# HYDROGEN DELIVERY USING ALTERNATIVE HYDROGEN CARRIERS: ANALYSIS AND RESULTS

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## 1. Introduction

A great deal of research has sought to identify or develop on-board hydrogen storage materials and methods that have the ability to store hydrogen more efficiently than compressed gas or liquid tanks. The gravimetric and volumetric densities of compressed or liquid hydrogen do not meet the technology development goals set by the Department of Energy's (DOE) Vehicle Technologies Program. The DOE goals are rooted in the practical constraints that limit the size and weight of on-board fuel storage. As a result, researchers are evaluating the potential for alternative hydrogen carriers to meet the DOE on-board storage goals. Potential alternative hydrogen carriers include metal hydrides, chemical hydrides, high surface-area carbon sorbents and liquid-phase hydrocarbons. Practical constraints limit the size and weight of hydrogen storage systems that can be used on-board vehicles. These limitations are illustrated by The Department of Energy's Vehicle Technologies Program technology development goals for on-board hydrogen storage. The DOE goals are shown below in Table 1.

| On-Board Storage Goals | 2010 | 2015 |
|---|---|---|
| Gravimetric Energy Density (kWh/kg) | 2.0 | 3.0 |
| System Weight Percent Hydrogen | 6% | 9% |
| Volumetric Energy Density (kWh/liter) | 1.5 | 2.7 |
| Storage System Cost ($/kWh) | $4.00 | $2.00 |

**Table 1: DOE Vehicle Technologies Program Hydrogen Storage Goals [1]**

While these alternative hydrogen carriers have the potential to provide on-board storage, alternative hydrogen carriers may also be used to improve the efficiency and cost of hydrogen delivery. Certain hydrogen storage technologies may not meet all of the requirements for use on-board vehicles, but hydrogen delivery has less restrictive requirements regarding volumetric and gravimetric capacity. As a result, technologies that fail to meet the on-board goals may still be viable mechanisms for hydrogen delivery.

For the purposes of this analysis and in accordance with H2A assumptions, hydrogen delivery is defined as the process of transporting hydrogen from a hydrogen production facility to the fueling station. In cases where chemical processing is required to store hydrogen using an alternative carrier, those processes are evaluated as a part of hydrogen delivery.

This paper attempts to address the possibility that alternative hydrogen carriers could serve as viable hydrogen delivery options. Given the variety of alternative hydrogen carriers and the numerous hydrogen loading processes associated with each carrier, it is difficult to make definitive conclusions for each specific material or material type. (*Note: the specific process of "loading" a hydrogen carrier depends on the material type, but potential process types include adsorption, hydrogenation, or multi-step chemical reactions such as the Brown-Schlesinger used to manufacture sodium borohydride. For simplification, unless referencing a specific process, this paper will refer to the processes of adding and removing hydrogen from the carrier as "charging" and "discharging."*). Unlike hydrogen compression or liquefaction, the process of charging and discharging an alterative carrier material can require complex processes that can add cost and complexity to the overall delivery system. In many instances there are multiple processing options available for each carrier material which can make a simple quantification of cost and energy-use far more difficult. For example, sodium borohydride can be reprocessed through a number of different reactions, each with unique energy and material requirements. As a result, it is difficult to easily assess the cost of using sodium borohydride as a delivery mechanism. Further complicating matters is the potential for new or improved processes that can change the overall economics of a particular carrier option. Such developments could make non-viable carriers an economically available solution.

In light of these concerns, this analysis seeks to identify the pathways (liquid truck, solid-state truck, pipeline, etc) in which various carriers can be used for hydrogen delivery, provide an analytical tool that accounts for all of the costs associated with the various carrier pathways, establish which characteristics contribute significantly to the delivery cost, and provide acceptable ranges for those characteristics.

## 2. Alternative Hydrogen Carriers

This analysis focuses on four types of alternative hydrogen carriers may be viable hydrogen storage mechanisms. Table 2 provides lists the types of materials considered in this analysis and highlights example materials and some of their unique characteristics.

| Material Type | Example Material | Storage State | $H_2$ Discharge |
|---|---|---|---|
| Metal Hydrides | Sodium Alanate | Packed Powder | Endothermic Desorption |
| Chemical Hydrides | Sodium Borohydride | Aqueous Solution | Catalyzed Exothermic Hydrolysis |
| Liquid-Phase Hydrogen Carrier | N-Ethylcarbazole | Liquid | Endothermic Dehydrogenation |
| High Surface Area Carbon Sorbents | AX-21 | Low-Temp Solid Powder | Endothermic desorption |

**Table 2: Hydrogen Carrier Classes and Example Materials**

This paper will not provide a detailed discussion of each carrier type, as research into unique material characteristics was not a focus of this analysis. Specific material characteristics that affect the potential use as a delivery mechanism will be identified in relevant sections.

## 3. Delivery Mechanisms

Before evaluating the cost of delivering hydrogen with alternative hydrogen carriers, the specific pathways must be defined. Throughout the process of identifying possible pathways, certain assumptions must be made regarding how different material types may be used in a delivery infrastructure. These assumptions are presented throughout the report, where relevant. To determine the available pathways, the DOE H2A Delivery Analysis was used as a baseline, as it specifies multiple methods to deliver compressed or liquid hydrogen. The H2A Components Model – one of the analytical tools developed as part of the H2A Delivery Analysis project – was modified to represent the various available pathways for alternative hydrogen carriers. The existing version of the H2A Components model evaluates three different delivery pathways:

- **Hydrogen Tube Trailer**: Compressed hydrogen is transported in high-pressure tubes which are dropped-off at the fueling station and used as on-site storage. Delivery includes picking-up an empty trailer and replacing it with a full trailer.
- **Liquid Hydrogen Trailers**: Liquid hydrogen is transported in cryogenic truck trailers. The liquid hydrogen is off-loaded into liquid storage tanks at the fueling station. Unlike compressed hydrogen tube trailer delivery, the trailer is not left at the fueling station.
- **Compressed Hydrogen Pipeline**: Hydrogen is distributed to fueling stations through a pipeline network that operates at low pressure (1,000-300 psi). To avoid large upstream demand spikes, hydrogen is supplied continuously to the fueling stations and compressed to high-pressure (6,250 psi) for immediate vehicle fueling, or compressed to 2,500 psi for storage in buffer storage tanks.

It is clear that each of these delivery pathways will require different types of components and will be evaluated with different sets of assumptions.

To specify the pathways that could employ alternative hydrogen carriers, it is necessary to evaluate the limitations of each carrier-type defined in Section 2 and determine what types of delivery systems could work within these limitations. The first differentiating feature is whether a carrier was a liquid or could be transported in a liquid form. Liquid carriers generally fall into one of three categories: pure liquids, solutions and slurries. This analysis assumes that all liquid carriers can be transported either in trucks or liquid pipelines. Specific carriers may require different assumptions, components, or processes, but given the proper inputs, these carriers can be evaluated for both the truck and pipeline mechanisms. When transporting via truck, it is assumed that liquid carriers can be rapidly off-loaded at the fueling station and stored in on-site storage tanks. In most cases, pure liquids are easier to transport than solutions or slurries, as there is no risk of the hydrogen carrier separating from the solvent. Certain potential carriers, such as the dehydrogenated phase of n-ethylcarbizole, have melting points that are above the ambient temperature, making it necessary to insulate, and potentially heat, the pipelines and trucks that return the carrier to the reprocessing facility.

Solid carriers have limitations that will require them to be transported via a slightly different pathway. In the case of solid materials such activated carbon, it is assumed that the material can only be transported in a truck trailer and that the material remains in the trailer at all times. While it may be possible to off-load and store a solid carrier material, there are a number of practical difficulties associated with handling solids (usually in the form of a powder). As a result, the off-loading of hydrogen carrying solids is not considered in this analysis. All solid materials are assumed to remain permanently on the trailer. When employing a solid transport material that must remain in the trailer, hydrogen can be delivered via two different pathways: 1) the trailer can be dropped-off at the fueling station and used as on-site storage, or 2) the hydrogen can be off-loaded from the trailer and stored in low-pressure storage tanks at the fueling station. For many solid-state carriers heat transfer is required to discharge the hydrogen from the carrier. The endothermic desorption processes required for activated carbon or metal hydride materials are good examples. As a result, it is assumed that heat exchange components are integral pieces of the delivery trailers, making them more expensive than conventional trailers. The heat source or sink will likely be off-board the trailer at the fueling station or reprocessing facility.

Given these initial assumptions the H2A Components Model was modified to evaluate the following delivery pathways:

- **Liquid Carrier Trailers**: Liquid carrier trailers transport pure liquids, solutions or slurries between a processing facility and the hydrogen fueling station. The liquid carriers are off-loaded at the hydrogen fueling station and either stored in tanks where the alternative carrier is delivered to the vehicle or the hydrogen is discharged at the fueling station and compressed hydrogen is delivered to the vehicle.
- **Solid Carrier Trailers**: Solid carrier trailers are assumed to permanently contain the carrier material. The charging/discharging of the carrier material occurs in situ. This often requires integral heat transfer equipment in the trailer, and will likely require and off-board heat source or sink. The model includes two options for delivery: 1) the trailer is dropped-off at the fueling station and hydrogen is desorbed over the demand period or 2) the trailer remains with the tractor and hydrogen is rapidly desorbed during

the delivery period and stored in low-pressure storage tanks at the fueling station.

- **Liquid Carrier Pipeline**: A two-pipe pipeline network is established to transport alternative hydrogen carriers from a processing facility to multiple fueling stations. Two pipes are employed so that charged and discharged material can be transported simultaneously. A single-pipe system that transports the charged/discharged materials at different times may be possible (similar to a plug-flow type pipeline that delivers different types of petroleum products), but was not considered in this analysis, as there are numerous flow management issues that add significant complexity to this type of system. As with the liquid truck pathway, the alternative carrier can be delivered to the vehicle or discharged at the fueling station.

The following sections outline the specific details of the evaluated transport pathways, and how those details were incorporated into a modified version of the DOE H2A Model.

## 4. General Truck Transport

It is highly likely that truck transport will be a primary method of transporting hydrogen stored in novel carriers. There are multiple types of delivery methods that utilize trucks as a delivery mechanism, including: liquid truck transport and solid-state truck transport. In addition, trucks can either be dropped off at fueling stations or a product (either hydrogen or the carrier material) can be off-loaded during a standard delivery stop. As a result, it is clear that there are multiple methods of truck delivery. Nevertheless, a metric that is important across all trucking methodologies is the quantity of hydrogen that can be delivered in a single truck trailer.

Truck capacity can be limited by either the overall volume or weight of the truck. While standards differ between states and types of roadways, typical maximum trailer dimensions are 8 feet wide and 53 feet long (75 $m^3$, assuming a cylindrical trailer), with a maximum overall GVW of 85,000 lbs (maximum cargo weight of 25,200 kg, not including the tractor). The cargo density that would yield the maximum volume and weight is approximately 336 $kg/m^3$. All of the carriers evaluated are significantly denser than 336 $kg/m^3$. As a result, the capacity of the trucks is limited by the weight, not the volume of the material. This limitation makes the gravimetric hydrogen capacity (referred to as the material weight percent) a very important metric. Figure 1, below illustrates the relationship between material weight percent and overall capacity, in relation to conventional carriers.

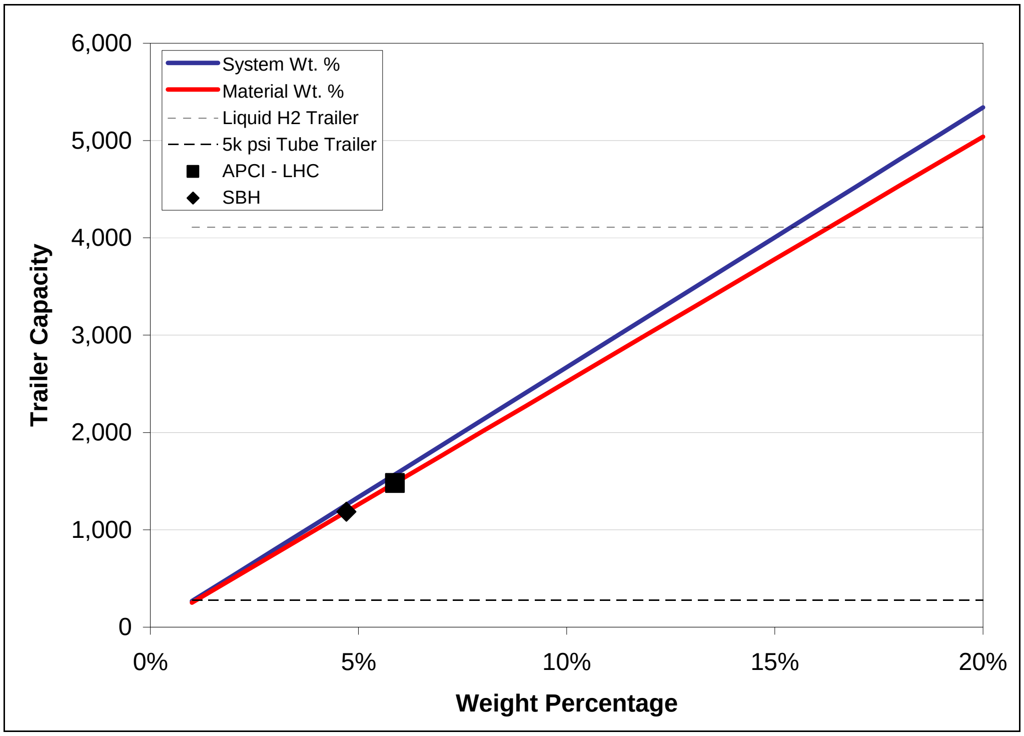


**Figure 1: Alternative Hydrogen Carrier Truck Capacity**

Figure 1, illustrates the overall hydrogen capacity as a function of weight percentage. Two types of weight percentage are shown: material weight percent and system weight percent. The material weight percent refers to the amount of hydrogen that can be stored in a material. It is assumed that this material can be transported in a standard stainless steel trailer similar to a standard gasoline trailer. The system weight percent considers not only the weight of the carrier material but also the weight of the tank and any components that must be included to charge or discharge the hydrogen. For example, AX-21, the low-temperature carbon adsorbent requires a heavily insulated, high-pressure vessel that has integral heat transfer tubes to facilitate the charging and discharging process. Given that this system is far more substantial than a typical gasoline tank trailer, the weight percent for AX-21 should be given as a system weight percent, not a material weight percent. The cargo weights used to determine the overall capacity are 25,200 kg for material only, and 27,200 kg for the entire system (assumes that the standard gasoline trailer weighs approximately 3,300 lbs. not including the glider). Figure 1 also includes the capacity for some promising alternative carriers.

It is evident that some carriers have the potential to offer better overall capacity than tube trailers, but fall considerably short of the capacity of a liquid trailer. If this is the case, it is necessary that the alternative carriers offer some benefit beyond capacity, such as cost, energy-use, or ease of handling. This model attempts to quantify some of those metrics to allow for a more complete and consistent evaluation of the various alternative carriers.

## 4. Liquid Truck Transport

Alternative liquid hydrogen carriers include pure liquids, solutions, and slurries. Examples of these liquid carrier types are shown in Table 3.

| Carrier Type | Material Class | Example Material | Developer and Notes |
|---|---|---|---|
| Pure Liquid | Liquid Hydrocarbon | Ethylcarbizole | Develop by APCI;<br>Dehydrided melting temperature: 80 °C |
| Solution | Chemical Hydride | Aqueous Sodium Borohydride | Developed by Rohm & Haas/M-Cell;<br>Water-based solvent consumed in reaction |
| Slurry | Metal Hydride | Magnesium Hydride Slurry | Developed by SafeHydrogen;<br>Oil-based solvent |

**Table 3: Liquid Transport Materials**

This analysis assumes that in a delivery scenario all carrier types are loaded and off-loaded at the processing facility and fueling station. Unlike gasoline or diesel, the alternative hydrogen carrier is a reusable material, not a consumable fuel; therefore, it is necessary to transport charged carrier from the processing facility to the fueling stations and return discharged material from the fueling station to the processing facility. As a result, there is an unloading and loading process at each end of the transport leg. This analysis assumes that a single transport trailer can perform both operations.

After the charged carrier is off-loaded at the fueling station, it is stored in underground or above-ground tanks. If compressed hydrogen is to be delivered to vehicles, hydrogen discharge occurs at the fueling station. The method of discharge will depend, partially, on the material kinetics. This analysis, and the corresponding model, allow for two discharge options: steady-state or on-demand. These options are described below:

- **Steady-State Discharge**: In this case, the material kinetics is sufficiently slow as to necessitate a continuous flow of material through the discharge reactor. In periods of low-demand, the hydrogen being discharged will be stored in low-pressure (2,500 psi) storage tubes at the fueling station. The assumptions that define the capacity and cost of the compressor and low-pressure storage in the alternative carrier model are the same as the assumptions found in the H2A model of conventional pipeline-fed fueling stations. H2A assumes that fueling stations fed by pipeline accept hydrogen at a constant flow rate. The discharge reactor is sized to meet the average hourly demand at the fueling station.
- **On-Demand Dehydrogenation**: In this case, the material kinetics is fast-enough to discharge hydrogen at a rate necessary to meet the individual hourly demand at the fueling station. As a result of the on-demand discharge, there is no requirement for low-pressure storage, buffer storage at the fueling station. The compressor assumptions used in the alternative carrier model are the same as the assumptions found in the H2A model of tube trailer fueling stations. H2A assumes that the tube trailers can supply hydrogen to the compressor as needed. The discharge reactor is sized to have the same capacity as the forecourt compressor.

The details of the various hydrogen fueling station configurations are specified in Section 8, Fueling Stations.

For liquid carriers that are off-loaded at the fueling station, the material characteristics that most significantly impact the cost of the trucking portion of delivery are the material's capacity to carry hydrogen (weight percentage of hydrogen) and the capital cost of the trailer. The carrier material's hydrogen weight percent is directly effects the overall capacity of the trailer, as the total cargo weight is limited to approximately 25,000 kg based on standard highway requirements limiting the overall GVW to a maximum of 80,000 lbs. To determine the effects of these variables, a sensitivity analysis was performed using plausible ranges for the input parameters. The ranges selected for material characteristics and equipment costs are explained in Table 4.

| | | |
|---|---|---|
| **Hydrogen Weight Percentage** | 24% Solution $NaBH_4$ | 4.71% |
| | Ethylcarbizole | 5.88% |
| | 2015 DOE Goal | 9.00% |
| **Trailer Capital Cost** | Gasoline Trailer | $90,000 |
| | $cH_2$ Tube Trailer | $225,000 |
| | $LH_2$ Cryo Trailer | $625,000 |

**Table 4: Liquid Carrier Trucking Sensitivity**

Figure 2 illustrates the cost truck-delivery when employing a variety of liquid-phase alternative carriers. The results are presented as a function of hydrogen capacity and capital cost. Other assumptions such as transport distance and fuel economy, that are assumed constant for all liquid hydrogen carriers, are specified in Appendix A.

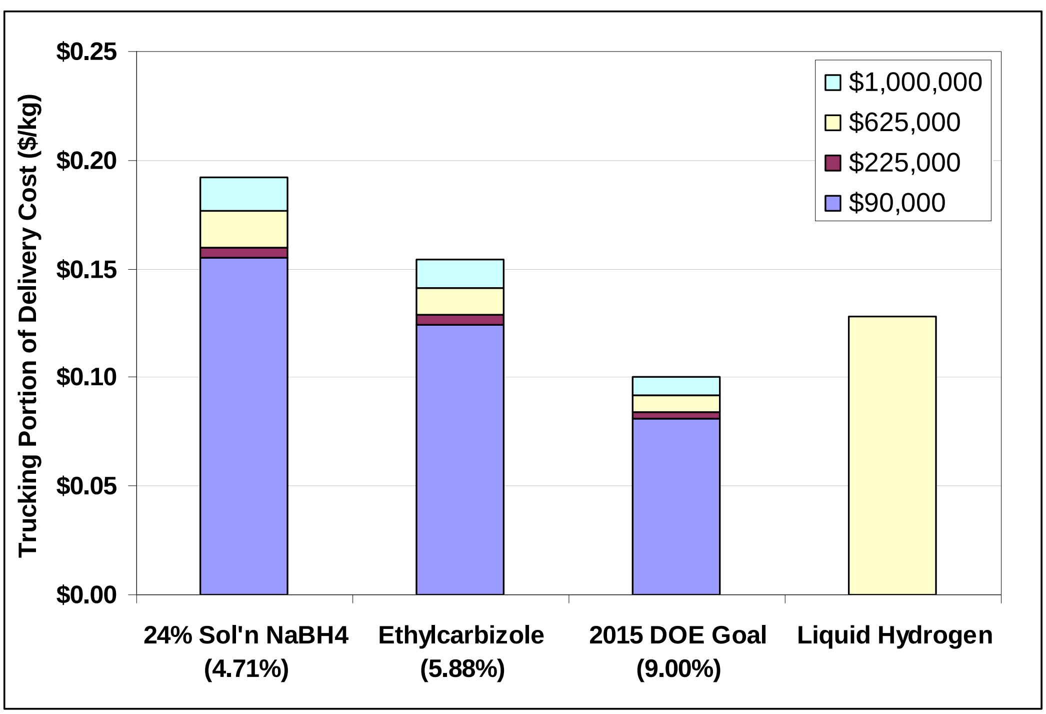

**Figure 2: Liquid Hydrogen Carrier Truckling Cost**

Figure 2 illustrates yields two important conclusions. First, the weight percent of hydrogen carriers has a far more significant impact than the capital cost of the truck on the cost of truck delivery. As shown in Figure 2, a 24% improvement in hydrogen capacity (4.71% to 5.88%) yields, on average, a 20% reduction in cost, whereas a 10-fold increase in trailer capital cost ($90,000 to $1,000,000) yields a cost increase of, on average, only 24%. Second, Figure 2 indicates that compared to the cost of trucking liquid hydrogen, these alternative carriers are competitive and have the potential to be less expensive than liquid hydrogen if the DOE technology goals are achieved.

Detailed cost breakdowns for the liquid carrier ethylcarbizole and liquid hydrogen are shown below in Figure 3.

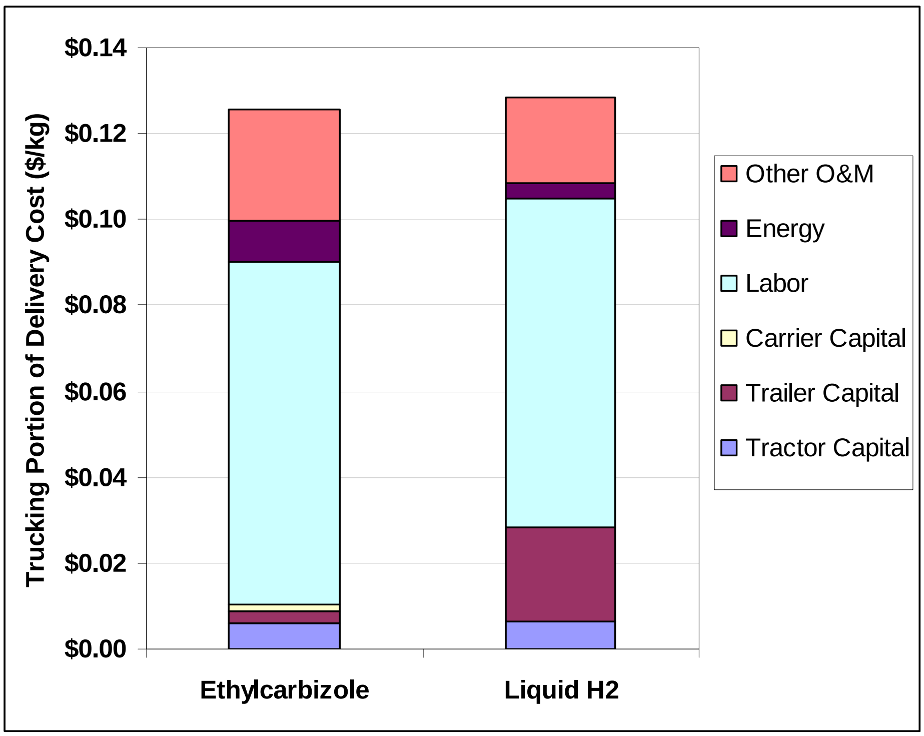


**Figure 3: Cost Breakdown of Ethylcarbizole and Liquid H2 Trucking**

Figure 3 illustrates that labor costs account for a significant portion of the total trucking cost. As a result, it is important to deliver the as much hydrogen as possible in each trip. This explains why the weight percent of hydrogen has such a large effect on cost, as it directly effects how much hydrogen a truck driver can deliver in a given period of time. The energy cost discrepancy illustrated in Figure 3 is created by the assumption that a truck carrying ethylcarbizole can make more deliveries in the course of the day due to a shorter drop-off time than a liquid hydrogen truck. This increased number of deliveries is offset by the lower capacity of a truck carrying ethylcarbizole.

The H2A-based model developed to support this analysis will allow technology developers to evaluate the cost of trucking various liquid hydrogen carriers on a consistent basis and compare those results against standard carrier options.

## 5. Solid-State Truck Transport

Unlike liquid hydrogen carriers that are off-loaded from the transport trailer at the fueling station, this analysis assumes that solid-state hydrogen carriers (usually in the form of powders) will remain on-board the transport trailers at all times. Solid-state hydrogen carriers include carbon sorbents and metal hydrides. Potential solid-state materials are listed in Table 5.

| Carrier Type | Material Class | Example Material | Developer and Notes |
|---|---|---|---|
| Solid-State | Carbon Sorbent | AX-21 | Low-Temperature Adsorbent; Argonne/NREL |
| Solid-State | Complex Hydride | Sodium Alanate | United Technologies |

**Table 5: Solid-State Transport Materials**

Unlike liquid carriers, there are multiple delivery options available when using solid-state carriers:

- **Trailer Drop-Off**: In this delivery scenario, a trailer is dropped-off at the fueling station and the discharge process takes place over the course of the demand period (~1-3 days). Trailers containing discharged material are picked up at the fueling station and returned to the processing facility. This delivery method is similar to tube-trailer delivery in that every station needs to have a trailer on-site in order to meet demand and the trailer serves as on-site storage.
- **Hydrogen Off-Load**: In this delivery scenario, the discharge process takes place during the delivery (<1 hr). This necessitates a carrier material with relatively rapid kinetics to facilitate the off-loading of hydrogen in a timely fashion. Off-loading hydrogen negates the need to have trailers at each fueling station, but will require low-pressure storage and a dedicated compressor at the fueling station.

In the trailer drop-off scenario, hydrogen will be discharged at the fueling station. This process can be steady-state or on-demand, as described in Section 4, Liquid Truck Transport. Because the solid-state material cannot be easily transferred on and off of the trailer, this material cannot be delivered to the vehicle, but it is possible for the same or similar materials to be contained in on-board storage tanks. In either case, the hydrogen must be discharged from the material at the fueling station. Fueling station details for a solid-state carrier are specified in Section 7, Fueling Stations.

The specific delivery scenario has a significant effect on the overall cost of delivering hydrogen using solid-state carriers. To determine the cost effect of the various scenarios, two carriers were compared: AX-21, a carbon sorbent and sodium alanate (NaAlH4), a complex hydride. Researchers have indicated that the kinetics of AX-21 is sufficient to allow for hydrogen to be desorbed rapidly, as would be required for a hydrogen off-load pathway. Given the rapid kinetics of AX-21, this analysis assumed that AX-21 would be employed in a hydrogen off-loading pathway. Despite this assumption, it is possible that AX-21 could be used in trailer drop-off scenario, but the low-temperature required may make it difficult to leave the trailer at the fueling station for long periods of time without the possibility of over-pressuring the trailer. The kinetics of sodium alanate is significantly slower and as a result trailers must be dropped-off at the fueling stations. Hydrogen discharge takes place over a longer period of time and at a constant rate. Details of the carriers analyzed are shown in Table 6.

| Variable | Material | Value | Notes |
|---|---|---|---|
| Hydrogen Weight Percentage | AX-21 at 150 bar | 4.60% | Temperature: 100 K |
| | AX-21 at 390 bar | 5.40% | |
| | Sodium Alanate, sys.* | 1.70% | Reactive material |
| | Sodium Alanate, max. | 5.60% | |
| Delivery Type | AX-21 at 150 bar | Off-Load | Rapid kinetics, LN2 requires to hydride |
| | AX-21 at 390 bar | Off-Load | |
| | Sodium Alanate, sys. | Trailer Drop-Off | 20 MJ/kg,H2 desorption energy req. |
| | Sodium Alanate, max. | Trailer Drop-Off | |

*Cannot deliver to 1,000 kg/day stations, insufficienct capactiy

**Table 6: Solid-State Carrier Trucking Sensitivity**

Figure 4 illustrates the per-kilogram trucking costs for the scenarios described in Table 6. The capital costs of the trailers used to transport solid-state carriers has not been sufficiently estimated by researchers or industry, therefore a range of options is shown. Of the trailer prices shown, \$90,000 is the approximate price for a full-size petroleum trailer and \$625,000 is the H2A assumption for liquid hydrogen trailers. \$1,000,000 is an assumed upper-bound for trailer price. Other assumptions such as transport distance and fuel economy, that are assumed constant for all solid-state hydrogen carriers, are specified in Appendix A.

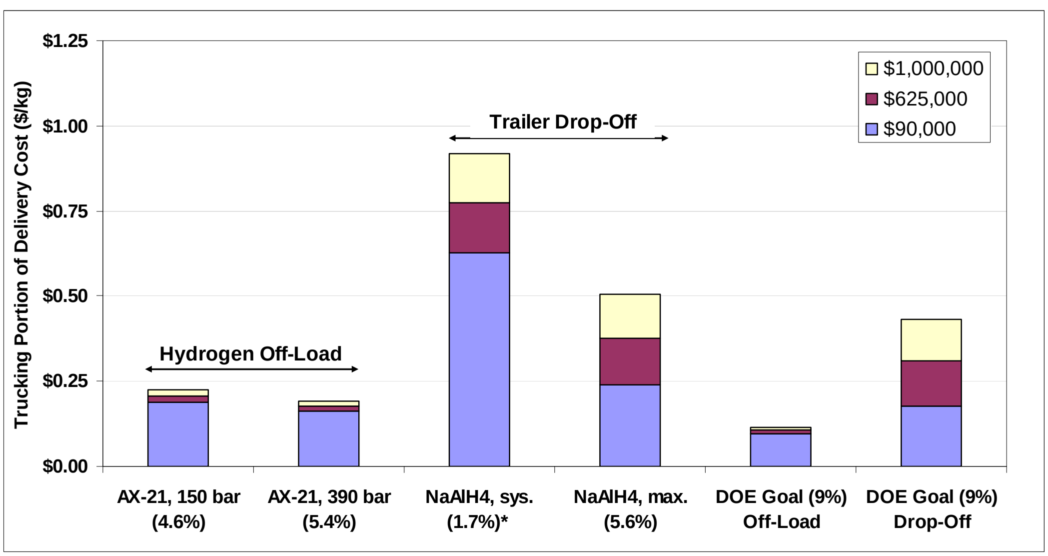


**Figure 4: Solid-State Hydrogen Trucking Cost**

Figure 4 illustrates the how highly variable the cost of delivery can be depending on the chosen pathway. The trucking costs under the trailer drop-off scenario are from 1.5-3.7 times more expensive than the hydrogen off-loading scenario. The primary driver of the high trailer drop-off cost is the distributed capital (trailers) at each fueling station. These cost differences, however, must be evaluated as a part of the overall delivery system. Additional low-pressure storage and a dedicated compressor are required at the fueling station to meet the needs of the hydrogen off-load delivery scenario. These additional fueling station costs are described and evaluated in Section 7, Fueling Stations.

## 6. Liquid Pipeline Transport

Another option for delivering alternative hydrogen carrier from the process facility to the fueling station is the use of pipeline networks that transport liquid carriers such as pure liquids, slurries, and solutions. Unlike a hydrogen, natural gas, or gasoline pipeline that transports a consumable product, a pipeline network delivering an alternative hydrogen carrier transports a recyclable material the must be returned to the processing facility. As a result, this analysis assumes that an alternative carrier pipeline network consists of two parallel pipelines throughout the network. The H2A model structure breaks the pipeline network into three levels: transmission, trunk and distribution. The transmission line transports liquid from the processing facility to the city, a variable number of trunk rings circle the city center, and distribution lines connect the fueling stations with the trunk rings. Figure 5 is a simplified illustration of how a three-level pipeline network might be designed. When transporting alternative carriers, each line shown in Figure 5 represents two parallel pipes, on for charged material and one for discharged material.

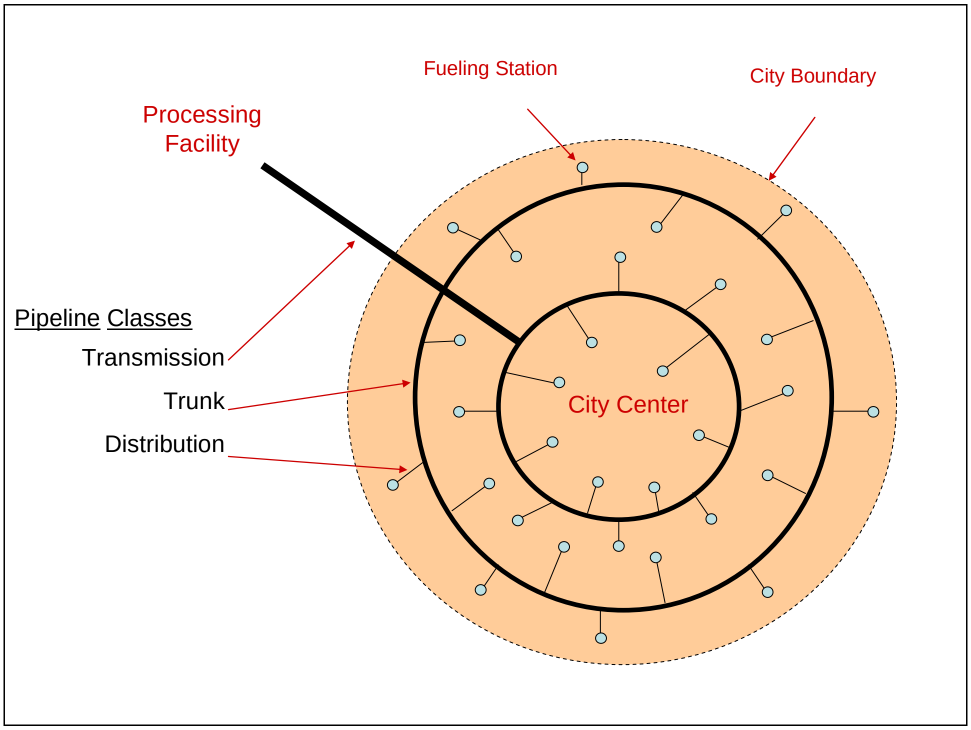


**Figure 5: Simplified Pipeline Diagram**

To assess the cost of delivering hydrogen, this analysis uses a number of assumptions taken from the H2A compressed hydrogen pipeline delivery model. The refinement of this cost estimate requires additional research to improve the accuracy of certain assumptions.

To estimate the capital cost of the alternative carrier pipeline, this analysis uses the cost equations employed in the existing H2A compressed hydrogen pipeline model. These equations are dependent on pipeline diameter and pipeline length and include labor, materials and other miscellaneous costs. For the alternative carrier analysis, the evaluated pipeline distance is twice the delivery distance to account for the two parallel pipes that carry hydrogenated and discharged material. Further research is required to improve the estimate for alternative carrier pipelines, but the assumptions included in the present analysis should provide a reasonable approximation of the costs for labor and materials. In addition to the capital cost of the pipeline, the total capital cost includes the carrier material contained in the pipeline and sets of liquid pumps for the transmission and trunk rings. The capital cost of the liquid pumps is based on the cost for comparably sized gasoline pumps. In addition to pipeline capital cost, the purchase or lease of right-of-way rights can be a relevant contributor to the overall cost of operating a pipeline network. The right-of-way cost estimate (also a function of diameter and distance) for the alternative carrier pipeline is the same as the H2A right-of-way cost estimate for compressed hydrogen pipelines. Unlike the capital cost estimates, the evaluated distance is the delivery distance, not the pipeline distance, as it is assumed that the two parallel pipelines will be laid side-by side and only one right-of-way is required. The diameter evaluated in the right-of-way cost equation is the sum of the diameters for the two pipelines.

Additional inputs used to evaluate pipeline delivery cost are shown in Table 7. Only a pure liquid carrier was assessed in this analysis. Slurries and solutions may also be transported by pipeline, but the potential for the carrier material to precipitate or fall out of solution could cause potential problems in a pipeline system. It should also be noted that carrier evaluated here, n-ethylcarbizole, has a melting point of 80°C when dehydrogenated. As a result, it is necessary to transport the dehydrogenated material in an insulated pipeline (provided the resonance time is not too long), adding to the capital cost of the overall pipeline network.

| Model Input | Unit | Value | Notes |
|---|---|---|---|
| Hydrogen Carrier Capacity | wt.% | 5.88 | n-Ethylcarbizole |
| Carrier Density | kg/m3 | 1,000/3,000 | n-Ethylcarbizole estiamte |
| Carrier Cost | $/gal. | $7.00 | n-Ethylcarbizole |
| Maximum Pipeline Velocity | m/s | 1.8 | Based on average speed of Colonial pipeline, 4 mph |
| Average Throughput | kg/day | 240,000 | Size of potential liquid hydrocarbon plant |
| Average Station Demand | kg/day | 3,000 | TIAX assumption |
| Transmission Pipeline Length | miles | 63 | H2A Components Model, cH2 Pipeline |
| Truck Rings | | 2 | H2A Components Model, cH2 Pipeline |
| Average Trunk Pipeline Length | miles | 70 | H2A Components Model, cH2 Pipeline |
| Ditribution Pipeline Length | miles | 1.6 | H2A Components Model, cH2 Pipeline |

**Table 7: Alternative Carrier Pipeline Model Inputs**

Initial analysis illustrates that the capital costs dominate the total delivery cost; therefore the sensitivity evaluated was aimed at reducing the capital costs associated with pipeline delivery. Given the expense of burying pipe, particularly in an urban area, the total cost is very sensitive to the amount of distribution pipeline in the system. In a scenario with constant hydrogen throughput (240,000 kg/day), the total length of the distribution pipeline depends on the length of each leg and number of distribution pipelines. If a pipeline network includes a fewer number of large fueling stations, as opposed to a greater number of smaller stations, than the overall length of distribution pipeline required will be reduced. The results of this sensitivity are shown in Figure 6.

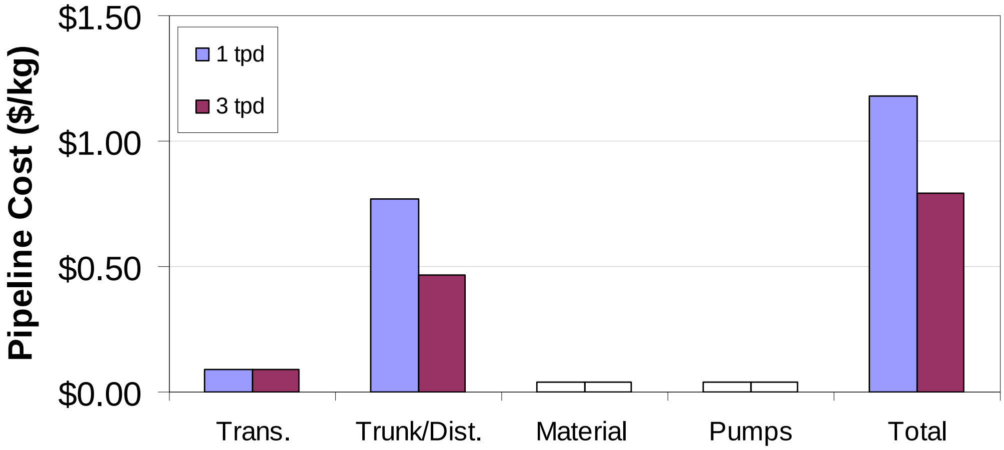


**Figure 6: Pipeline Delivery Cost Breakdown**

The difference in the total costs presented is a result of the reduced distribution pipeline that results from having fewer stations in the network.

Given the present assumptions – which require additional refining – delivering alternative hydrogen carrier in a pipeline may be prohibitively expensive. The need for two parallel pipelines is the primary driver of the overall cost. The second leg of the pipeline system is responsible for $0.37/kg of the $0.79/kg total cost of delivering hydrogen carrier in a pipeline network (assuming 3,000 kg/day stations).

## 7. Fueling Stations

Hydrogen fueling stations are the final component in the hydrogen delivery infrastructure. In conventional (compressed or liquid) delivery scenarios, the fueling station is likely to account for 30-60% [2] of the total hydrogen delivery cost, thus highlighting the need to properly evaluate and estimate the fueling station cost. The use of alternative carriers has the ability to significantly alter the design and required components at a hydrogen fueling station. This analysis attempts to identify all of the fueling station components required if alternative carriers are to be employed as a delivery mechanism. A single H2A-based model was developed to model the various fueling station configurations associated with different materials and delivery methods.

To systematically assess the various fueling station types and required components, the fueling stations types were defined by a number of metrics, including: the vehicle fueling method, the delivery method, and the method of discharge.

**Vehicle Fueling Method**

In the context of this analysis, hydrogen can be delivered to the vehicle in one of two ways: as compressed hydrogen or as a charged alternative carrier.

- **Compressed Hydrogen Fueling**: Hydrogen is delivered to vehicles to fill 5,000 psi on-board tanks (requires 6,250 psi cascade storage at the fueling station). This fueling pathway includes discharging hydrogen from the alternative carrier at the fueling station. For purposes of estimating cost, much of the compressed hydrogen fueling station infrastructure (compressor, cascade storage) is assumed to be the same as that included in H2A models for tube trailers or pipeline stations (depending on assumptions regarding hydrogen discharge). In addition to the compressed hydrogen components, this fueling method may require discharge reactors, alternative carrier storage, trailer bays, and/or low-pressure gaseous hydrogen storage. Further metrics used to classify fueling stations will determine the specific components required
- **Alternative Carrier Fueling**: The alternative carrier is not discharged at the fueling station. Instead, the carrier is delivered to the vehicle and hydrogen discharge occurs on-board. In addition to on-board discharge equipment, this fueling pathway requires that the discharged carrier be removed from the vehicle at the fueling station for return to the processing facility. This likely necessitates additional storage on-board the vehicle and an advanced dispenser that can remove the discharged carrier. Delivering the alternative carrier to the vehicle reduces the need for on-site discharge equipment and compressed hydrogen hardware at the fueling station. This will likely result in a significant reduction in fueling station capital cost. This cost reduction, however, may be offset by the increased cost and complexity of storing and discharging the carrier on-board the vehicle. A synthesis of on-board and off-board analyses is necessary to evaluate the total cost associated with this fueling pathway.

**Delivery Method**

Within the scope of alternative hydrogen carrier delivery pathways, multiple delivery options are available. The details of the specific delivery pathways are discussed in Sections 4-6. The effects that these various pathways have on fueling station equipment are discussed below.

- **Liquid Carrier Drop-Off**: As discussed earlier, this delivery pathway relies on trucks to transport the alternative carrier from the processing facility to the fueling station where it is off-loaded into liquid storage tanks. If the vehicles are being fueled with compressed hydrogen, a discharge reactor is required at the fueling station, as well as liquid storage for both the charged and discharged carrier. Depending on the discharge method selected, the compressed hydrogen infrastructure (compressor and storage) will be the same as the infrastructure at tube trailer or compressed hydrogen pipeline fueling stations.
- **Solid Carrier Off-Load**: Section 5 discussed solid carrier trucking. In the hydrogen off-load pathway the kinetics of the material are fast enough to allow for the hydrogen to be off-loaded during a regular delivery stop (1

hr. assumed max. drop-off time). The off-loading scenario reduces the need to leave a trailer at every fueling station, but does create a need for hydrogen storage and a dedicated off-loading compressor at the fueling station (analysis assumes 2,500 psi storage at fueling station). The off-loading compressor must compress the entire truck's worth of hydrogen for storage in the span of the drop-off, necessitating a compressor with a very high throughput (assuming a reasonable material storage capacity). Discharge equipment is likely required at the fueling station, but will generally consist of equipment required to provide heat transfer fluid to the trailer, as the solid-state materials generally store hydrogen through adsorption. As a result, the desorption process is activated by increasing the temperature of the storage medium.

- **Solid Carrier Truck Drop-Off**: Similar to the tube-trailer scenario, it is possible to drop-off alternative carrier trailers at the fueling station and use the trailers for on-site storage. This pathway is required if a solid material with slow material kinetics is employed. If the kinetics are fast enough, the discharge process can occur on-demand (reducing the need for low-pressure buffer storage) or at a constant rate. The distributed capital – in the form of trailers at each fueling station – is one of the drawbacks of this delivery method. The large number of trailers required to deliver hydrogen to the fueling stations makes the overall delivery cost more sensitive to the per-trailer capital cost.
- **Pipeline**: Liquid alternative carriers can potentially be delivered by pipeline. If the vehicle fueling method is compressed hydrogen, the discharge process will occur at the fueling station. This analysis assumes that the pipeline is continually supplying the fueling station and hydrogen is subsequently discharged at a constant rate. This assumption agrees with the compressed hydrogen, pipeline-supplied fueling stations that are assumed to draw on the pipeline network at a constant rate throughout the day. It is possible for the liquid carrier to be stored in buffer storage and hydrogen discharge to occur on-demand, but this scenario is not evaluated in this analysis. Assuming discharge at a constant rate, hydrogen is subsequently stored in 2,500 psi storage vessels. In this case, the compressed hydrogen infrastructure (compressor and gaseous storage) is the same as the fueling station infrastructure modeled in the H2A assessment of compressed hydrogen pipeline-supplied fueling stations.

  Pipelines may also supply alternative carrier for delivery onto vehicles. The alternative carrier could be stored on-site in liquid tanks and distributed to vehicles using the same advanced dispensers that would be required for dispensing liquid hydrogen carrier at a truck-supplied station.

**Discharge Method**

The potential exists for slow material kinetics to severely limit the ability to discharge hydrogen when needed to meet vehicular demand at the fueling station. As a result, the model considers two discharge options.

- **Steady-State**: If material kinetics limit the ability to discharge as needed, a steady-state scenario discharges hydrogen at a constant rate and stores it in low-pressure (2,500 psi) buffer storage. This discharge option can be employed for liquid drop-off and trailer drop-off, and is required for the pipeline scenario (given present modeling assumptions).
- **On-Demand**: If the kinetics allow, the model will also evaluate a fueling station that discharges hydrogen to meet the hourly demand at the fueling station. This scenario reduces the need for buffer storage, but does require a larger reactor to meet the more variable demand. The compressed hydrogen infrastructure is assumed to be the same as that at a tube-trailer station, which also supplies hydrogen to the compressor on-demand, and not at a constant rate.

After identifying the various fueling station configurations, an H2A-model was modified to allow the user to evaluate all of the various fueling station scenarios within one modeling framework. The characteristics discussed above serve as inputs to determine the components (and associated costs) that need to be included for each fueling station scenario. The capacities of these components are also a function of the material properties and demand at the fueling station. Table 8 illustrates the components that are included for the various fueling station configurations that can be evaluated using this model.

| Delivery Method | Vehicle Fueling Method | Steady-State or On-Demand | Trailer Bay | Off-Load Comp. | Liquid Storage | Dehydrogenation Reactor | Low-P Storage | High-P Comp. | Cascade Storage | Dispenser Type |
|---|---|---|---|---|---|---|---|---|---|---|
| Liquid Carrier Drop-Off | cH2 | SS | | | Y | Y | Y | Y | Y | cH2 |
| | | OD | | | Y | Y | | Y | Y | cH2 |
| Liquid Carrier Drop-Off | Liquid Carrier | ND | | | Y | | | | | Liq |
| Solid Carrier H2 Off-Load | cH2 | OD | | Y | | Y | Y | Y | Y | cH2 |
| Solid Carrier Truck Drop-Off | cH2 | SS | Y | | | Y | Y | Y | Y | cH2 |
| | | OD | Y | | | Y | | Y | Y | cH2 |
| Pipeline | cH2 | SS | | | | Y | Y | Y | Y | cH2 |
| | | OD | | | | Y | | Y | Y | cH2 |
| Pipeline | Liquid Carrier | ND | | | Y | | | | | Liq |

***SS= Steady-state; OD = On-demand; ND = No Dehydrogenation at Fueling Station**

**Table 8: Fueling Station Components**

One of the most glaring facts illustrated inn Table 8 is the amount of equipment required to dispense compressed hydrogen to vehicles. The liquid carrier fueling options only require alternative carrier storage and a dispenser. While both of these components have their own complexities (insulated/heated storage for charged and discharged material; dispensers that supply and remove carrier to and from the vehicle), the lack of reactors, compressors, and storage is likely to significantly reduce the overall fueling station cost. It should be noted again that by supplying alternative carrier to the vehicle, many of the issues and costs are transferred from the fueling station to the vehicle, such as the cost and complexity of discharging the carrier to meet variable vehicular demand. This transfer of components and costs to the vehicle has the potential to increase the cost of the entire hydrogen delivery system, including the vehicle.

**Cost Assessment**

Given the lack of compressed hydrogen equipment at fueling stations that supply alternative carrier to vehicles, it is clear that those stations will have a cost benefit relative to the fueling stations supplied by alternative carriers and distributing compressed hydrogen. In addition, this analysis did not model the on-board costs required to utilize alternative carriers and thus cannot provide a full cost analysis of using alternative carriers for both delivery and on-board storage. As a result, this analysis of fueling stations focuses on evaluating the costs of alternative carrier stations dispensing compressed hydrogen.

A potentially important cost variable is the cost of the discharge reactor. At present, little research has gone into evaluating the costs of reactors for use at fueling stations. Most existing alternative carrier analysis focuses on the cost of on-board equipment or estimates of the capital costs associated with large-scale processing facilities. As a result, there are very few existing studies available that specify the costs of fueling station reactors. Furthermore, the variability in capability makes it difficult to assume a universal cost for reactors used at fueling stations that are using different types of carrier material. For example, desorbing hydrogen from AX-21 will require – at most –supplying heat transfer fluid to the sub-cooled material in order to increase the temperature of the material and desorb hydrogen. This heat transfer mechanism is likely far cheaper than the catalytic reactor required for the endothermic hydrolysis process required to discharge hydrogen from sodium borohydride or the high temperature reactor that supplies significant amounts of heat to dehydrogenate hydrogen from a liquid hydrocarbon. As a result, this analysis evaluated the various fueling station scenarios with a variety of discharge reactor costs. The range of reactor costs used was $0-20,000/(kg/hr) of hydrogen reacted. In estimating this range, costs for a variety of different reactors and processing plants were considered, including: plant-scale reactors for n-ethylcarbizole ($5,600/(kg/hr)), a complete n-ethylcarbizole plant ($16,600/(kg/hr)), sodium borohydride reprocessing plants ($45, 000-53,000/(kg/hr)). While fueling station reactors will not have the systematic complexity of processing plants, they also do not have the advantage of scale and still require all of the safety equipment required when working with hydrogen. As a result, the costs considered are $0/(kg/hr), which was included to evaluate the cost without the reactor, $5,000/(kg/hr) for the heat transfer systems that will likely be used with solid-state carriers, and $10,000-20,000/(kg/hr) for the more complex reactors likely required for liquid hydrocarbons or chemical hydrides. Ascertaining the proper costs for these components is a primary research objective in the second phase of this analysis.

Given the costs assumptions for dehydrogenation reactors and the additional assumptions listed in Appendix A, fueling station cost estimates were determined for a variety of fueling station configurations and presented in Figure 6.

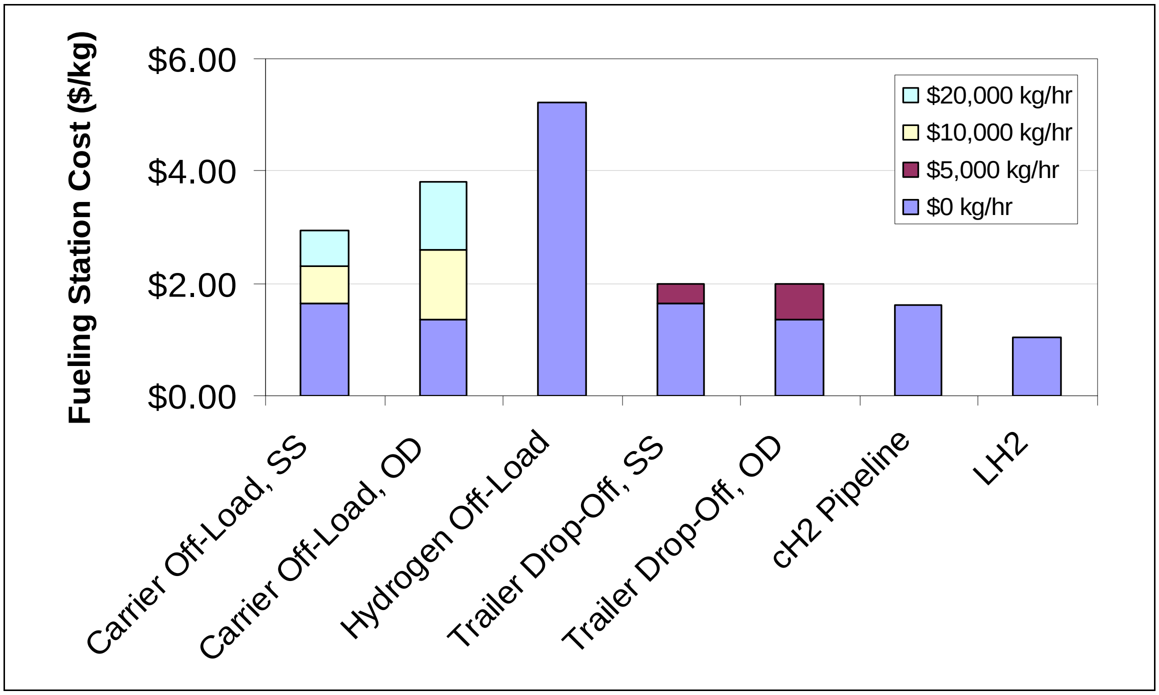


**Figure 7: Fueling Station Costs for a Variety of Delivery Options w/ Variable Costs for Discharge Reactors**

The results shown in Figure 7 only magnify the need to better quantify the cost associated with the discharge reactors, as the discharge reactors may potentially contribute more than $2.00/kg to the overall cost of delivered hydrogen.

The carrier off-load scenario was evaluated under two different discharge options: steady-state and on-demand. Unless the discharge equipment is extremely affordable, the results indicate that it will generally be more cost effective to have a lower capacity reactor in combination with low-pressure storage than have a high-capacity reactor and no low-pressure storage.

The results of the hydrogen off-load scenario clearly indicate that the cost associated with adding a high-capacity compressor and significant low-pressure storage (assuming a delivery of ~1,450 kg/day and 1,000 kg/day station demand) is prohibitively expensive. Hydrogen off-loading was considered as a way to reduce the need for the distributed capital associated with leaving trucks at each fueling station, but the results illustrate that compressing and storing hydrogen at low-pressure is not an effective method for minimizing that cost of distributed trailers.

Due to the potentially low cost of discharge equipment for solid-state carriers, the fueling station costs for the trailer drop-off pathway are comparable to the costs of pipeline-supplied or liquid-supplied fueling stations. In all of these scenarios, the baseline costs for high-pressure hydrogen compressors and cascade storage are included. From a delivery perspective, the potential for alternative carriers to really offer a cost advantage over conventional transport options lies in the ability to supply alternative carriers to vehicles and reduce the need for compressed hydrogen equipment at the fueling station.

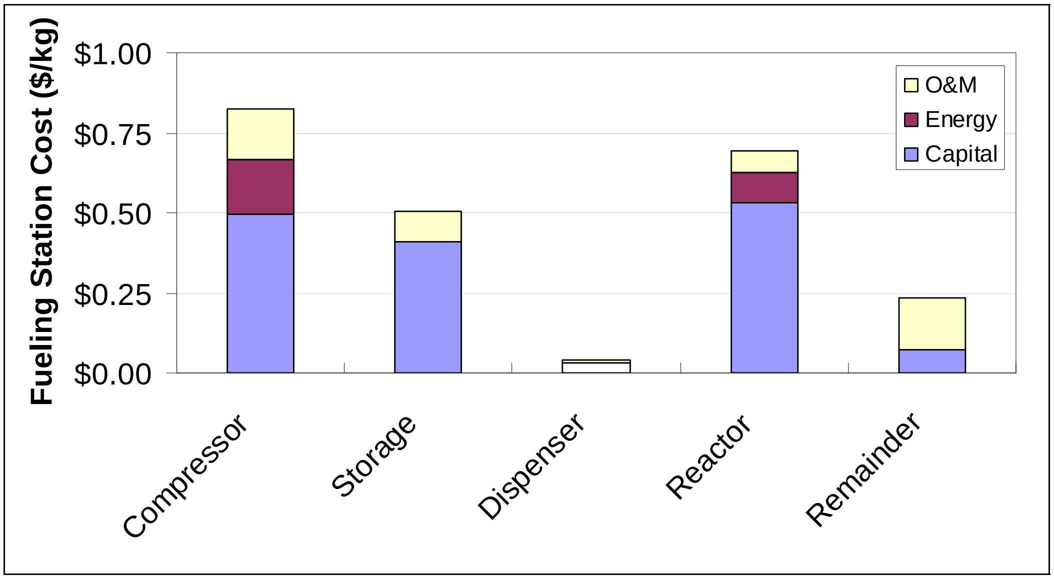


**Figure 8: Cost Breakdown for Carrier Drop-off/cH2 Station**

Figure 8 shows a cost breakdown of a carrier drop-off scenario that illustrates the significant effect that the compressor, reactor and storage components have on the overall fueling station cost. Delivering alternative carrier to the vehicle will significantly reduce or remove those three contributors to the overall cost. The potential for such a reduction favors liquid carriers that can easily be transferred from storage at the fueling station to a tank on the vehicle.

## 8. Other Issues

In addition to the considerations discussed above, there are other issues that must be addressed when evaluating the viability of a novel carrier. One such issue is material toxicity. The present analysis does not explicitly address whether a particular carrier has the potential to negatively affect human health, cause environmental damage, or lead to the degradation of storage containers and material processing and handling equipment. When selecting a carrier, the potential hazards associated must be considered. In some instances the dangers or drawbacks associated with a carrier will immediately remove that carrier from consideration. In other situations, it will be necessary to weigh the potential hazards with the energy or cost benefits associated with that carrier.

A good example of potential hazards is the reactivity of sodium alanate. When in the presence of water or air, sodium alanate can undergo a highly exothermic chemical reaction. Such a situation could be highly problematic in a delivery scenario where there will be large amounts of material in storage tanks or trucks on the roadways.

Considerations such as the toxicity or reactivity of a material are highly subjective and are not appropriately handled in a modeling architecture such as H2A. As a result, developers and investors must evaluate these issues when deciding whether to move forward.

## 9. Selecting a Carrier

When determining the viability of an alternative carrier, there are multiple metrics on which a carrier can be evaluated, such as energy-use, GHG emissions, total cost, or potential hazard. In addition there are multiple roles that an alternative carrier can play in the development of the hydrogen infrastructure. An alternative carrier could offer an improvement over tube trailers for small-scale delivery in the near term, could compete with liquid hydrogen for larger-scale delivery, or could provide an alternative to compressed hydrogen pipelines for a fully developed infrastructure. Given the variety of evaluation metrics and use-scenarios, it is very difficult to offer a simple method for down-selecting carriers. In addition, many of the processes used to charge and discharge hydrogen are continually improving, making the metrics for a particular carrier variable with time. As a result, it is inappropriate to explicitly rule-out certain carriers based on the present generation of technology development.

- Determine type of use
- Evaluate costs (is it within a range of competitiveness)
- Is it practical?
- What advantages does it offer compared to conventional methods?

## 10. Conclusions

This analysis has only served to scratch the surface of alternative carrier delivery analysis, but it has provided direction for further research and identified places where an improved cost assessment is required. For example, the fueling station analysis indicates that using alternative carriers in a pathway that discharges hydrogen at the station and supplies compressed hydrogen to vehicles will offer little or no benefit for fueling station costs because the alternative carriers have not reduced the need for compressed hydrogen equipment at the fueling station. In addition, a costly reactor can significantly increase the cost of overall cost of the fueling station. Alternative carriers have the ability to significantly reduce fueling station costs if the alternative carriers are delivered to the vehicle. Liquid carrier options offer the best case for such a pathway, as they benefit significantly from the ease with which they can be transferred between storage medium. The transport difficulty inherent in the solid carriers makes it difficult to envision a pathway in which the alternative carrier material is used for delivery and on-board storage without a discharge process in the between a delivery transport option (such as a truck) and the vehicle.

The trucking analysis indicated that the focus should be on improving the hydrogen capacity of the carrier without regard to the costs of the transport trailer, as it has little effect on the overall delivery cost (at least in a carrier drop-off scenario). The benefits of the hydrogen off-loading pathway (no distributed trailers) are almost certainly not worth the additional costs for a high-capacity compressor and significant low-pressure storage at the fueling station.

While there are other small conclusions that can be taken from this analysis, the major successes are the development of a model that identifies a variety of pathway options and identifies all of the components required for each pathway. In addition, this analysis has illustrated the need to perform delivery cost analyses across the entire delivery spectrum from the processing facility to the vehicle. For example, results of this analysis indicate that dispensing liquid alternative carriers to vehicles offers the cheapest pathway for hydrogen delivery. However, without identifying the costs of the equipment on-board the vehicle, this analysis and the subsequent conclusions are incomplete. The various pathways for hydrogen production and delivery must be evaluated throughout the use chain to determine the overall cost and allow various pathways to be compared against one another. This model will provide the framework for evaluating a portion of that entire lifecycle cost.

## 11. Analytical Contributors

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Nexant: Bruce Kelly
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## 10. References

1. U.S. Department of Energy, Vehicle Technologies Program: *About the Program*, November 15, 2005. http://www1.eere.energy.gov/vehiclesandfuels/about/partnerships/freedomcar/fc_goals.html

2. H2A HDSAM: Pipeline Fueling Station is $1.70 of $3.09 total and Liquid Fueling Station is $1.12 of $3.51 total (both assume 1 mill. pop; 1,000 kg/day station)

## 11. Appendix A

### Trucking Assumptions

| Model Input | Unit | Value | Notes |
|---|---|---|---|
| Truck Cargo Weight | kg | 25,200 | Cargo for max GVW (80,000 lbs) |
| Material Cost | $/gal | $7.00 | n-Ethylcarbizole |
| Carrier Density | kg/m3 | 1,000 | n-Ethylcarbizole estimate |
| Truck Useable Fraction | | 97.5% | H2A assumption |
| Round Trip Distance | km | 80 | H2A assumption |
| Average Station Demand | kg/day | 1,000 | TIAX estimate |
| Time to Fill Liquid Trailer | hrs | 0.75 | TIAX estimate |
| Time to Empty Liquid Trailer | hrs | 0.75 | TIAX estimate |
| Time to Drop-off & Pick-up Trailer | hrs | 1.00 | Max acceptable delivery time |
| Average Truck Speed | km/hr | 58 | H2A assumption |
| Truck Gas Mileage | km/L | 2.6 | H2A assumption |
| Tractor Cost | | $75,000 | H2A assumption |

### Pipeline Calculation Assumptions

| Model Input | Unit | Value | Notes |
|---|---|---|---|
| Hydrogen Carrier Capacity | wt.% | 5.88 | n-Ethylcarbizole |
| Carrier Density | kg/m3 | 1,000/3,000 | n-Ethylcarbizole estiamte |
| Carrier Cost | $/gal. | $7.00 | n-Ethylcarbizole |
| Maximum Pipeline Velocity | m/s | 1.8 | Based on average speed of Colonial pipeline, 4 mph |
| Average Throughput | kg/day | 240,000 | Size of potential liquid hydrocarbon plant |
| Average Station Demand | kg/day | 3,000 | TIAX assumption |
| Transmission Pipeline Length | miles | 63 | H2A Components Model, cH2 Pipeline |
| Truck Rings | | 2 | H2A Components Model, cH2 Pipeline |
| Average Trunk Pipeline Length | miles | 70 | H2A Components Model, cH2 Pipeline |
| Ditribution Pipeline Length | miles | 1.6 | H2A Components Model, cH2 Pipeline |

### Fueling Station Assumptions

| Model Input | Unit | Value | Notes |
|---|---|---|---|
| Hydrogen Carrier Capacity | wt.% | 5.88 | n-Ethylcarbizole |
| Carrier Density | kg/m3 | ,000/3,000 | n-Ethylcarbizole estiamte |
| Carrier Cost | $/gal. | $7.00 | n-Ethylcarbizole |
| Discharge Pressure | atm | 20 | |
| Off-Load Discharge Rate | kg/hr | 1,000 | |
| Carrier Storage Factor | storage/demand | 1.5 | |
| Discharge Energy | MJ/kg,H2 | 25 | n-Ethylcarbizole estimate |
| Heat Recovered | % | 25% | n-Ethylcarbizole estimate |
| High-Pressure Storage | psi | 6,250 | H2A assumption |
| Low-Pressure Storage | psi | 2,500 | H2A assumption |
| Number of High-Pressure Compressors | | 3 | H2A assumption |
| Number of Compressors in Operation | | 2 | H2A assumption |
| Compressed H2 Infrastructure Cost | All cH2 Infrastructure Costs based on H2A Assumptions; see H2A documentation | | |