2011

Top Consequence Hazardous Materials by Commodities & Failure Modes

2005-2009

Pipeline and Hazardous Materials Safety Administration

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Report Summary

The Pipeline and Hazardous Materials Safety Administration (PHMSA) evaluates safety risk and historical consequences in hazardous materials transportation when setting priorities, making policy, budgeting and allocating resources, drafting rules, targeting inspections, measuring performance, and communicating with stakeholders. In carrying out our mission to protect people and the environment from the risks inherent in transportation of hazardous materials, PHMSA uses data reflecting outcomes signaling areas of concern to the Administration and the nation, particularly those of high consequence to people and the environment.

This paper outlines the hazardous materials (hazmat) in transport that have been responsible for the most serious consequences in terms of deaths and major injuries during the years 2005 to 2009. It also identifies failure modes and the corresponding transportation phases that have resulted in the most high-impact casualties during this same period.

As PHMSA analyzes alternatives to increase the safety of hazmat transportation, the agency will consider several findings from this report:

- Some hazardous materials have high consequences due to their high levels of transport (i.e. high exposure) while in other cases it is the sheer volatility or danger of the substance that leads to significant consequences despite modest exposure;
- Most of the deaths and injuries due to hazmat can be linked to a small sub-section of all hazardous materials;
- Nearly all of the hazmat fatalities between 2005 and 2009 occurred during either rail or highway transport. (The exception was a single multiple-fatality waterborne incident.) The vast majority of major injuries (85%) were also associated with these two modes; and
- Rollover and Derailment while in transit are the principal failure causes recorded (and are specific to road and rail transportation, respectively), followed by Human Error across all phases of transportation.

A note of caution: while the five-year period analyzed here presents a valuable snapshot of the leading causes of hazmat-related losses in the U.S. recently, it does not supplant consideration of long-term trends and the need for a robust hazmat safety, incident prevention, and emergency response regime equipped to deal with both predictable and unpredictable events and avert catastrophe whenever possible. This is only the first step in a concerted series of efforts to identify areas of concern, target risks, and project future initiatives.

Preface: Uses and Limitations of the Data and Analysis

Probability and Risk

The commodity rankings in the report reflect documented incident consequences. Outcomes such as those under consideration here highlight some areas of needed improvement but do not represent all aspects of underlying risk. Many hazardous materials present a special kind of risk – low-probability, high-consequence (LPHC) risk – that might not appear in the historical data, especially when the reference period is short. This analysis used a five-year reference period, in part, to help illustrate recent/current kinds of risk since these can change over time, and to align with recent data from the Commodity Flow Survey. This five-year period includes at least one LPHC incident: the train derailment at Graniteville that resulted in multiple deaths and injuries associated with chlorine. Without context, this incident might overstate the risks of chlorine. The same might be true for other commodities that are presented in the tables with very few deaths or injuries, particularly those with only one over a five year period. At the same time, there are other kinds of incidents, with other commodities, that have occurred outside the most recent five years but that still present some risk. Further analysis, and perhaps a longer reference period (with more data), is needed to help present a better picture of these LPHC risks.

Injury Weighting

Most of the rankings in this analysis use weighted numbers of incidents, where injuries are weighted less heavily than fatalities. This reflects a difference in the degree of consequence, and follows the same convention used in most benefit-cost analyses for rulemaking. However, the difference between a serious injury and death is sometimes a matter of "chance" or some other extraneous factor like physical condition of the victim, proximity to the release, etc. An unweighted sum of the incidents that cause any harm to people reflects the role of uncertainty in the safety risks we are trying to address in accordance with PHMSA's primary performance measure for hazardous materials safety being the number of incidents involving death or major injury. Weighting of injuries also introduces an assumption about the severity of injuries to compensate for the fact that the incident data do not provide any injury severity information. Further research is needed on this to help refine the weighting in this analysis as well as for regulatory analyses.

Normalization

Normalizing hazmat incident data to account for differences in risk exposure helps to identify "hidden" risks—those commodities that might present a higher inherent risk, but that do not present high numbers of incidents simply because the exposure is small. Normalization might be especially helpful in targeting interventions since a high inherent risk might suggest a gap in defenses. That said, we also recognize that the exposure data from the Commodity Flow Survey is limited for this purpose. It covers only a quarter of the individual commodities with any associated incidents in the past five years, and provides only hazard class for all other hazmat. There might be ways of estimating the exposure for commodities that present death or injury incidents, but this will require further analysis beyond the scope of this report. This could provide more insight on the risks associated with the commodities not included in the tables.

Two exposure measures were used to normalize the data in this analysis: tons and ton-miles. Tons are probably a better denominator for loading, unloading, and temporary storage incidents, where the amount of material handled is an important risk factor. Ton-miles are probably better for enroute incidents, where the length of haul is an important risk factor. Further analysis might break out the incidents by transportation phase, and associate different incidents with different denominators, depending on the phase of transportation in which they occurred.

Failure Modes

The analysis of failure causes draws on data as reported by carriers, without further judgment. In some cases, there might be incidents that have been misclassified with respect to cause, as hundreds of different people might have interpreted reporting guidance differently. Further examination of individual cases might reveal better coding for some cases, but this was beyond the scope of the current analysis.

One of the broader limitations from this analysis is the uncertainty surrounding the numbers, especially the smaller numbers, as a representation of risk. While we believe there is some underreporting of hazardous materials incidents, reporting of deaths and injuries is probably the most reliable since these incidents are not easy to ignore or hide. However, we are still dealing with some very small numbers, sometimes only one or two incidents involving a particular commodity over a five-year period. Any other five-year period is likely to show a different mix of commodities for these small-number cases. A longer reference period might help. Another possibility is to identify important risk factors using conditional probabilities, then use incidents with these risk factors to help extend the data to a broader set of incidents. Some preliminary analysis with conditional probabilities suggests this could be a promising approach, but it will require further work.

Section 1:

Commodity Data

The top 10 commodities based on high-impact casualties are displayed below in multiple rankings to reflect the varying policy uses and conclusions resulting from different emphases in the ranking methodologies,

Table 1.1 is based on aggregate weighted consequences in terms of high-impact casualties (Ca); the data do not consider casualties *per unit* of commodity carried. High-impact casualties in this table are the weighed sum of deaths and major injuries or hospitalizations, in accordance with MAIS coefficients for DOT's established value of a statistical life (VSL).[1] Major injuries are assumed at an average level of MAIS 4 ("severe," 18.75% of VSL), compared to fatalities (MAIS 6).[2] While not so consequential as fatalities, major injuries are considered in this context for their likelihood of causing permanent, disabling alterations to quality of life. Overall, this list has applications for resource allocation and program prioritization in light of reducing high-profile fatalities.

Among the commodities that top the list of high consequences are several whose high rate of exposure (i.e. high levels of transport) are largely responsible for the magnitude of their consequences. Gasoline and diesel fuel are two examples of commodities that fall into this category. Conversely, the sheer volatility or danger of other substances has led to significant consequences despite only modest exposure. Sulfuric acid and chlorine are examples of commodities that fall into this category.

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[1] Available at http://ostpxweb.dot.gov/policy/reports/VSL%20Guidance%20031809%20a.pdf.

[2] The range of MAIS values applicable to hospitalized injuries may reach from 2 (moderate, 1.55% VSL) to 5 (critical, 76.24% VSL); due to the lack of detailed information on injury severities, MAIS 4 was selected as a plausible intermediate.

Table 1.1 – Top 10 Commodities 2005-09 Ranked by Weighted High-Impact Casualties
(High Impact Casualties = Fatalities + [Major Injuries or Hospitalizations * VSLweight])

Rank	Commodity Name	High-Impact Casualties (Weighted)	Fatalities	Major Injuries	Incidents
1.	Gasoline	35.94	32	21	1,386
2.	Chlorine	24.56	9	83	48
3.	Diesel fuel	15.69	14	9	2,714
4.	Propylene	4.94	1	21	15
5.	Fireworks	4.19	4	1	2
6.	Liquefied petroleum gas (LPG)	4.00	1	16	471
7.	Carbon dioxide, refrigerated liquid	3.56	3	3	51
8.	Sulfuric acid	3.31	2	7	1,270
9.	Propane	3.00	3	0	31
10.	Argon, refrigerated liquid	3.00	3	0	42

All of the casualties calculated in Table 1.1 were associated with either rail or highway transport, except for those attributable to a multiple-casualty argon incident, which occurred aboard vessel transport. Additionally, the principal incident mode is the same as the principal carrier mode for all of the commodities in Table 1.1 (Extending the period of analysis back 10 years to 2000-2009, the list changes only in that anhydrous ammonia and alcohols replace argon and propane.)

When we simply sum the number of high-impact casualties for each commodity (reflecting the agency's overall goal of accounting for and reducing all casualty incidents), the list appears as follows in **Table 1.2**:

Table 1.2 – 10 Commodities Ranked by Unweighted High-Impact Casualties
(High Impact Casualties = Fatalities + Major Injuries or Hospitalizations)

Rank	Commodity Name	High-Impact Casualties (Unweighted)	Fatalities	Major Injuries	Incidents
1.	Chlorine	92	9	83	48
2.	Gasoline	53	32	21	1,386
3.	Diesel fuel	23	14	9	2,714
4.	Propylene	22	1	21	15
5.	Liquefied petroleum gas (LPG)	17	1	16	471
6.	Sodium hydroxide, solid	11	1	10	2,298
7.	Sulfuric acid	9	2	7	1,270
8.	Ammonia, anhydrous	8	1	7	317
9.	Corrosive liquids, toxic, n.o.s.	8	0	8	511
10.	Carbon dioxide, refrigerated liquid	6	3	3	51

Over the past 10 years, hydrochloric acid and fireworks would replace toxic corrosive liquids and carbon dioxide on the list.

To add another dimension to the rankings, **Tables 1.3(a) and (b)** not only calculate the high-impact casualty cost of an incident when it occurs, but also the *frequency* of past events relative to the amount of the commodity carried (known as exposure). The first normalization variable selected utilizes millions of ton-miles (MTM), taken from the US DOT 2007 Commodity Flow Survey (CFS), as a benchmark measure of exposure, incorporating the dimensions of both volume and distance. By contrast, the second methodology utilizes thousands of tons (kT), also from the CFS. The differing uses of the two, as explained in the preface, emphasizes the likelihood of consequences occurring in different phases of transport. As a result, these *per-unit* measures serve as a further factor for consideration when ranking the top 10 commodities.

Table 1.3(a) – Top 10 Commodities by *Normalization by Exposure*
(Weighted Casualties per Million Ton-Miles)

Overall Ranking			Consequences			Exposure
Rank	**Commodity Name**	**Normalization Factor x 1,000 (N = Ca / MTM)**	**High- Impact Weighted Casualties (Ca)**	**Fatalities**	**Major Injuries**	**Million Ton-Miles (MTM, CFS 2007)**
1.	Amines, liquid, corrosive, flammable, n.o.s.	26.79	0.38	0	2	14
2.	Toxic liquids, flammable, organic, n.o.s.	11.72	0.19	0	1	16
3.	Corrosive liquids, toxic, n.o.s.	10.56	1.50	0	8	142
4.	Chlorine	7.69	24.56	9	83	3,195
5.	Propane	4.65	3.00	3	0	645
6.	Calcium hypochlorite, hydrated	3.02	0.19	0	1	62
7.	Corrosive solid, basic, inorganic, n.o.s.	2.70	0.38	0	2	139
8.	Corrosive liquid, basic, organic, n.o.s.	1.64	0.19	0	1	114
9.	Ammonia solutions	1.05	0.19	0	1	179
10.	Corrosive liquid, acidic, inorganic, n.o.s.	1.05	0.94	0	5	897

Table 1.3(b) – Top 10 Commodities by *Normalization by Exposure*
(Weighted Casualties per Thousands of Tons)

Overall Ranking			Consequences			Exposure
Rank	Commodity Name	Normalization Factor x 1,000 (N = Ca / kT)	High- Impact Weighted Casualties (Ca)	Fatalities	Major Injuries	Thousands of Tons (kT, CFS 2007)
1.	Sodium hydroxide solution	65.34	2.88	1	10	44
2.	Amines, liquid, corrosive, flammable, n.o.s.	10.42	0.38	0	2	36
3.	Chlorite solution	9.87	0.56	0	3	57
4.	Propylene see also Petroleum gases, liquefied	6.25	4.94	1	21	790
5.	Corrosive liquids, toxic, n.o.s.	6.25	1.50	0	8	240
6.	Butyl acetates	3.02	0.19	0	1	62
7.	Chlorine	2.88	24.56	9	83	8,533
8.	Sulfur dioxide	1.93	0.19	0	1	97
9.	Calcium hypochlorite, hydrated	1.48	0.19	0	1	127
10.	Corrosive solid, basic, inorganic, n.o.s.	1.47	0.38	0	2	255

What these lists show is that the consequences attributable to a commodity group such as liquid amines, sodium hydroxide, or flammable organic toxic liquids have recently been disproportionate to their exposure. The corrosive liquids subgroups, for example, exert a noticeable dominance over the list normalized by ton-miles; not surprisingly, incidents involving these materials generally occurred enroute.

A downside of the analysis presented in Tables 1.3(a) and (b), however, is that the CFS is not encyclopedic; it does not have exposure figures for all commodities with recorded hazmat incidents, including some with multiple fatalities such as propylene or argon.[3]

PHMSA has elected not to estimate exposure figures for other commodities due to concerns about impartiality and the complexity of reproducing CFS methods. Were the data available, a pure normalization by exposure would possibly bring still other commodities and concerns to the foreground; nonetheless those that dominate here are worth further evaluation.

[3] There were over 900 UN hazmat codes referenced in incident reports between 2005 and 2009; fewer than 200 of them had corresponding values recorded in the Commodity Flow Survey.

Section 2:

Failure Mode in each Transportation Phase

Failure mode, or the specific cause of an incident, is an important factor to consider when mitigating hazardous materials incidents. As a result, PHMSA analyzed failure modes across all phases of transportation (i.e. Loading,

Enroute [also listed as "in transit"], Temporary Storage, and Unloading) for all commodities from 2005-2009. **Table 2.1** below ranks the top 10 failure modes by high impact casualties and indicates the primary transportation phase(s) in which each failure mode occurs. This table also takes into consideration if multiple failure modes were listed on the incident report form, and separates them into another category.

Again, high-impact casualties (Ca) in this paper are the weighed sum of deaths and major injuries or hospitalizations, in accordance with MAIS coefficients for DOT's established value of a statistical life (VSL).[4] Major injuries are assumed at an average level of MAIS 4 severe," 18.75% of VSL), compared to fatalities (MAIS 6).

Based on the data in the failure mode table:

- Rollover Accidents and Derailments, which solely occur during the Enroute transportation phase, result in the highest casualties;[5]
- Human Error is the only failure mode of the top 10 failure modes that occurs in each of the four transportation phases; and
- The high number of injuries due to Item Dropped are primarily due to a single incident involving a trimethylamine release in Singapore which sickened 40 people.

Note that PHMSA does not collect the failure mode for a significant number of incidents that result in high impact casualties, and 16 incidents had two failure modes recorded.

Prior to 2005, failure modes were coded differently and a comparison between the two periods would not be apt.

[4] Available at http://ostpxweb.dot.gov/policy/reports/VSL%20Guidance%20031809%20a.pdf.

[5] Rollover and Crash are sometimes treated the same by reporting individuals; PHMSA believes that Rollovers may be underestimated.

Table 2.1 – Top 10 Failure Modes (across all Transportation Phases) Ranked by Weighted High Impact Casualties
(High Impact Casualties = Fatalities + [Major Injuries or Hospitalizations * VSLweight])

Rank	Failure Mode	High-Impact Casualties (Weighted)	Casualties (Unweighted)	Fatalities	Major Injuries	Incidents with Fatalities or Major Injuries	Primary Transportation Phase(s) (with corresponding weighted casualties)
1.	Derailment	133.19	133	24	109	3	Enroute –133.19
2.	Rollover Accident	25.19	39	22	17	27	Enroute- 25.19
3.	Cause Not Reported	22.00	48	16	32	35	Enroute – 15.63 Unloading - .94 Loading – 5.44
4.	Human Error	10.38	25	7	18	19	Enroute – 2.19 Temporary Storage – 4.38 Unloading – 3.44 Loading - .38
5.	Component or Device*	11.06	46	3	43	20	Enroute – 7.44 Unloading – 3.25 Loading - .38
6	Vehicular Crash or Accident Damage	9.31	15	8	7	11	Enroute – 9.31
**	Multiple Causes	8.44	19	6	13	16	Unloading - .38 Loading - .19 Enroute – 7.88
7.	Dropped	7.69	41	0	41	2	Unloading – 7.69
8.	Fire, Temperature, or Heat	2.50	9	1	8	5	Enroute – 2.31 Unloading - .19
9.	Impact with Sharp or Protruding Object (e.g. nails)	1.94	6	1	5	3	Enroute – 1.56 Temporary Storage - .38
10.	Inadequate/ Improper Preparation for Transportation***	1.50	8	0	8	6	Enroute – 1.13 Loading - .19 Unloading - .19

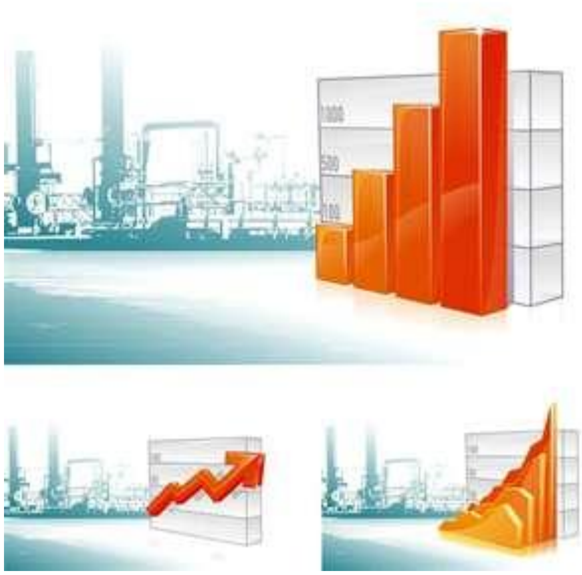
**This failure mode is an aggregate of five failure modes: 1) Broken Component or Device; 2) Loose Closure, Component or Device; 3) Defective Component or Device; 4) Missing Component or Device; 5) Misaligned Material, Component or Device. The values provided have been adjusted to assure that there is no double counting as a result of this aggregation.*
*** This category contains incidents for which there were two or more failure mode reported*
**********This failure mode is an aggregate of two failure modes: 1) Improper Preparation for Transportation; 2) Inadequate Preparation for Transportation. The values provided have been adjusted to assure that there is no double counting as a result of this aggregation.*

Of the 16 incidents that had two failure modes, only two did not have one of the ten specific failure modes listed in Table 2.1 as a cause of failure; 11 of these incidents had a combination of failure modes solely from the top 10. These combinations (without respect to order) include:

- Fire, Temperature, or Heat and Rollover Accident (3 incidents)
- Rollover Accident and Vehicular Crash or Accident Damage (2 incidents)
- Inadequate Preparation for Transportation and Loose Closure, Component, or Device (2 incidents)
- Human Error and Dropped (1 incident)
- Human Error and Rollover Accident (1 incident)
- Human Error and Impact with Sharp or Protruding Object (1 incident)
- Human Error and Missing Component or Device (1 incident

In addition to the four incidents that have human error as one failure cause listed above, there is a fifth where the second failure mode is Deterioration or Aging. These five incidents that include human error as one failure mode resulted in three fatalities and three hospitalizations. Human Error is still the most often cited failure mode across all transportation phases, indicating a need for additional analysis.

One method, root cause analysis, attempts to trace the chain of failures from the *proximate cause*—the last failure in the chain—to the *root cause*—the reason why the chain of failures occurred in the first place. For example, the immediate cause of a hazmat release might be a failure to tighten a fitting while the more fundamental problem might be the design of the fitting or the qualifications of the person with the responsibility to tighten the fitting. The aim is to identify and solve the underlying problem, or the key interaction of problems in the chain of events, rather than only the surface manifestation of that problem.



Section 3:

General Conclusions and Further Considerations

Examining commodities resulting in the greatest consequences and casualties in transport is more than just an exercise in deriving ranking statistics. At a macro level, the data presented in this paper shows that the great majority of casualties attributable to incidents associated with the transport of hazardous materials result from a small core number of hazmat commodities being transported. The top 10 commodities in Table 1.1 accounted for 102.19 weighted casualties out of 135.69 overall (from 80 fatalities and nearly 300 major injuries) over the last five years for which data are available, or about 75 percent.

Hazmat from Classes 3 (flammables, including gasoline and diesel fuel), 2 (gases, including chlorine), and 8 (corrosives, including sodium hydroxide and sulfuric acid) accounted for the vast majority of the total casualties, as summarized in **Chart 3.1**.

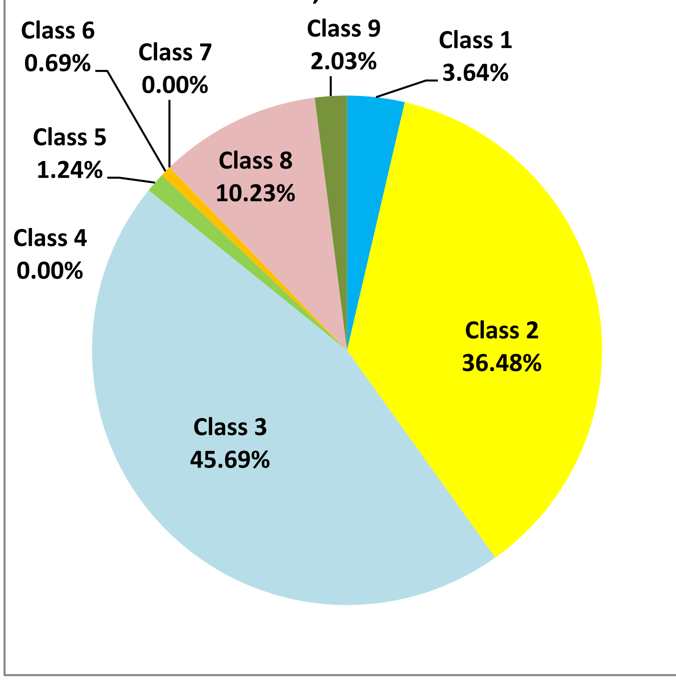


Chart 3.1: Weighted High-Impact Casualties by Hazard Class as Percent of Total, 2005-2009

Source: HIP, February 2011

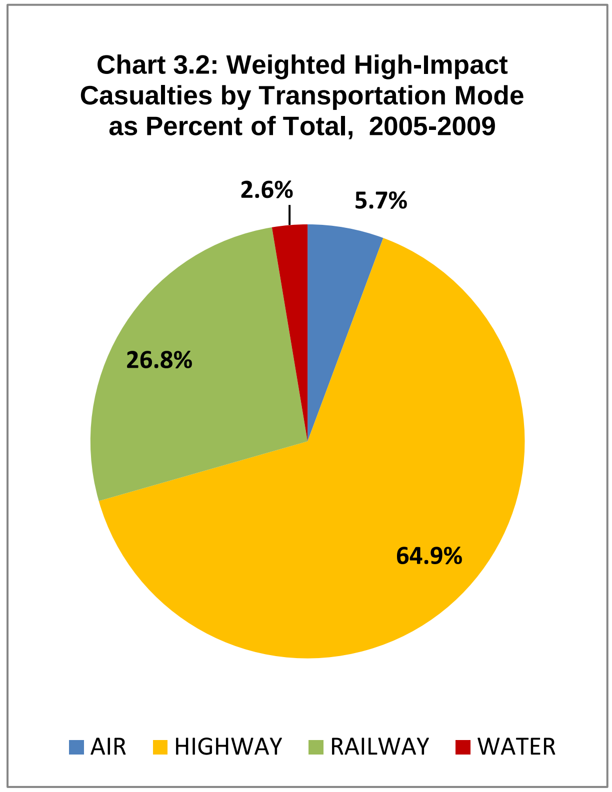
While hazard class serves as a functional summary shorthand for commodities, failure mode is related more closely to mode of transportation: for example, Derailments are naturally only a risk for railways. **Table 3.1** further illustrates the impact of the mode of transportation when considering fatalities and injuries caused by hazardous materials.

Table 3.1 – Incident Consequences by Transportation Mode, 2005-2009

Mode of Transportation	Total Number of Fatalities	Total Number Hospitalized	Incident Count
AIR	0	41	8,255
HIGHWAY	65	123	75,090
RAILWAY	12	130	3,593
WATER	3	3	386
TOTAL	**80**	**297**	**87,324**

Nearly three quarters of all weighted consequences are attributable to highway incidents (see **Chart 3.2**, below), but casualties *per rail incident* were consistently higher than for all other modes:

- For example, there were 1.3 weighted casualties (fatalities or major injuries) per *casualty-causing* rail incident as opposed to 0.6 for road incidents;
- Over *all* incidents, the difference was even more pronounced: note in particular that there are roughly the same number of major injuries (and a factor of five in fatalities) between the two modes despite there being <u>20</u> times as many incidents recorded on roadways as on railways.



Source: HIP, February 2011

While the incident data PHMSA collects can provide an overview of past consequences and bolster efforts to remediate extant needs for regulation, this information is a lagging indicator. As an agency with a complex mission, PHMSA strives to address emerging threats and prevent catastrophic events for commodities that have not yet amassed a robust record of incident consequences. In these cases, PHMSA reviews data and research information on production, consumption and new technologies associated with hazardous materials.

Emerging risks in hazardous materials commodities include materials ranging from biofuels and compressed hydrogen to fireworks and ammonium nitrate, commodities with an anticipated increase in production and consumption volumes in the United States.

Increasing rail and trucking transport for these commodities is also expected. There remains a need for further analysis of the challenges these commodities may present in transportation.

The Office of Hazardous Materials Safety envisions a further series of reports to pick up where this leaves off, exploring both (1) the dimensions of risk probability attributable to individual commodities or transportation processes and (2) an overview of the distribution of consequences and potential frequency of their occurrence.

The source data for the commodity analysis were obtained from PHMSA's Hazmat Intelligence Portal (HIP) in September 2010 with modifications in February 2011 to account for incidents reported late; the data were cleaned to combine instances of commodities listed under multiple identification numbers (e.g., diesel fuel, which is reportable as both UN1202 and NA1993) and to remove records of casualties not attributable to hazmat. The source data for the analysis of transportation phase and failure mode were obtained from HIP in November 2010.