FINAL REPORT

HYDROGEN DELIVERY MODEL FOR H2A ANALYSIS:
A SPREADSHEET MODEL FOR HYDROGEN DELIVERY SCENARIOS

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A SPREADSHEET MODEL FOR HYDROGEN DELIVERY SCENARIOS

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INTRODUCTION

As part of the H2A effort, we are developing models of hydrogen delivery systems, for use of hydrogen as a vehicle fuel. The delivery system is defined as all the equipment between the hydrogen production plant and the hydrogen refueling station. This includes hydrogen compression or liquefaction, hydrogen storage, and hydrogen distribution in trucks or pipelines. The goals of the H2A delivery group are to: 1) develop a database on delivery system component cost and performance; 2) develop delivery scenarios for set of well defined "base cases" that span major markets and demand levels ,and 3) estimate delivery costs for these base cases. In this report for NREL contract No. SCM-2-32067-01, we describe work related to goal 2). In particular, we have developed an EXCEL spreadsheet model of various hydrogen delivery scenarios. The spreadsheet is included as a separate file.

HYDROGEN DELIVERY SCENARIOS

The design and cost of a hydrogen delivery system depends on the total demand, the amount of hydrogen dispensed at each refueling station, the distance from the central hydrogen plant to the stations, and the amount of storage is needed to handle variations in demand. We develop scenarios for several delivery "base cases", encompassing three types of markets that are likely to be important in a future hydrogen economy (metropolitan, interstate and rural) and four levels of market penetration (1%, 10%, 30%, and 70%). Our delivery base cases are summarized in Table 1.

Table 1. Delivery Base Cases

Market Type	Early Fleet Market (1%)	General Light Duty Vehicles: Market Penetration		
		Small (10%)	Medium (30%)	Large (70%)
Metro	X	X	X	X
Rural			X	
Interstate			X	

Various delivery modes could be used to serve the demand for each base case. We consider three delivery modes:

- Delivery Cost by Compressed Gas Truck
- Delivery Cost by Liquid H2 Truck
- Delivery Cost by Gas Pipeline

The goal is to define a configuration for each base case and each delivery mode, as a basis for calculating the delivered hydrogen cost.

In this work, we will analyze costs for "pure" delivery modes (e.g., all the hydrogen is delivered via one mode), recognizing that this is a simplification, and it is possible that several delivery modes plus forecourt production might be used simultaneously.

In the future, we will also analyze some these cases for a more realistic mixed mode of delivery. For example; pipeline delivery to a terminal located at a city boundary and truck distribution to the refueling stations in the city.

DEFINING THE METRO BASE CASES

In our analysis of hydrogen use in metropolitan areas we make the following assumptions:

- **Consider 2 city sizes (100,000, 1 million).**
  - Average population density over entire city = 700-1200 people/km^2 (the city center has a higher density, suburbs have a lower density)
  - Average # light duty vehicles person =0.5-1.2 (#LDV/person is lower in the city center).

- **Consider two hydrogen refueling station sizes : 100 kg/d and 1500 kg/d**
  - Refueling stations are assumed to operate at 70% capacity factor, so the average amount dispensed per station is 70 kg./d, 1050 kg/d for the small (large) station
  - For a given case, it is assumed that all stations are the same size (e.g. either all the stations are 100 kg/d or all the stations are 1500 kg/d)

- **Customer convenience/station "coverage" and selecting a station size**
  - After market introduction into mass light duty vehicle (LDV) markets, H2 stations must be convenient enough so that # of H2 stations >10% x (# of current gasoline stations).
  - In selecting which size station to use, it is assumed that the number of hydrogen stations is somewhere between 10% and 100% of the number of gasoline stations today. It is assumed that each gasoline station today serves an average fleet of 2000 LDVs (each H2 station serves between 200 and 2000 H2 cars.

- **Siting refueling stations**

- Refueling stations are sited within the city according to an idealized model of a city, as described below.

- **Consider a range of central H2 plant sizes from 50,000 – 500,000 kg/d (~20-200 million scf H2/d)**

- **Location of the central H2 plant relative to the refueling stations**
  - The central hydrogen plant is located 100 km from the city, if the city-wide demand is << 50 tonne/day (e.g. it is assumed that the central plant is shared among several cities).
  - If the demand > 50t/d, the hydrogen plant is located at the "city gate" (the city has its own "dedicated" hydrogen plant.

- **Hydrogen storage**
  - Hydrogen storage is needed to handle fluctuations in demand, and to assure reliability of supply.
  - The hydrogen storage terminal is located at the central hydrogen plant. It is assumed that 6 days of LH2 storage (for LH2 truck delivery) or 2 days of compressed hydrogen storage would be needed (for pipeline delivery).
  - The compressor (for compressed gas storage) or liquefier (for LH2 storage) are sized to match the hydrogen plant output.
  - Trucks are loaded at the hydrogen terminal at the central plant

- **Assumed Hydrogen use in vehicles**
  - For mass light duty vehicle markets, average hydrogen consumption per vehicle = 0.72 kg/day (Based on a light duty hydrogen vehicle driven 14,950 miles/yr with an fuel economy of 57.5 mpg equivalent. This fuel economy was used in the 2050 study)

  - For early fleet vehicles, average hydrogen consumption per vehicle = 0.96 kg/day (Based on a light duty hydrogen vehicle driven 20,000 miles/yr with an fuel economy of 57.5 mpg equivalent)

- **We assume that there are 0.89 (large city) - 1.16 (small city) light duty vehicles per person, which is typical for the US.**

DESIGNING THE DELIVERY SYSTEM CONFIGURATION FOR EACH METRO BASE CASE AND DELIVERY MODE

Here we describe the system configuration, including equipment sizes, number of stations, location of stations for each metro base case(1%, 10%, 30%, 70% market penetration) and each delivery mode (compressed gas truck, liquid hydrogen truck, pipeline).

Idealized model of a city

To model a metro area, we assume an idealized "circular" or "square" city, with a population density that is higher in the central core and lower in the outlying regions.

The city of 1 million people is assumed to have an average population density of 795 people/km^2 or an area of 1258 km^2 (radius of 20 km)

The city of 100,000 people is assumed to have an average population density of 654 people/km^2 or an area of 155 km^2 (radius of 7 km)

Truck delivery in the city is assumed to take place to a uniformly distributed group of equally sized stations (the number will be estimated below), as shown in Figure 1a

Pipeline delivery is assumed to take place along a "ring" structure of gas mains as shown in Figure 1b. For large numbers of stations, the ring might have "service line" branches leading away from the mains to additional stations. Alternatively, a "spoke"-like structure could be used for pipelines.

METRO SIZING AND SITING CALCULATIONS

Calculate total hydrogen demand in the city:

Total H2 demand in city (kg/d)
= #people in city x #LDVs/person x fraction H2 LDVs x H2 use/vehicle(kg H2/d/LDV)

Select refueling station size (100 or 1500 kg/d capacity)

For customer convenience, we need to provide H2 at some number of stations equal to at least 10% of current gasoline stations. Today there is about one gasoline station for every 2000 light duty vehicles.

The number of gasoline stations
= #people in city x #LDVs/person/ (2000 LDVs/gasoline station)

To find the number of hydrogen stations for each station size, divide the total H2 demand in the city by the H2 station average output (70 kg/d or 1050 kg/d). Then check to see how this compares to the number of gasoline stations today. Select a H2 station size that gives an reasonable amount of "coverage"

All other considerations being equal the larger size station should give a lower delivered hydrogen cost.

For all cases, except the 1% market penetration case, the 1500 kg/d station is preferred. For the 1% market penetration case, the 100 kg/d station is used.

Calculate number of refueling stations in city

To find the number of stations divide the total city hydrogen demand by the average amount of hydrogen dispensed per station (accounting for the 70% forecourt capacity factor)

For the 10%,30% and 70% market penetration cases:
H2 stations = H2 demand in city/1050 kg/d

For the 1% market penetration cases:
H2 stations = H2 demand in city/70 kg/d

Locate hydrogen production plant (shared or dedicated)

If the hydrogen demand in the city << 50 tonne/d, locate the H2 plant 100 km from the city.

If the hydrogen demand in the city > 50 tonne/d, locate the H2 plant at the edge of the city ("city gate")

Estimate amount of storage needed to assure reliability

For LH2truck delivery, the storage needed is 6 x the city H2 demand per day.
For pipeline delivery, the storage needed is 2 x the city H2 demand per day.

METRO DELIVERY SYSTEM DESIGN

Metro Truck Delivery Cases

Station location and truck delivery distances using an idealized model of a city

To find truck delivery distances, we estimate where stations are located relative to the hydrogen plant. An idealized model of a city is used.

City area (km2) = #people in city/population density (people/km2)

For truck delivery, , with stations located evenly around the city., we model the city as a square. Each station serves an equal area

Area per H2 station (km2) $\simeq$ City area (km2)/# H2 stations

The average distance between stations (km) ~ [Area per H2 station (km2)] $^{0.5}$

$\simeq$ [City area (km2)/# H2 stations] $^{0.5}$

If stations are located along a rectangular grid, the average round-trip distance from the hydrogen plant to a refueling station can be shown to be (see Figure 1a):

Average round-trip distance from H2 plant to H2 refueling station
= 2 x distance(H2 plant to city gate) + 1.5 x [City area (km2)] $^{0.5}$

Truck distribution for metro areas

In this section, we describe metro truck delivery scenarios for hydrogen, corresponding to the metro area delivery cases. We assume that the distribution system based on "trucked-in" hydrogen is roughly analogous to the gasoline system today.

Today's Gasoline Distribution System:

- Gasoline truck capacity = 35,000 liters or about 25 tonnes gasoline/truck
- Gasoline refueling stations (2000 light duty vehicles served per gasoline station)
- Gasoline storage terminals (100 refueling stations served per terminal)

Liquid Hydrogen Truck Delivery System

- Liquid Hydrogen truck capacity = 4000 kg H2/truck (large truck, cab + trailer)
- = 400 kg (small truck)
- # LH2 refueling stations (see calculation of number of stations above)
- It takes 3 hours to load and 3.5 hours to unload a LH2 truck. LH2 boil-off losses are 6% during loading and unloading.

- Compressed Gas Hydrogen Truck Delivery System
- Compressed gas tube trailer H2 truck capacity = 300 kg H2/truck
- In all cases, we assume that the truck delivers its entire load to one station (rather than making multiple stops).
- Full Tube trailers are "dropped" off at the station, and empty ones picked up to be recharged at the H2 storage terminal.
- It takes 3 hours to load a compressed gas trailer, 1 hour to drop it off at the station and pick up an empty trailer.

Hydrogen storage terminal

- We assume that the H2 storage terminal is located at the central hydrogen production plant, although it could be placed at another convenient location within a large city.
- The size of the hydrogen storage terminal is assumed to be 2 days production from the central plant for pipeline delivery, and 6 days storage for LH2 delivery. These numbers were estimated from conversations with industrial gas suppliers on storage capacity needed to provide adequate "back-up" capacity for plant outages.
- For Liquid hydrogen storage, we assume the liquefier is sized to match the output of the H2 plant. Electricity use for liquefaction is assumed to be 13.5 kWhe/kg H2.

- For gaseous hydrogen storage, we assume the compressor is sized to match the output of the H2 plant.

Hydrogen compression energy use
0.6-0.7 kWhe/kg H2 300 ->1000 psi, 70-80% adiabatic eff 1.5-1.7% energy in H2
2.6-3.6 kWhe/kg H2 100->7000 psi, 6.6-9.1%

In Table 2, we compare truck delivery for gasoline, liquid hydrogen and compressed gas hydrogen.

Table 2. Comparison of Truck Delivery Systems for Gasoline and Hydrogen

	Gasoline today	LH2 Large refueling station	LH2 small refueling station	Tube Trailer small refueling station
Truck capacity	35,000 liters or 25 tonnes gasoline	4000 kg H2	400 kg H2	300 kg H2
Refueling station size	2000 LDVs /station =3290 gal/day 12,400 liter/day	1500 kg H2/d	100 kg H2/d	100 kg H2/d
#Truck deliveries per station	35,000/12,400 ~ 3 =>1 truck every 3 days	4000/(1500) ~3 =>1 truck every 3 days	400/100 ~ 4 => 1 truck every 4 days	300/100 ~ 3 => 1 truck every 3 days

From Table 2, it is apparent that tube trailer delivery would not be practical for the 1500 kg/d refueling station. Compressed gas tube trailers are a good match for the 1% market penetration case, but are not considered for market penetrations of 10% or higher

Truck travel time for one roundtrip from H2 Plant to Station and return

Truck trip time = load time at Central H2 plant terminal + travel from H2 plant to station + unload time at station + return to central H2 plant

If the truck travels at 70 km/h between the H2 plant and the city, and 40 km/h within the city

Truck trip time
= Ave travel distance highway/highway speed + ave. travel distance city/city speed
+ load time + unload time

Number of trucks needed to serve a certain demand in a city

If the trucks operate 24 hours/day,

trips/day/truck = 24/Truck trip time

The amount of hydrogen delivered per day per truck (kg/d/truck)
= Truck load size x #trips/day/truck

The number of stations served.day = # truck trips per day.

days between truck visits to station = truck capacity/H2 dispensed per day/station

trucks needed = # stations in city/# days between visits to station

For compressed gas trucks, trailers are left at each station. Each cab is attached to a trailer. Plus an equal number of trailers should be at the terminal ready to be picked up the cabs. A few spare trailers (=10% of the total number of trailers) are available for back-up.

Total number of trailers =
2 x #cabs + #stations + spares (=10% of total)

In Table 4, we summarize the design and cost parameters for various metro demand/delivery scenarios.

Metro Pipeline Delivery Cases

Pipeline configurations for cities are estimated using models developed by researchers at Argonne National Laboratory. Sample pipeline layouts are shown in Figure 1b.

Delivery Cases Analyzed in Detail

From the calculations above, we were able to eliminate certain possibilities. Compressed gas trucks are considered only for 1% market penetration. Pipelines are considered only for market penetrations of 10% or more.

Table 3. Delivery Base Cases with Modes Analyzed
(CT = compressed gas truck; LT = LH2 Truck, P =pipeline)

Market Type	Early Fleet Market (1%)	General Light Duty Vehicles: Market Penetration		
		Small (10%)	Medium (30%)	Large (70%)
Metro	X (CT,LT)	X (LT, P)	X (LT,P)	X (LT,P)
Rural			X	
Interstate			X	

DELIVERY SCENARIO SPREADSHEET

We have created an EXCEL spreadsheet summarizing the calculations presented above. Results are given for each of our base cases in Table 4.

Table 4.

	Small City 100,000 people Area =155 km^2 City radius = 7 km				Large City 1 million people Area = 1258 km^2 City radius = 20 km			
	Fleet 1%	10%	30%	70%	Fleet 1%	10%	30%	70%
City H2 Demand tonne/d	1	8.3	25	58	9	63	191	446
H2 Station Capacity (kg/d)	100	1500	1500	1500	100	1500	1500	1500
Ave H2 dispensed/sta kg/d	70	1050	1050	1050	70	1050	1050	1050
# H2 Sta.	16	8	24	56	122	61	183	426
Coverage= #H2 sta/ # gasoline sta today	0.28	0.14	0.41	0.97	0.27	0.14	0.41	0.96
Central H2 plant	shared	shared	shared	dedicated	shared	dedicated	dedicated	dedicated
Distance from H2 plant -> city km	100	100	100	0	100	0	0	0
Ave. # km between H2 sta in city	3.1	4.4	2.5	1.7	3.2	4.5	2.6	1.7
Average roundtrip distance traveled by truck from plant to station (km)	216	219	219	19	239	53	53	53
Comp gas trucks/ trailers	2/22	-	-	-	13/ 165	-	-	-
LH2 Trucks	2	2	5	7	11	7	21	48
Pipeline length km	-	40	68	121	-	293	525	980

Configurations for each case are sketched in the spreadsheet, showing equipment sizes, and hydrogen flows.

FUTURE WORK

Once the delivery system design is specified, the economics of hydrogen delivery will be estimated using the data from the Delivery Components spreadsheet to find a levelized cost of delivery ($/kg) and to conduct a cash flow analysis. For each base case in Table 1 the goal is to create a separate EXCEL Workbook where the delivery cost is estimated for various delivery modes.

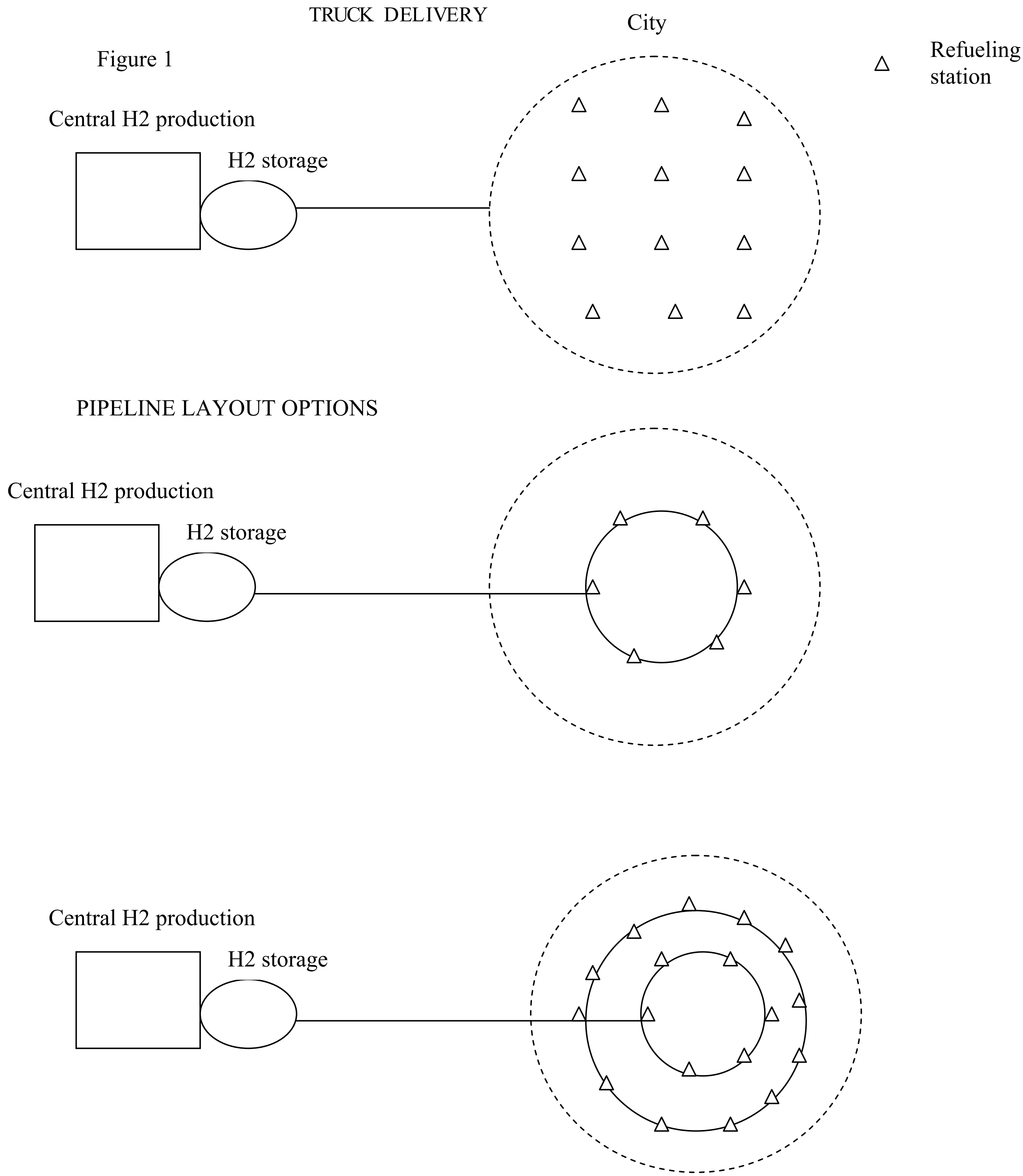
POSSIBLE EXTENSIONS OF THIS ANALYSIS

As we have formulated the analysis, the delivery infrastructure will be designed for a **static** demand. That is, we assume that demand does not change over the lifetime of the delivery system equipment (~20-30 years). This is equivalent to looking at cases where the ultimate market penetration of hydrogen is 10%, 30% or 70%.

This simplified, static approach avoids the complexities of doing a full, dynamic transition analysis, where the delivery system changes over time to meet a growing demand. Another possible advantage of doing static analysis is that it may be easier to understand how costs depend on various factors. However, a static analysis is limited because it probably won't reflect the kind of delivery system that would evolve in response to any of the demand scenarios in the Appendix. In a dynamic analysis, we would expect that supply would change considerably over time, and a mix of delivery modes might be present. The delivery system layout and cost might be quite different in a static analysis for 10% market penetration, compared to a dynamic transition analysis, where the system passes through 10% market penetration rapidly on the way to 100% penetration (e.g. President's Initiative case). **The results of our static analysis should not be too broadly construed as representing time points or "snap-shots" along the demand scenarios.**

The members of the delivery team felt that there is value in looking at static cases. (In particular, we speculated that results of a static analysis for the 1% and 100% market penetration cases might be fairly close to what would be found in a dynamic analysis.) However, it is important to stress the limitations of the present analysis as compared to a full systems analysis of a transition. Conducting full transition analyses should be a high priority as a follow-on to this work.

Figure 1


TRUCK DELIVERY
City
Refueling station
Central H2 production
H2 storage
PIPELINE LAYOUT OPTIONS
Central H2 production
H2 storage
Central H2 production
H2 storage