s decision is more heavily weighted towards the Worry generated in making random trips. Thus all drivers are in more similar circumstances, and if one driver finds it beneficial to switch the rest are more likely to reach the same conclusion. While in reality drivers will have individual situations and preferences that we have so far not taken into account, there nevertheless appears to be a lesson that can be drawn. Hydrogen vehicles marketed towards commuters (for whom Inconvenience is presumably a prime consideration) may face less risk of an utter failure but also less chance of a complete conversion to hydrogen than if they are marketed towards consumers for use in longer trips.

![Figure 7](image1.png)  
**Figure 7** Transition of Figure 4 with different weighting coefficients.

![Figure 8](image2.png)  
**Figure 8** Worry and Inconvenience factors.

While reducing the benefits at the outset can “kill” a transition like that of Figures 7 and 9, gradually reducing a subsidy as the transition gains momentum may be quite tolerable. This effect is illustrated in Figure 10, similar to Figure 7 except that the subsidy has been reduced as a function of penetration, reaching zero at roughly 60% penetration. This results in an ultimate penetration of just over 50%. (Had the subsidy been reduced even slightly at the beginning, the transition would have failed, with all the initial seed stock of vehicles and stations quickly disappearing.)

The presence or absence of suburbs does not appear to have a large effect. Figure 11 shows the simulation of Figure 4, but with no concentrations of drivers in suburb regions. Under these conditions the same ultimate penetration is achieved, but the transition takes more time. This effect will be explored more fully in future work.
CONCLUSIONS

Our work so far cannot be considered a complete picture of reality. The model contains only two types of agents, and the Driver agents in particular do not contain the many variations characteristic of real drivers. Also, our model does not approach the level of true economics in describing agent behavior. Nevertheless, we feel the responses of the model to variations in parameters are of interest and may be helpful in guiding the development of more sophisticated models. We find that the initial growth period of the transition is critical – the ultimate success or failure of the transition is determined in the first few years. Correct initial placement of hydrogen fueling stations is important and may make the difference between success and failure. Interestingly, the relative importance that consumers place on being able to fuel their vehicles near home or work as opposed to concerns about finding fuel in longer trips greatly influences the sensitivity of the transition to vehicle and/or fuel subsidies.
References


Lempert, R. J., Popper, S. W. and Bankes, S. C., 2003, Shaping the Next One Hundred Years: New Methods for Quantitative Long Term Policy Analysis, Rand Pardee Center, Santa Monica CA.


