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Report 3 : Adams Model Simulations of Tank Car Impact

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Report 3: ADAMS Model Simulations of Tank Car Impact

by
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National Research Council Canada
Ottawa

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16. Abstract

This report describes the Automatic Dynamic Analysis of Mechanical Systems (ADAMS) model simulations of multi tank car impacts with fifteen different configurations of hammer and anvil cars. The project was a continuation of a Transport Canada study of a series of multi car impact tests in 1995 and the development of the ADAMS impact model in 1996. A modified ADAMS model was first used to simulate the tested water-filled (160,000 lb) tank car impacts. The impact test results were used to further validate the ADAMS model. Model runs were then performed to generate additional impact data with simulated car payloads increased to a level of 263,000 lb vehicle gross weight. One of the major findings from the analysis is that increasing the impact speed increases the maximum impact force. Controlling the impact speed is the most effective way of limiting the impact force and protecting the tank car structure from damage. The test results and model runs will be used by Transport Canada to refine the allowable impact speeds for tank cars in switchyards and to produce guidelines for tank car structural inspection criteria.

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16. Résumé

Ce rapport décrit la simulation, à l'aide du modèle ADAMS (de l'anglais *Automatic Dynamic Analysis of Mechanical Systems*), du comportement aux chocs de wagons-citernes assemblés en quinze configurations différentes de «rames-béliers» et de «rames-enclumes». Ce projet s'inscrivait dans le prolongement d'une série d'essais aux chocs de wagons-citernes réalisés en 1995 par Transports Canada, et de la mise au point du modèle ADAMS, en 1996. Les chercheurs se sont d'abord employés à valider le modèle en simulant, à l'aide d'une version modifiée de celui-ci, le comportement aux chocs de wagons-citernes remplis d'eau (160 000 lb) pour lesquels ils disposaient de données d'essais en vraie grandeur. Ils ont ensuite procédé à plusieurs passages du modèle, qui ont permis de caractériser le comportement aux chocs de wagons-citernes dont la masse brute augmentait à chaque passage, culminant à 263 000 lb. Une des conclusions marquantes de l'étude est la corrélation entre la vitesse d'accostage et la force maximale de l'impact. Il s'ensuit que la réduction de la vitesse d'accostage représente le plus sûr moyen de limiter la force d'impact et de protéger le wagon-citerne contre tout dommage structural. Transports Canada compte utiliser les données issues des essais et des passages du modèle pour modifier, au besoin, les vitesses d'accostage admissibles dans les gares de triage et pour élaborer des lignes directrices sur les critères d'inspection de la résistance structurale des wagons-citernes.

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EXECUTIVE SUMMARY

This project was initiated in response to a request from Transport Canada to develop regulations with respect to the structural integrity of railway tank cars, to refine allowable impact speeds for rail cars in switchyards, and to produce guidelines for inspection criteria. It was a continuation of the static and dynamic tests [1] conducted in 1995, and the development of the Automatic Dynamic Analysis of Mechanical Systems (ADAMS) impact model [2] in 1996. The ADAMS model revealed phenomena that could affect existing Transport Canada regulations. The validation of the model was based only on the data obtained from single-car impact tests. The multi-car impact tests were required to further validate the model and provide a base for the improvement of the regulations. The results of this work may also be applied by tank car manufacturing companies to improve product designs.

The project included yard impact testing and ADAMS model simulations of tank car impacts. This report describes the ADAMS model simulations of tank car impact.

The yard impact testing was conducted at the impact test facility of the Centre for Surface Transportation Technology (CSTT), National Research Council Canada. Eight stub sill tank cars were used in the tests. The maximum number of hammer tank cars was three and the maximum number of anvil tank cars was five. Fifteen different cases were tested. Their configurations were: a combination of water-filled tank cars, empty tank cars, and a concrete-filled tank car. The cases covered most situations that would occur in the practical operations at a railway switchyard. The test setup, procedure, vehicle configurations, tank car characteristics, instrumentation, and impact results are summarized in this report and described in detail in reference [3]. It should be emphasized that in the actual tests, the loaded tank cars were filled with water for a gross weight of approximately 169,000 lb., and thus were lighter than the design weight of 263,000 lb.

This report covers three main topics:

- Use of the ADAMS system model to simulate water-filled (169,000 lb.) tank car impacts;
- Model validation by comparing simulation results with actual test results; and
- Use of the validated models to predict the impact force of acid-filled (263,000 lb.) tank cars.

Various configurations of hammer cars and anvil cars were considered in the system models. Each vehicle was idealized as a multi-body dynamic system, consisting of masses, linear or non-linear elements, and constraints. The performance characteristics of the friction draft gear were represented by splines and determined by a trial-and-error method from test data. A simple liquid-vehicle interaction model was applied to simulate the liquid behaviour in the tank car.

On the basis of the 15 different test cases, the same number of ADAMS system models were built. The results of the analysis indicate that the calculated maximum impact force

on coupler #1 agrees very well with the test data, thus validating the ADAMS system dynamic models.

The validated models were applied to empty cars and to acid-filled tank cars with a car gross weight of 263,000 lb. The major findings from the analysis of 15 cases are:

- Increasing the impact speed increases the maximum impact force. Controlling the impact speed is the most effective way of limiting the impact force and protecting the tank car structure from damage.
- At the same anvil conditions, the maximum impact force on coupler #1 from a single hammer car is lower than that from a multi-hammer car impact at a given speed. In the case of a multi-hammer car, the mass of the first hammer car is the most critical. It makes a major contribution to the maximum impact force on coupler #1. The second hammer car is less critical, but also makes a significant contribution to the impact force. The other hammer car makes a very minor contribution to the impact force.
- At the same hammer conditions, the mass of the first anvil car is the most critical. It makes a significant contribution to the maximum impact force on coupler #1. The contributions of the other anvil cars to the impact force are minor.

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1. Militaru, D., "Tank Car Stub Sill Analysis", Centre for Surface Transportation Technology, National Research Council Canada, technical report no. CSTT-RYV-CAT-026, May 1996

2. Dong, R. and Militaru, D., "Dynamic Structural Characterization of Stub Sill Tank Cars Utilizing ADAMS and ANSYS Simulation Models", Centre for Surface Transportation Technology, National Research Council Canada, technical report no. CSTT-RYV-TR-010, March 1997

3. Tong, X. and Dong, R., "Transport Canada Multi Tank Car Impact Tests and Analysis, Report 1: Yard Impact Testing". Centre for Surface Transportation Technology, National Research Council Canada. TP13192E (to be published), Transportation Development Centre, March 1998

SOMMAIRE

Cette étude faisait suite au projet de Transports Canada d'élaborer une réglementation concernant l'intégrité structurale des wagons-citernes, de modifier, au besoin, les vitesses d'accostage admissibles dans les gares de triage, et de mettre au point des lignes directrices sur les critères d'inspection des wagons-citernes. Elle s'inscrivait dans le prolongement d'essais statiques et dynamiques [1] menés en 1995, et de la mise au point du modèle ADAMS (de l'anglais *Automatic Dynamic Analysis of Mechanical Systems*) [2], en 1996. Le modèle ADAMS a mis au jour des phénomènes qui pourraient avoir des incidences sur la réglementation actuelle de Transports Canada. Le modèle n'avait été validé que pour des essais aux chocs de wagons-citernes uniques. D'autres essais mettant en jeu des ensembles de wagons s'imposaient donc pour valider de façon plus complète le modèle et fournir une assise solide à la nouvelle réglementation projetée. Les résultats des présents travaux peuvent également servir aux constructeurs de wagons-citernes désireux de perfectionner leurs produits.

L'étude a comporté des essais en gare de triage et des simulations au moyen du modèle ADAMS du comportement aux chocs de wagons-citernes. Ce rapport décrit les simulations à l'aide du modèle ADAMS.

Les essais en gare de triage ont eu lieu aux installations du Centre de technologie des transports de surface du Conseil national de recherches du Canada. Huit wagons-citernes à longrine centrale courte ont alors été utilisés. Les «rames-béliers» étaient constituées d'au plus trois wagons, et les «rames-enclumes», d'au plus cinq wagons. Quinze essais ont été réalisés, mettant en jeu diverses configurations comportant des wagons-citernes remplis d'eau, des wagons-citernes vides et un wagon-citerne rempli de béton. La gamme des essais reproduisait la plupart des situations d'impact susceptibles de survenir dans une gare de triage ferroviaire. Le banc d'essai, le protocole, les configurations mises en oeuvre, les caractéristiques des wagons-citernes, l'instrumentation et les résultats sont résumés dans ce rapport et exposés en détail dans le rapport en référence [3]. Il convient de noter que les wagons-citernes remplis d'eau utilisés pour les essais en vraie grandeur avaient une masse brute de 169 000 lb, ce qui est en deçà de leur masse de calcul, de 263 000 lb.

Ce rapport aborde trois grands sujets :

- l'utilisation du modèle ADAMS pour simuler le comportement aux chocs de wagons-citernes remplis d'eau (169 000 lb);
- la validation du modèle, par la comparaison des résultats des simulations avec les résultats des essais en vraie grandeur;
- l'utilisation des modèles validés pour prévoir la force d'impact de wagons-citernes remplis de solution acide, pesant 263 000 lb.

Diverses configurations de «rames-béliers» et de «rames-enclumes» ont été modélisées. Chaque ensemble était étudié comme un système dynamique à composants multiples, constitué de masses, d'éléments linéaires ou non linéaires et de restrictions. Les caractéristiques de performance de l'appareil de traction à friction, représentées par des

splines, ont été déterminées par une méthode d'approximations successives appliquée aux données d'essai. Un modèle simple d'interactions liquide-véhicule a servi à simuler le comportement des liquides à l'intérieur des wagons-citernes.

Les 15 configurations d'essai ont donné lieu à autant de modèles de systèmes dynamiques ADAMS. Les résultats des analyses révèlent une concordance entre la force d'impact maximale calculée à l'attelage n° 1 et les données d'essai, ce qui constitue une validation des modèles de systèmes dynamiques ADAMS.

Les modèles ainsi validés ont été appliqués à l'étude du comportement aux chocs de wagons vides et de wagons-citernes remplis d'une solution acide et ayant une masse brute de 263 000 lb. Voici les grandes conclusions de l'analyse de 15 configurations :

- L'augmentation de la vitesse d'accostage augmente la force d'impact maximale. La limitation de la vitesse d'accostage est le plus sûr moyen de limiter la force de l'impact et de protéger le wagon-citerne contre tout dommage structural.
- Pour des configurations de «rames-enclumes» équivalentes, la force d'impact maximale exercée sur l'attelage n° 1 par un wagon bélier unique est plus faible que celle engendrée par l'impact d'une «rame-bélier» de wagons multiples, à une vitesse donnée. Dans le cas où la «rame-bélier» est composée de wagons multiples, la masse du premier wagon bélier est celle dont le rôle est le plus déterminant sur la force de l'impact mesurée à l'attelage n° 1. Le deuxième wagon d'une «rame-bélier» à wagons multiples a un effet moindre, mais quand même significatif, sur la force de l'impact. Quant au troisième wagon de la «rame-bélier», son apport à la force de l'impact est négligeable.
- Pour des configurations de «rames-béliers» équivalentes, la masse du premier wagon-enclume est déterminante. Elle contribue pour beaucoup à la force maximale du choc engendré sur l'attelage n° 1. L'apport des autres wagons-enclumes à la force de l'impact est négligeable.

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1. Militaru, D., "Tank Car Stub Sill Analysis", Centre de technologie des transports de surface, Conseil national de recherches du Canada, rapport technique n° CSTT-RYV-CAT-026, May 1996

2. Dong, R. et Militaru, D., "Dynamic Structural Characterization of Stub Sill Tank Cars Utilizing ADAMS and ANSYS Simulation Models", Centre de technologie des transports de surface, Conseil national de recherches du Canada, rapport technique n° CSTT-RYV-TR-010, March 1997

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1.0 INTRODUCTION

Railway stub-sill type tank cars are often used to transport dangerous goods. Their damage may result in the loss of property and may have serious impacts on safety, life, and the environment. It is generally believed that high impact force in the railway switchyard is one of the major causes of crack initiation or even direct damage to the tank cars. In 1995, a series of static and dynamic tests [1] were carried out for Transport Canada at the Centre for Surface Transportation Technology (CSTT), National Research Council Canada (NRC), as the first step in understanding the characteristics of the impact forces and stresses within stub-sill cars. To further investigate the behavior of the stub-sill cars under impact, a tank car impact model utilizing the state-of-the-art computer simulation software package, ADAMS (Automatic Dynamic Analysis of Mechanical Systems), was developed at CSTT [2]. The theoretical model was validated by the test data obtained.

In October 1997, Transport Canada contracted NRC's CSTT to conduct a series of dynamic impact tests using CSTT's impact facility. The objectives were to provide more tank car impact force data under various vehicle configurations and operating conditions, to develop a new fluid-flow model, and to further validate the previously developed tank car impact model. The series of dynamic impact tests were conducted between October 1997 and December 1997. The test setup, procedure, vehicle configurations, tank car characteristics, instrumentation, and impact results are summarized in this report and described in detail in reference [3]. It should be emphasized that in the actual tests, the loaded tank cars were only filled with water for a gross weight of approximately 169,000 lb., and as such were lighter than the design weight of 263,000 lb.

This report covers three main topics:

- ADAMS system model used to simulate water-filled (169,000 lb.) tank car impacts;
- Model validation by comparing simulation results with actual test results; and
- Validated models are used to predict the impact force of acid-filled (263,000 lb.) tank cars.

2.0 TEST SETUP

2.1 Test Consists

The test consists were designed to cover most of the car configurations that would occur in practical operations in a railway switchyard. They were classified into six groups for test purposes, as shown in Figures 1 to 6. The Group 1 tests were designed to investigate the effects of the number of hammer cars on the impact force. The number of the anvil cars was fixed in the test group. Among the five anvil cars, four were water-filled tank cars (98% fill level) and the remaining one was a concrete-filled tank car in Cases 2 and 3. In case 1, all five anvil cars were water-filled tank cars (98% fill level). The Group 2 and Group 3 tests were designed to investigate the effects of the number of anvil cars on the impact force. In Group 2 tests, three water-filled tank cars were used as hammer cars, while the number of anvil cars was varied. In Group 3 tests, a single water-filled hammer car was used, with the number of anvil cars varied. In Group 4 tests, three water-filled tank cars were used to impact five anvil cars. However, the first hammer car in the test group was empty. The Group 5 test was a repeat of the Group 1 test except that all hammer cars in the group were empty. In Group 6 tests, the first anvil car was empty. This test group was designed to check whether the highest magnitude of impact forces occurs at the striking coupler or other coupler locations.

2.2 Tank Car Characteristics

Photographs of the hammer and anvil tank cars are shown in Figures 7 and 8. A total of nine tank cars were used in the tests and are listed in table:

Table 1 Tank cars used in the tests

Car Number	Year Built	Capacity	Comments
(NRC 1)	05-67	11585GAL/52666L	instrumented car
(NRC 2)	07-68	11493GAL/52248L	
(NRC 3)	09-73	11470GAL/52144L	
PROX 14281 (PROCOR)	05-73	11472gAL/52153L	
PROX 14277 (PROCOR)	05-73	11424GAL/51935L	
PROX 14258 (PROCOR)	11-73	11440GAL/52007L	
PROX 14264 (PROCOR)	04-73	11425GAL/52062L	
PROX 14259 (PROCOR)	11-73	11421GAL/51920L	
(NRC 4)			concrete filled

One of the tank cars, NRC 4, was filled with concrete and positioned at the end of the anvil car consist. All had been previously used in service. They have approximately the same capacity. The tank car used for instrumentation, NRC1, is representative and its characteristics are described below:

Tank car classification:	111A100W
Type of car:	Stub sill design with continuous pad
Year of construction:	1967
Truck type:	Conventional 3-piece truck (36”/914.4mm wheels)

Capacity:	11585 gal imp / 52666 liters
Ld lmt:	210100 lb. / 95300 KG
Ltwt:	52900 lbs. / 24000 KG
Gross weight at rail:	263,000 lb. / 119300 kg
Car length over striker faces:	39’-9” / 12.116m
Distance between truck’s pivots:	28’- 10” / 8.788m
Coupler type:	Type e or f double shelf
Tank length:	36’-9.5” / 11.214m
Tank diameter:	98.5 / 2.502m
Tank shell:	0.5” / 12.7mm – A515 steel
Type of shell:	Not insulated
Surge pressure device:	65 100 psi frangible disc
Typical load:	Sulfuric acid

It should be noted that water was used as the commodity and the total weight on rail was less than normal weight on rail when sulfuric acid is in the tank. Because of this, the impact forces reported are less than what would be expected if tanks were loaded to the normal 263,000 pounds. The ADAMS model is used to predict the impact forces produced, for the various cases, when the loaded tank car weight is 263,000 lb. These results are presented in this report.

2.3 Instrumentation

The instrumentation used during the tests was designed to measure and record various aspects of the tank cars’ responses during a variety of impacts with different impact speeds. The instrumentation used for the impact tests is identified in Table 2.

Table 2 Instrumentation for impact tests

Items Measured	Transducer/Equipment
Impact force	Dynamometer coupler
Impact speed	Speed transducer or laser speed device
Longitudinal acceleration of the instrumented car	Accelerometer
Pressure inside the tank of the instrumented car	Pressure transducer
Longitudinal displacement at the striking coupler	Displacement transducer
Vertical displacement at the striking coupler	Displacement transducer
Vertical displacement of car body at left side of front axle	Displacement transducer
Vertical displacement of car body at left side of rear axle	Displacement transducer
Vertical displacement of car body at right side of rear axle	Displacement transducer
Vertical displacement of car body at right side of rear axle	Displacement transducer

Three dynamometer couplers, strain gauged and calibrated by NRC personnel, were installed in the first anvil car and in an additional tank car, which was used as either a hammer car or an anvil car in terms of the test consists.

The speed of the test car was measured using two different devices. A Patriot model PV-2000B position/velocity transducer and a laser sensor, model WL 12L, manufactured by SICK Optic-Electronics, Inc.
Three accelerometers (Figure 9) were mounted on the first anvil car (instrumented car) to provide the longitudinal acceleration data during the impact. Five pressure transducers (Figure 10) were installed at different locations on the tank to measure the pressure variations during the impact. The locations of these transducers are illustrated in Figure 11. In addition, several displacement transducers were installed to measure the longitudinal and vertical displacement of the chosen coupler and the lift of the car (Figures 12 and 13). Their locations are also shown in Figure 11.

The data acquisition system used in the tests comprised an Analog Devices 2B31L instrumentation amplifier and signal condition cards, a Burr-Brown PCI-20000 data acquisition system, and a PC 486 computer system. The analog signals yielded by the sensors were filtered using a 60 dB per decade low pass filter (3 dB down point, at 600 Hz).

3.0 SYSTEM DYNAMIC MODEL DEVELOPED IN ADAMS

ADAMS is a general-purpose multi-body dynamics software package. It has a powerful user-graphic interface. The feature it provides has made it easy to model non-linear elements such as draft gears and truck suspensions. In the study, ADAMS was employed to develop the model for the railway tank car impact simulation.

3.1 Assumptions

The major assumptions made in developing the system dynamic model are:

- The impact is assumed to occur on a straight track and the reaction is limited to a vertical plane parallel to the rails. This means that only vertical, longitudinal, and pitch motions are allowed for each component in the model.
- The liquid inside the tank always takes a quasi-static shape that depends on the vertical and longitudinal accelerations.
- All couplers remain in contact without any draft or buff forces between them at time of impact.
- Slipping between couplers occurs when the vertical coupler force exceeds the frictional resistance due to the longitudinal coupler force.
- Coulomb's friction law is assumed for the truck friction wedges.

The model of an empty tank car is show in Figure 14.

3.2 Car body model

The car body is modeled as a rigid body.

3.3 Truck Model

The truck bolster is modeled as a rigid body. The connection between the car body and truck bolsters at the center plate is actually very rigid. A hinged joint is used for this connection. This does not allow the separation of the center plate from the center bowl and causes a small increase in the car body's effective mass in the vertical direction when the car body lifts off the bolster. The mass of the truck bolster is relatively small compared to the car body so that the approximation made here will not significantly affect the result. Also, the time period of such a situation is usually very short. The lift-off of the center plate was monitored by the dynamic force on the suspension. The suspension force is equal to zero when the spring reaches its free length. In this way, good stability as well as modeling efficiency is achieved, and the vehicle system is also well represented.

The rest of the truck components are modeled as a lumped equivalent mass. A stiff spring-damper system is used to model the longitudinal stiffness of the truck. It links the bolster and the lumped truck mass in the longitudinal direction. In the vertical direction, a piece-wise linear spring is used to represent the truck suspension. If the relative displacement between the bolster and the side-frame exceeds the static deflection at the truck location, then the car lifts off the truck springs. In such a condition, the reaction force on the truck is taken as zero. If the relative displacement under the dynamic condition exceeds the allowable travel of the truck springs as specified by the designers and manufacturers, then the springs are considered to have bottomed out. Under this condition, an increased bottom stiffness is used to compute the truck reaction force. The combined bottom stiffness consists of the bolster stiffness, the bottomed spring stiffness, and the side-frame stiffness.

The truck friction wedges are energy dissipation elements used in the truck for reducing the amplitudes of truck motion. In the model, the wedges are represented by Coulomb's dry friction damping elements. At every time step, the relative velocity of the car at the truck bolsters is computed; a positive or negative sign is then assigned to the calculated damping force such that the damping force always opposes the motion. The damping force can be constant or can vary with the spring travel distance.

Braking may be applied to the back-up vehicles in some impact cases. A constant force is used to represent the braking force. The force direction, is determined by the longitudinal travel direction of the vehicle.

3.4 Track Model

Although the track equivalent mass has little effect on the coupler impact forces the rail mass is used in the model. The track is assumed to be an elastic support and it is represented by a linear spring-damper system. The track stiffness is calculated based on the track model of a beam on an elastic foundation. For a single wheel, the stiffness is calculated using the following formulas:

$$K_r = 2(4E_r I_r k^3_f)^{0.25} \qquad (1)$$

Where

K_r: Track stiffness per wheel
E_r: Young's modulus for rail steel
I_r: Rail second moment of area
Kf: Foundation stiffness per unit length

The total stiffness for a truck is estimated as

$$\mathbf{K_r} = 4K_r \qquad (2)$$

The track damping is estimated as

$$C_r = 4 \times c_r \times L_r \qquad (3)$$

Where

C_r: Total track effective damping
c_r: Track foundation damping per unit length
L_r: Effective damping track length per wheel

3.5 Models for draft gears and couplers

An equivalent mass is used to represent the coupler, yoke, and a part of the draft gear mass. Its connection to the car body is modeled as a non-linear coupler force in the longitudinal direction, and is constrained to the car body by a translational joint.

The longitudinal coupler force is critical and significantly affects the behavior of the model. The coupler force depends on the draft gear performance characteristics and on the status of the draft gears on the adjacent cars. Draft gears are energy dissipation devices with some special features. The force developed in the draft gear is not only a function of the travel distance of the coupler relative to the car body, but also of the travel direction and speed. The influences of these factors on the force are also non-linear and it is difficult to use a simple function to describe it accurately. The standard performance characteristics are usually obtained from drop hammer tests. The performance characteristics of a Mark 50 draft gear were used in this investigation. Its standard performance characteristics are shown in Figure 15. It is called a Xo–Yo curve in the report.

Several methods have been used by others to model the friction draft gear characteristics. The most popular one is to represent the characteristics with several segments of straight lines and compute the coupler force based on the coupler travel distance and status, as used in [5]. In this study, the travel and recoil curves of the draft gear characteristics were represented by two splines. When the direction of the relative motion changed, the curve used for the computation was switched. The switch was smoothed by a step function built into ADAMS, which gave good stability to the calculation. The available draft gear performance curve is usually up to 500 kips. Beyond this point, a stiffness of 2,400 kips/in. was used to compute the increased portion of the coupling force.

This method does not take into account the influence of the magnitude of the travel speed. Because there is a difference between the static and moving friction coefficients, there is usually a jump in the draft gear force as the travel speed of the draft gear is reduced to zero, as reported in [4]. Such a feature usually creates a sharp peak in the dynamic force, if the full travel length of the draft gear is not saturated. Researchers had found that the performance characteristics of draft gear is a function of impact speed [4]. From test data of multi-tank car impact tests conducted by CSTT in 1997, this phenomenon has been proved again. Figure 16 shows force-deflection curves of draft gear from test data of case 12. The tank car configuration of case 12 is shown in Figure 5. This figure shows that impact speed will change the behavior of the draft gear. It was also found from multi-tank car impact tests, the tank car configurations would affect the behavior of the draft gear at a given speed. As an example, at similar or same speeds, in tank car configurations of cases 2, 12, 15, the performance characteristics of the draft gear are different. The curves are shown in figure 17.

Thus, modification of the standard performance characteristics of the draft gear obtained from drop hammer tests is required before input into the ADAMS model. A trial-and-error method was applied to modify Xo-Yo curve at different speeds and different configurations. The modified Xo-Yo curves used in ADAMS models are shown in Figure 18.

The vertical coupler force depends on the longitudinal coupler force, the relative displacement of the adjacent couplers, and the friction coefficient at the coupling interface. The vertical coupler force is calculated based on the following condition: the relative vertical displacement at adjacent couplers is calculated, and it is dependent on the vertical and rotational or pitch status of the adjacent cars. If the relative displacement does not exceed the vertical coupler slack, the force is considered to be zero. If the slack is exceeded, the vertical coupler force is calculated using the vertical restraining spring stiffness between the coupler and the car body. The friction force is also calculated using the friction coefficient and the longitudinal coupler force. If the friction force is less than the vertical spring force, the friction force is taken as the force acting on the couplers. Otherwise, the spring force is used for the active force on the couplers.

3.6 Liquid-vehicle interaction model

In the tank car impact, a part of the liquid may undergo turbulent flow in a partially filled tank and some part of it may even be separated from its main body. It is very difficult to model the liquid reaction accurately. In this study, it is assumed that the liquid inside the tank always takes a quasi-static shape in the impact process, as shown in Figure 19. The angle (α) between the liquid surface and the horizontal plane depends on the vertical and longitudinal accelerations. With such an assumption, the pressure at the impacted end will achieve a maximum value and gradually reduce as the distance increases from the end. This may not reflect the exact distribution of the pressure, but its basic tendency is consistent with reported experimental data [6].

Based on the above assumption for the liquid reaction shape, the center of gravity (CG) can be calculated for any shape of tank at any fill level using a geometry calculation program. The tank shape can be assumed to be same as that in a static situation because it has little effect on the CG. For various longitudinal accelerations, the CG will move in the space and a CG curve or trace can be found. A spline curve is used to represent the CG curve in the model. Figure 20 shows examples of the curves for several fill levels.

The liquid inside the tank is modeled as a lumped mass and its CG is constrained to the CG curve in the dynamic reaction, as shown in Figure 21. The dynamic reaction force is assumed to take a perpendicular direction to the tangential direction of the CG curve. To consider the energy consumption and the compression effect of the liquid in the impact, a damper is attached to the liquid mass in the longitudinal direction. The damping value should be a function of the fill level and the viscosity of the material contained in the tank. The determination of this function involves a detailed modeling of the fluid reaction under impact conditions and is beyond the scope of this investigation. n this study, the damping value is indirectly estimated from the impact test data. This value is found by approximately matching the theoretical and experimental impact forces at a given impact speed for a given fill level.

The liquid used in this investigation is water. It is found that the damping value increases approximately linearly from the empty to the 98 percent fill level, as shown in Figure 22. However, the damping value increases dramatically at higher fill levels. This is probably because the liquid is effectively compressed at such high levels and it reacts like a water hammer. This observation is consistent to the finding by Ye et al. [7]. It is expected that increasing the viscosity of liquid will increase the equivalent damping value. The total surge force of the liquid is equal to the dynamic force acting on the damper plus the dynamic force acting on the CG curve constraint.

3.7 System model

The relationship between two adjacent couplers is represented by an impact element built into ADAMS. For the purposes of this study, in order to simplify the computations, the pulling force on the couplers was not considered. The couplers can separate freely, in which case the longitudinal and vertical coupling forces are equal to zero. The coupler pulling force can be considered without principal difficulties.

Fifteen cases of ADAMS system models were built. These tank car configurations of the ADAMS models are shown in Appendix A. They are the same as the test configurations.

Each system model consists of two groups. One is the hammer car group; the other is the anvil car group. An impact element (impact force) is built into two adjacent couplers. Each group is a combination of different unit tank cars. Case 10 is an example; its schematic diagram of the system model is shown in Figure 48 (app1-4) of Appendix A. The hammer car group consists of an empty tank car (the first hammer car) and two liquid-filled tank cars (the second and the third hammer cars). The anvil car group consists of four liquid-filled tank cars (leading anvil cars) and one concrete-filled tank car (the fifth anvil car).

3.8 Major parameters used in the modeling

The major parameters employed in this study are taken from the cars used for the impact tests and are listed in Table 3:

Table 3 Major parameters used in the modeling

	Description	Value	Unit
1	Total weight of the concrete-filled tank car	232,000	lb.
2	Total weight of the empty tank car	54,868	lb.
3	Stub-sill tank car capacity	52,666	litres
4	Total weight of each truck	9,800	lb.
5	Equivalent mass for coupler, yoke, and draft gear	800	lb.
6	Truck suspension stiffness per truck	20,000	lb. / in.
7	Truck spring travel length	3.6876	In.
8	Track stiffness per truck	1.736e6	lb. / in.
9	Track damping per truck	800	lb.-sec / in.
10	Friction force on the truck friction wedge	2,000	lb.
11	Friction coefficient on coupler	0.3	
12	Total weight of a water-filled tank car (98% fill level)	169,000	lb.
13	Total weight of an acid-filled tank car (98% fill level)	263,000	lb.

4.0 MODEL VALIDATIONS

Analytical results of 15 different combinations of the water-filled tank cars, empty tank cars, and the concrete-filled tank car are shown in Figures 23 to 37 from the calculated maximum impact forces on coupler #1, in comparison to the test data, it can be seen that:

- For cases 1, 5, 6, 7, 8, 9, 10, 13, 14, and 15, analytical results match the test data.

- For cases 2, 3, 4, 11, and 12, analytical results are slightly over estimated, but on the safe side

In the most cases, analytical results have very good agreement to the test results. In some cases, analytical results are in the range of the test data and on the safe side. The comparison of test data and theoretical ADAMS Models can be seen on the plots shown in Figures 23 to 27. Therefore, the ADAMS system models are considered validated by the test data. These system models may be used to predict the maximum impact forces in multi tank car impacts with the combinations of the acid-filled, empty, and concrete-filled tank cars.

5.0 MODEL APPLICATIONS

The validated ADAMS system models were used to predict the maximum impact forces on coupler #1 for both hammer and anvil cars; the weight of those filled with water at 169,000 lb., was increased to 263,000 lb. The empty cars in the field tests remained empty in the ADAMS analysis.

5.1 System models to acid-filled and empty tank cars

All 15 system models used to simulate acid-filled and empty tank cars are the same as those used in the case of water-filled tank cars, their configurations are shown in Appendix A. The only difference is to modify the amount of mass for the “liquid” part of the model for both hammer and anvil cars by increasing their gross weight from 169,000 to 263,000 lb. The empty cars remained empty.

5.2 Analytical results

The analytical results of the 15 cases in which all liquid-filled cars weighed 263,000 lb. gross weight are shown in figures 23 to 37. Applying interpolation to the analytical results, the maximum impact forces at speeds of 5 mph, 6 mph, 7.5 mph and 9 mph were determined and are listed in Table 4.

5.3 Result analysis

The major findings from the analytical results of the 15 cases are almost the same as those from the test results, and are outlined below.

Table 4 Maximum impact force on coupler #1 (Klb) at speeds of 5,6,7.5,and 9 mph

Impact Speed	Maximum impact force on coupler #1 (klb)														
(mph)	Case 1	Case 2	Case3	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9	Case 10	Case 11	Case 12	Case 13	Case 14	Case 15
5	360	720	720	680	700	710	400	410	400	450	250	270	270	290	450
6	540	1010	1020	970	990	1000	590	620	600	680	340	370	380	400	680
7.5	980	1460	1460	1420	1420	1440	990	1050	1040	1010	590	630	640	670	1020
9	1600	1890	1880	1860	1860	1870	1530	1630	1600	1310	950	1030	1040	1090	1320
Hammer/ Anvil Combinations	IF/ 5F*	2F / 5F	3F / 5F	3F / 1F	3F / 2F	3F / 3F	1F / 1F **	1F / 2F	1F / 3F	2F,1E / 5F	1E / 5F	2E / 5F	3E / 5F	1F/1E,4F	2F/1E,4F

* 1F / 5F stands for 1 full hammer car / 5 full anvil cars, where F: Full car, E: empty car

** Miner / Cardwell-Westinghouse provided a set of actual 1F / 1F test results that are shown in appendix 2. It was shown that for case 7, higher coupler forces on coupler #1 were produced in comparison to the ADAMS results.

5.3.1 Effect of the impact speed

In all 15 cases, the curve of maximum impact force vs. impact speed for each case shows that the maximum impact force increases as impact speed increases.

5.3.2 Effect of the number of hammer cars

To investigate the effects of the number of hammer cars on the impact force, various numbers were used in the tests, one hammer car in Case 1, two hammer cars in Case 2, and three hammer cars in Case 3. All hammer cars were 98% full. In each case, five anvil cars were used. In Case 2 and Case 3, four of these anvil cars were tank cars (98% filled) and the last one was a concrete-filled tank car. In case 1, all five anvil cars were tank cars (98% filled). As be seen from the test results, the maximum magnitude of peak impact forces in all cases occurred at the striking coupler, namely coupler #1. At low impact speed (less than 4 mph), the number of hammer cars had little effect on the maximum magnitude of peak impact force. When the impact speed was beyond 5 mph, the peak impact force at coupler #1, measured in Case 1, was significantly lower than those measured in Case 2 and Case 3. However, for the same speed range, the peak impact forces at coupler #1, measured in Cases 2 and 3, were only marginally different. These observations suggest that:

- At low impact speed (less than 4 mph), the number of cars has little effect on the peak impact force.

- At high impact speed (larger than 5 mph), the maximum impact force with two hammer cars is higher than that with only one hammer car. However, increasing the number of the hammer cars from two to three influences the maximum impact force only marginally. Based on this finding, it can be predicted that further increasing the number of hammer cars would have little effect on the maximum impact force, but the high-level impact force could last longer as the number of hammer cars is increased.

These observations were consistent with the results obtained from the model simulation revealing the effect of the number of hammer cars. Cases 1, 2, 3, 10, 11, 12, and 13 have similar or same anvil conditions, force/speed curves of Cases 1, 2, and 3 are on figure 38. Force/speed curves 11, 12, and 13 are on figure 39. Force/speed curves of Cases 1, 2, and 10 are shown on figure 40. It is found from those figures that the maximum impact force on coupler #1 from a single hammer car is lower than that from a multi-hammer car impact at a given speed. In the case of multi-hammer cars, the mass of the first hammer car is the most critical. It makes a major contribution to the maximum impact force on coupler #1. The second hammer car is less critical in comparison to the first one, but it still makes a significant contribution to the impact force. The other additional hammer car makes a very minor contribution to the impact force.

5.3.3 Effect of the number of anvil cars

To investigate the effects of the number of anvil cars on the impact force, six cases in Group 2 and Group 3 were considered. In Group 2 tests, three water-filled cars were used as hammer cars, while in Group 3 tests, a single water-filled tank car was used as a hammer car. The number of anvil cars used in these tests was varied from one to three cars. In Cases 4 and 7, only one anvil car was used. In Cases 5 and 8, two anvil cars were used. In Cases 6 and 9, three anvil cars were used. All anvil cars and hammer cars were tank cars with 98% fill.

As can be seen from the test data, the maximum magnitude of the peak impact forces occurred at the striking coupler in all test cases except Cases 8 and 9 in certain speed ranges. For Cases 8 and 9, in speed ranges between 5 to 6 mph, the maximum magnitude of peak impact force at coupler locations other than the striking coupler is slightly higher than that at the striking coupler. In these cases, the peak impact forces were not high and they may not be of practical concern.

At low impact speed (less than 5 mph), the maximum magnitude of peak impact force increased slightly as the number of anvil cars increased. When the impact speed is beyond 6 mph, the peak impact force at coupler #1, measured in Case 4, is relatively lower than those measured in Cases5 and 6. As the number of anvil cars further increased from two to three, as from Case 5 to Case 6, the peak impact force at coupler #1 was also increased. However, the amount of increase was not as significant as from one anvil car to two anvil cars. In Cases 8 and 9, the change in the anvil cars had little effect on the impact forces.

These observations suggest that:

- One anvil car is not sufficient to represent a general impact situation.
- However, a large number of anvil cars, say more than three, may not be required to represent a general impact situation for obtaining the maximum impact force.

Note also that the number of hammer cars and anvil cars as identical in Case 6. Hence, the system configurations in the case were theoretically symmetrical. Thus, the peak coupler forces at locations 2 and 3, obtained from the tests, were very close. This suggests that the impact forces on the hammer and anvil cars would be identical if their configurations were the same.

These observations were consistent with the results obtained from the model simulation.

In analysis, Cases 1 and 14, Cases 2 and 15, Cases 3, 4, 5, and 6, Cases 1, 7, 8, and 9, each of them, have the same hammer conditions. Force/speed curves of Cases 1 and 14 are on figure 41. Force/speed curves of Cases 2 and 15 are in figure 42. Force/speed curves of Cases 3, 4, 5, and 6 are on figure 43. Force/speed curves of Cases 1, 7, 8, and 9 are in figure 44. It can be found from those figures that the mass of the first anvil car is the most critical element in the anvil cars. It makes a significant contribution to the maximum impact force on coupler #1. The contributions of the other anvil cars to the impact force are minor.

5.3.4 Effect of empty car as hammer car

The effect of an empty car as hammer car on the impact force was considered in Case 10, in which the first hammer car was empty, and in Cases 11, 12, and 13. Comparing Case 10 with Case 3, one can observe that by using an empty tank car, the peak impact force at the striking coupler was reduced significantly. This suggests that the worse case should be when the tank cars involved in the impact are loaded. If the striking tank car were empty, either on hammer side or on anvil side, or on both, the impact force would be reduced. Comparing Cases 11, 12, and 13, with their similar consists of loaded hammer cars, one can conclude that when using empty hammer cars the impact speed can be increased by about 2 mph to generate the same level of peak impact forces as with 98% loaded hammer cars. Only if, the commodity in the tank car has a density similar to that of water.

6.0 CONCLUSIONS

In the system models, various configurations of hammer cars and anvil cars were considered. Each vehicle was idealized as a multi-body dynamic system, consisting of masses, linear or non-linear elements, and constraints. The performance characteristics of the friction draft gear were represented by splines and determined by trial-and-error method from test data. A simple liquid-vehicle interaction model was applied to simulate the liquid behavior in the tank car.

Referring to 15 different test cases with water-filled tank cars and empty cars described in [3], the same number of ADAMS system models was built, and are shown in Appendix A. The results of the analysis are shown in Figures 23 to 37. It indicates that the calculated maximum impact force on coupler #1 has very good agreement to the test data. This provides validation of the ADAMS system dynamic models.

The validated models were applied to acid-filled tank car with car gross weight of 263,000 lb. and empty cars. The major findings from the analysis of the 15 cases are outlined below:

- Increasing the impact speed increases the maximum impact force. Controlling the impact speed is the most effective way of limiting the impact force and protecting the tank car structure from damage.
- Under the same anvil conditions, the maximum impact force on coupler #1 from a single hammer car is lower than that from a multi-hammer car impact at a given speed. In the case of multi-hammer cars, the mass of the first hammer car is the most critical. It makes a major contribution to the maximum impact force on coupler #1. The second hammer car is less critical in comparison to the first one, but it still makes a significant contribution to the impact force. The other hammer car makes a very minor contribution to the impact force.
- Under the same hammer conditions, the mass of the first anvil car is the most critical. It makes a significant contribution to the maximum impact force on coupler #1. The contributions of the other anvil cars to the impact force are minor.

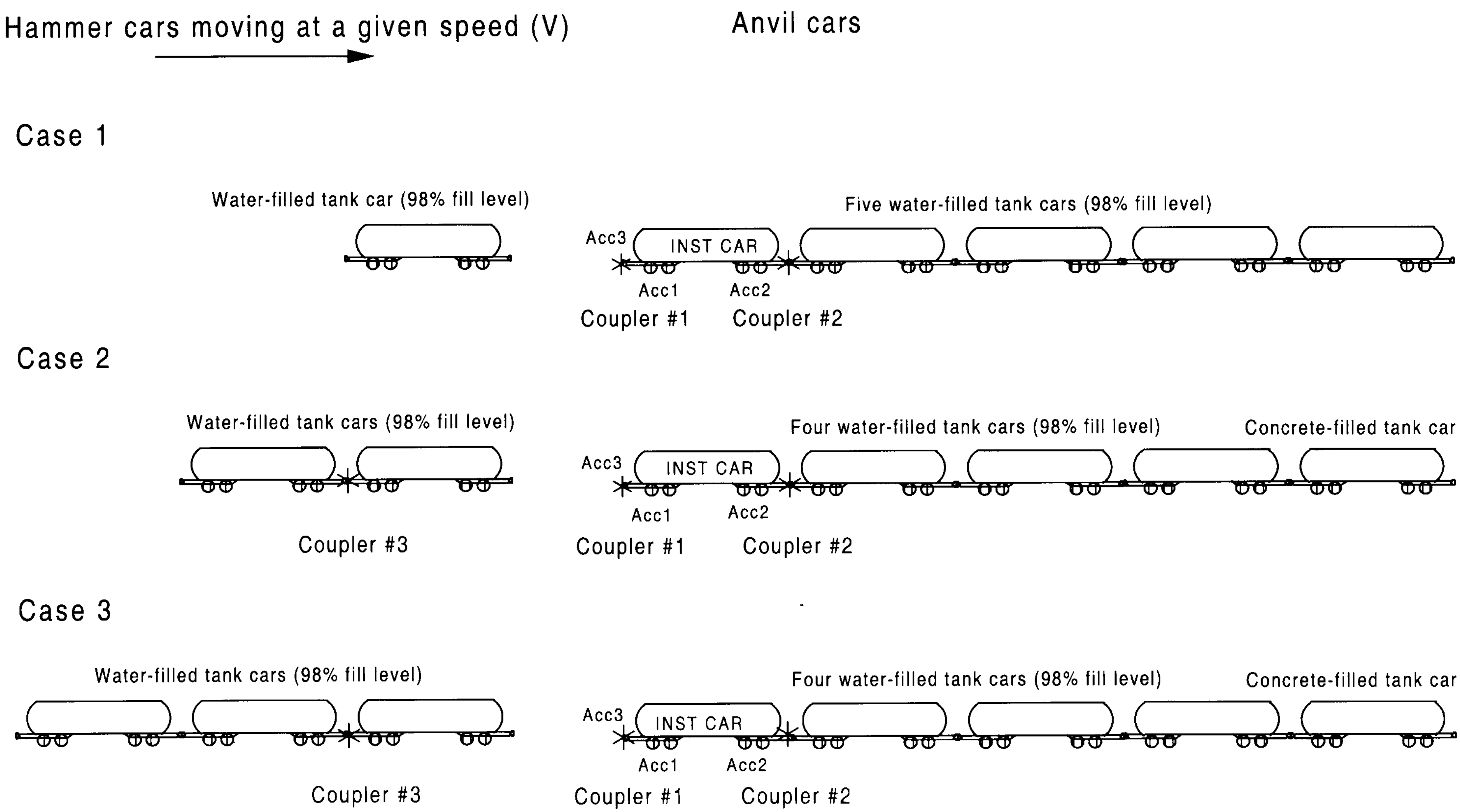


Figure 1. Tank car configurations in Group 1 Tests

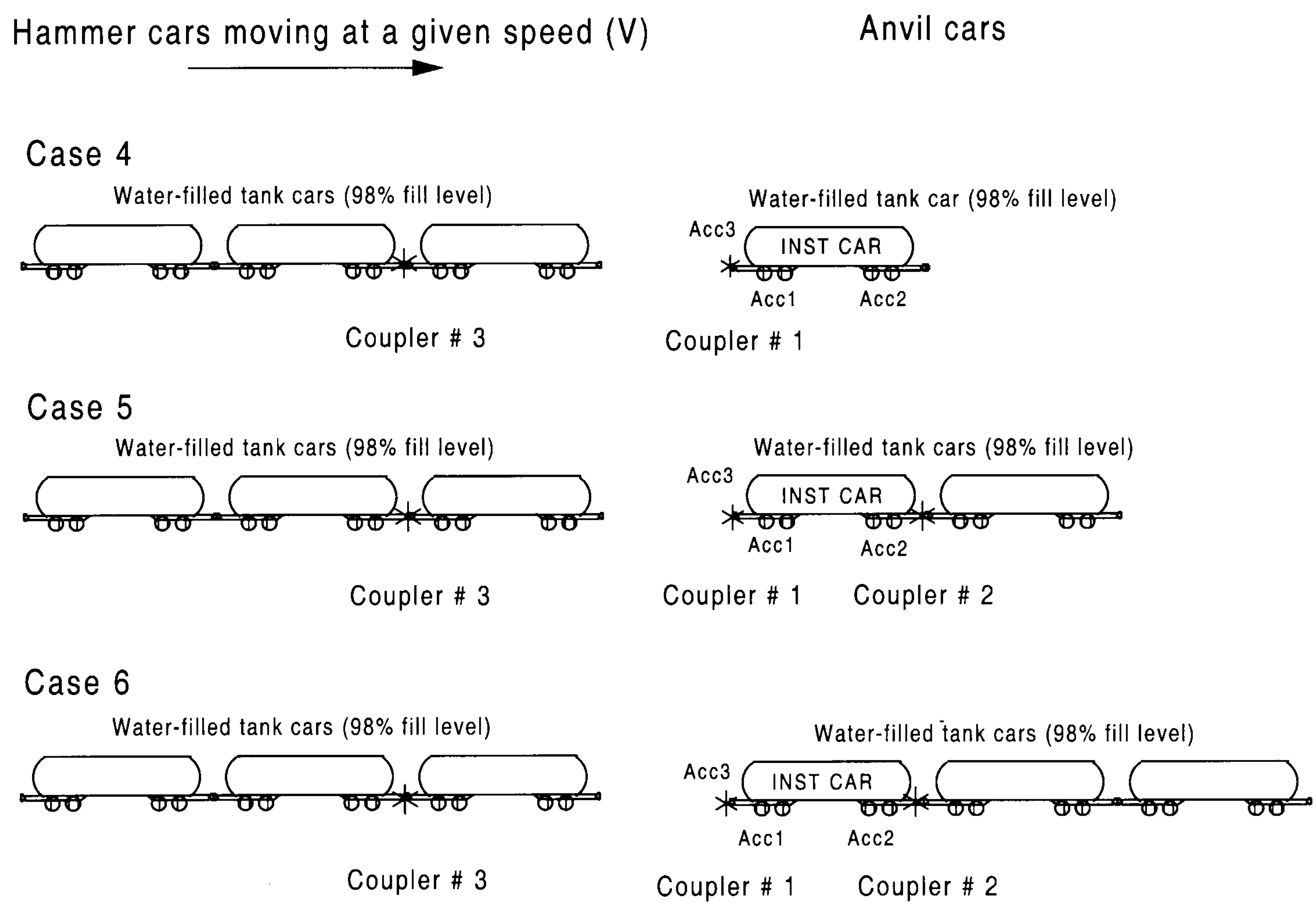


Figure 2. Tank car configurations in Group 2 Tests

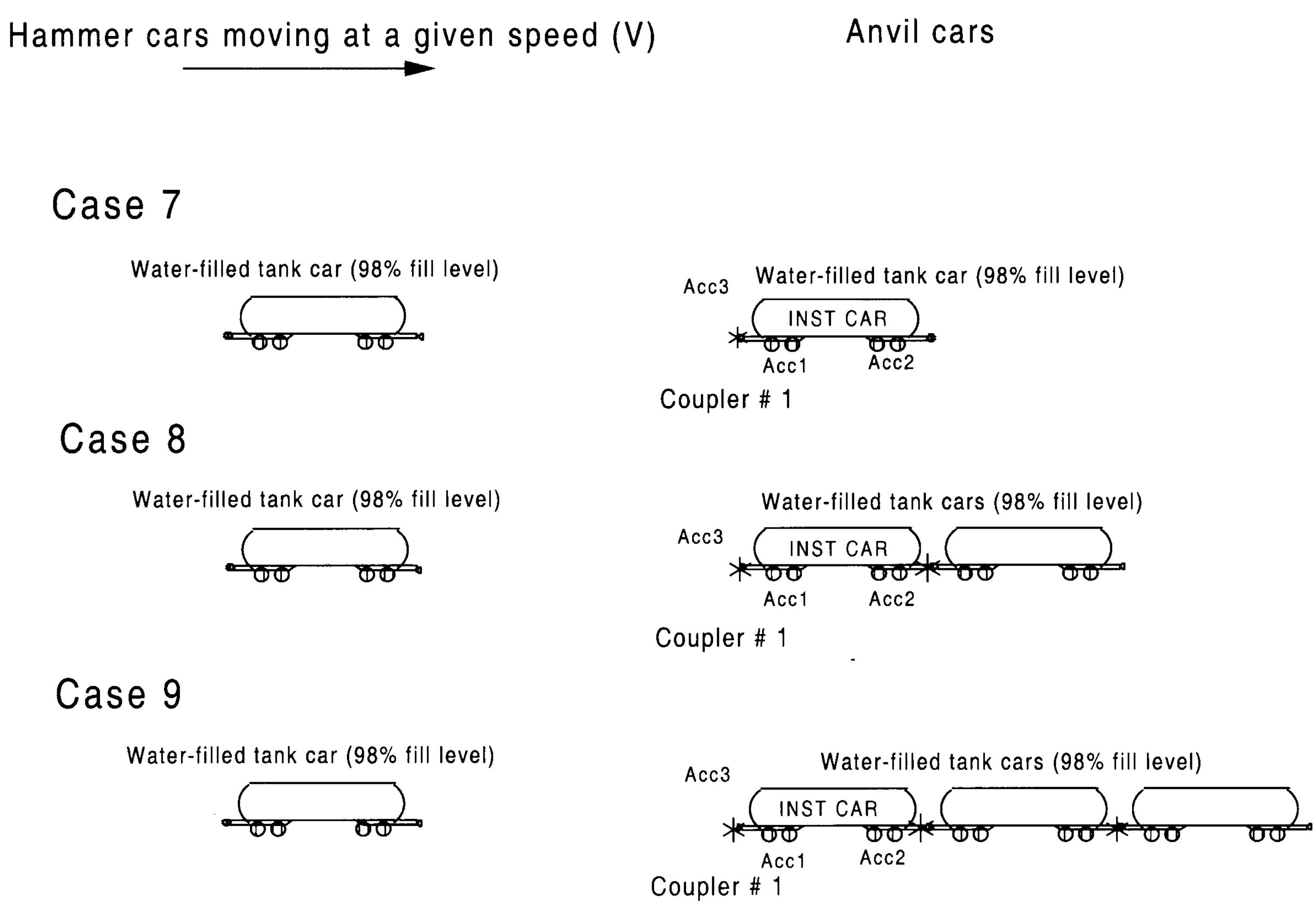


Figure 3. Tank car configurations in Group 3 Tests

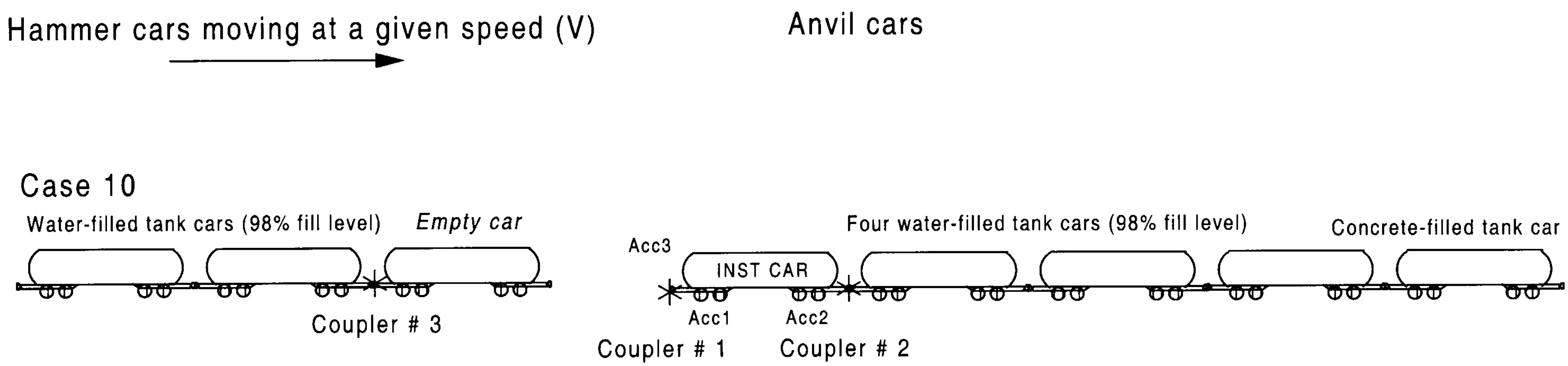


Figure 4. Tank car configurations in Group 4 Tests

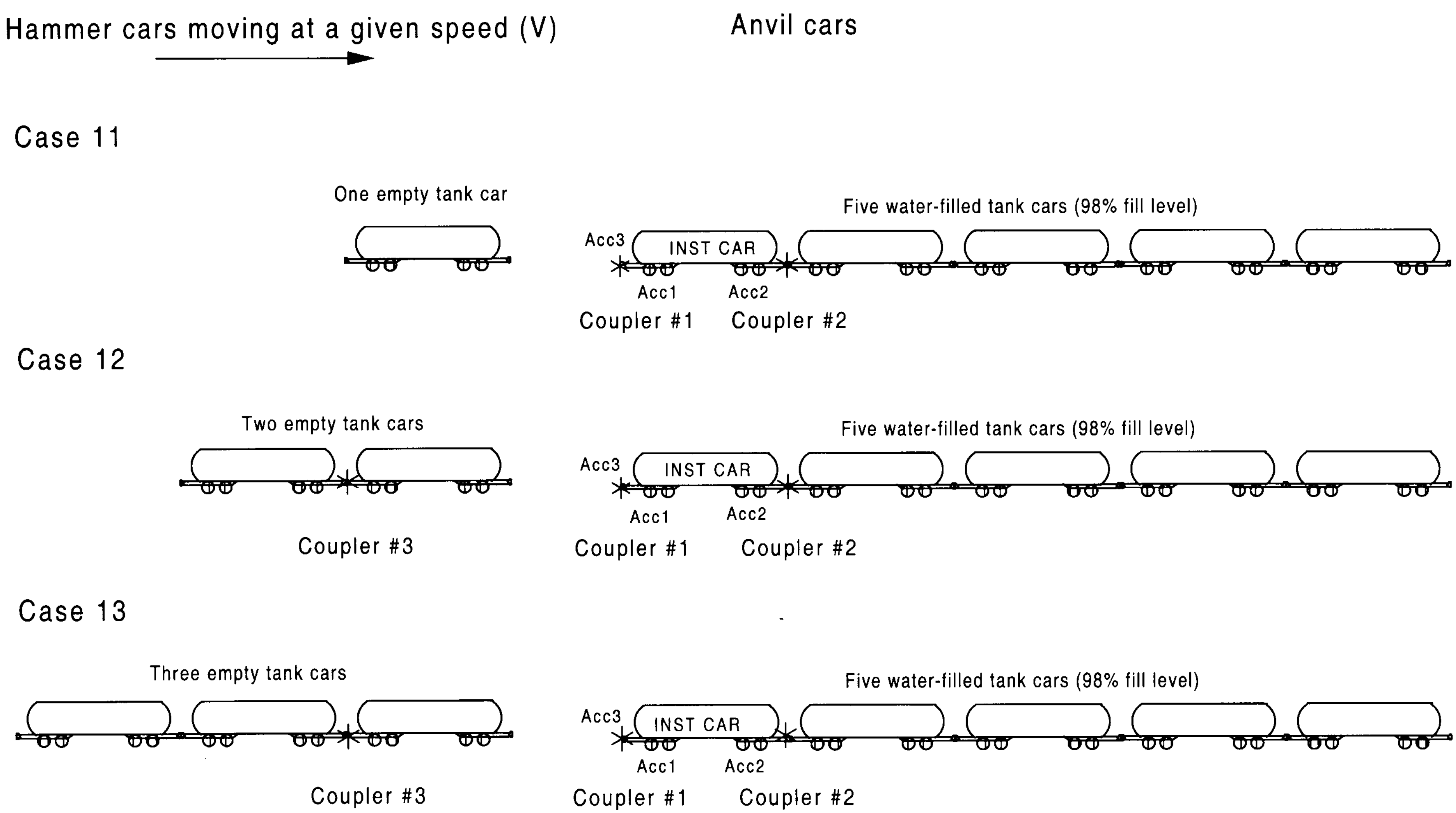


Figure 5. Tank car configurations in Group 5 Tests

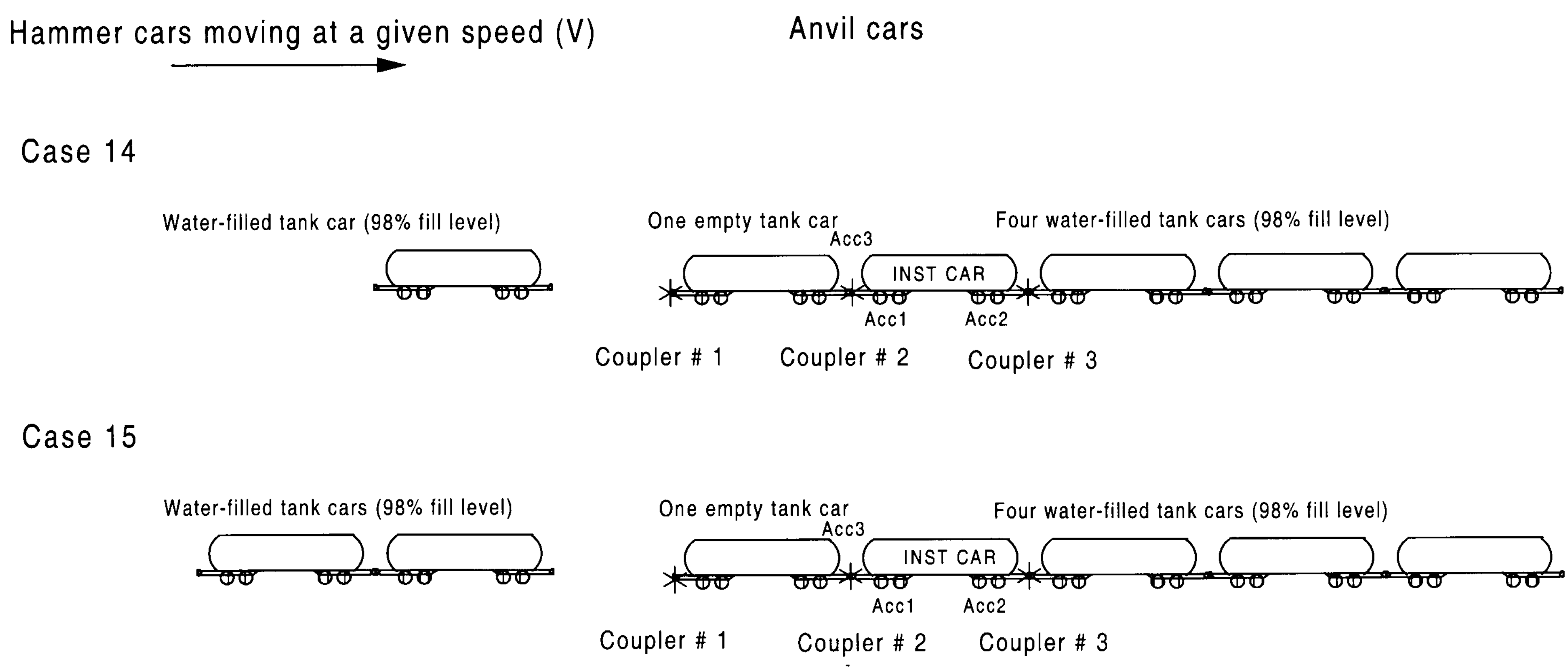


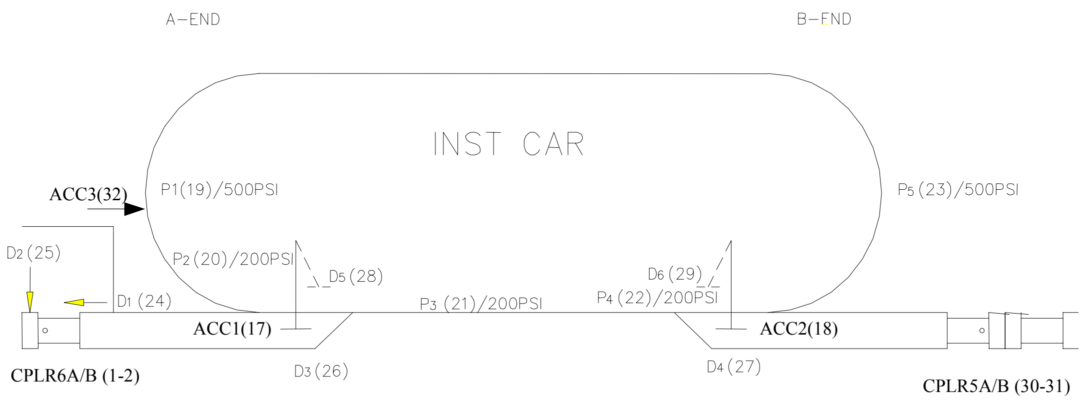
Figure 6. Tank car configurations in Group 6 Tests

Figure 7 Hammer cars positioned for impact tests

Figure 8 Anvil cars positioned for impact tests

Figure 9 Accelerometer

Figure 10 Pressure transducer



Note: The number in the bracket is the channel no. of the data acquisition system as in Table 2.

CPLR6A(1): Coupler force	CPLR6B(2): Coupler force	SPEED2(3): Impact speed
CPLR1A(9): Coupler force	ACC1(17): Acceleration #1	ACC3(32): Acceleration #3
ACC2(18): Acceleration #2	P1(19) Pressure #1	P2(20): Pressure #2
P3(21): Pressure #3	P4 22): Pressure #4	P5(23)Pressure #5
CPLR5A(30): Coupler force	CPLR5B(31): Coupler force	

D1(24): Longitudinal displacement of coupler
D2(25): Vertical displacement of coupler
D3(26): Vertical displacement of car body at left side of front axle
D4(27):Vertical displacement of car body at left side of rear axle
D5(28): Vertical displacement of car body at right side of front axle
D6(29):Vertical displacement of car body at right side of rear axle
CPLR1B(10): Coupler force (Not shown on this diagram, see tank car configuration diagrams)

Figure 11 Locations of sensors on the instrumented car

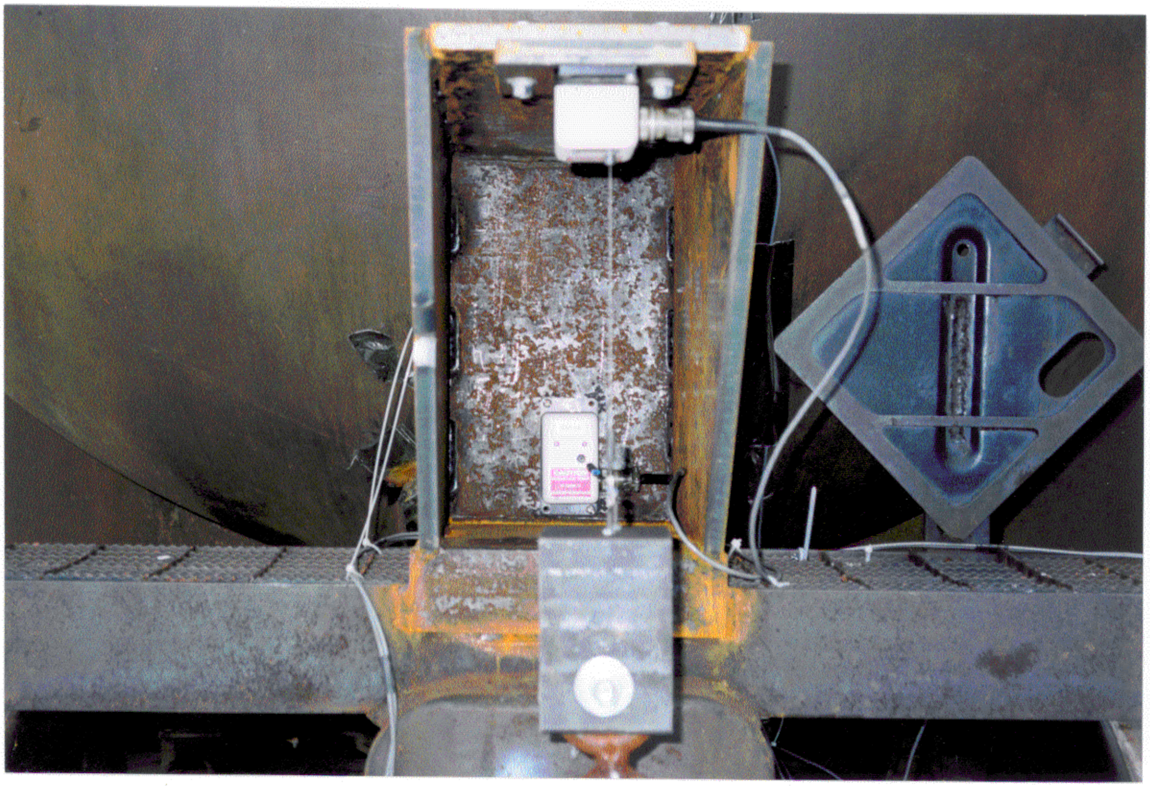


Figure 12   Longitudinal and vertical displacement transducers
For displacement measurement at coupler # 1

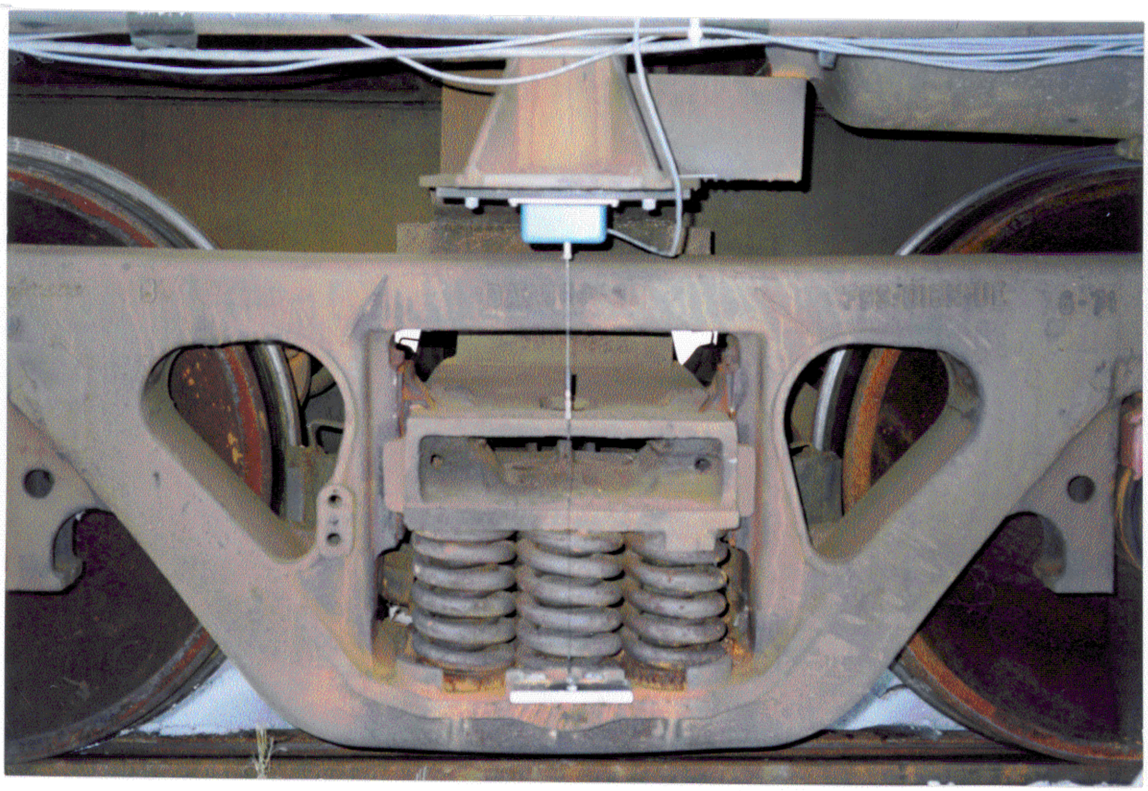
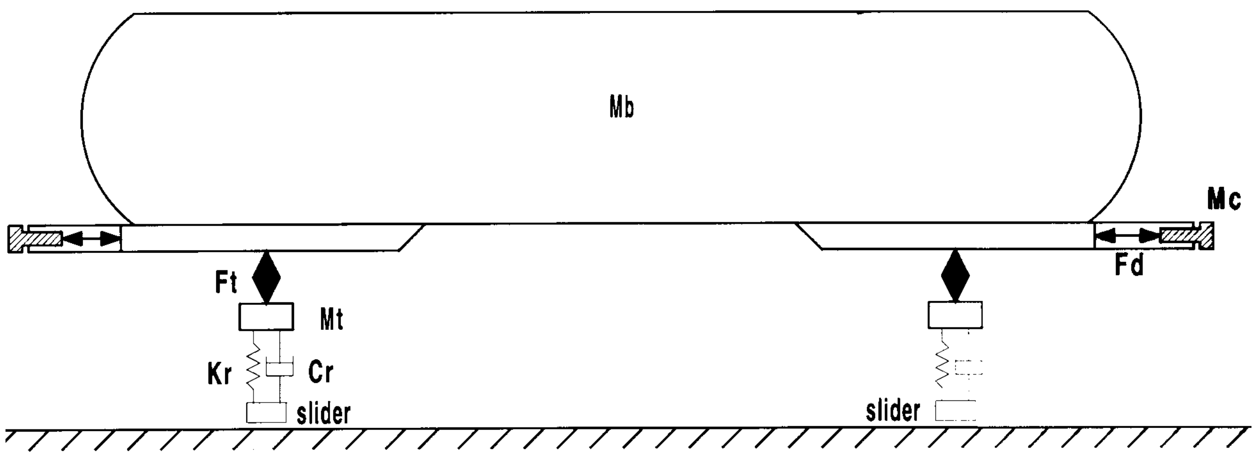


Figure 13   Vertical displacement transducer for measuring car lift



Mc: Coupler equivalent mass
Mt: Truck equivakent mass
Mb: Car body mass
Fd: Non-linear force representing the draft gear
Kr: Track stiffness per track
Cr: Track damping per track
Ft: Non-linear force representing the body-truck connection
(friction damping included in this force)

Figure 14 Vehicle System Model

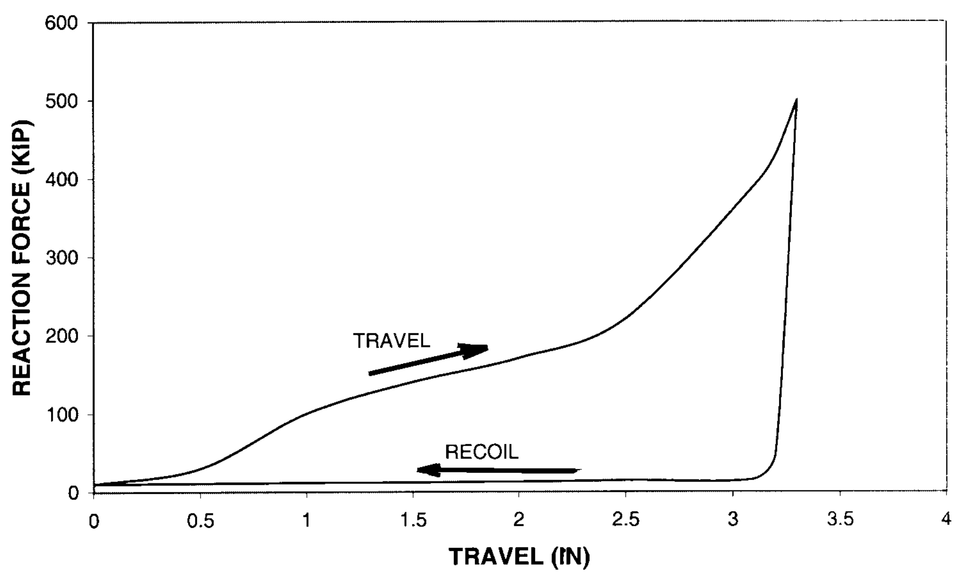


Figure 15 Craft Gear (MARK 50) Performance Characteristics

Figure 16: Impact speeds will change behavior of draft gear

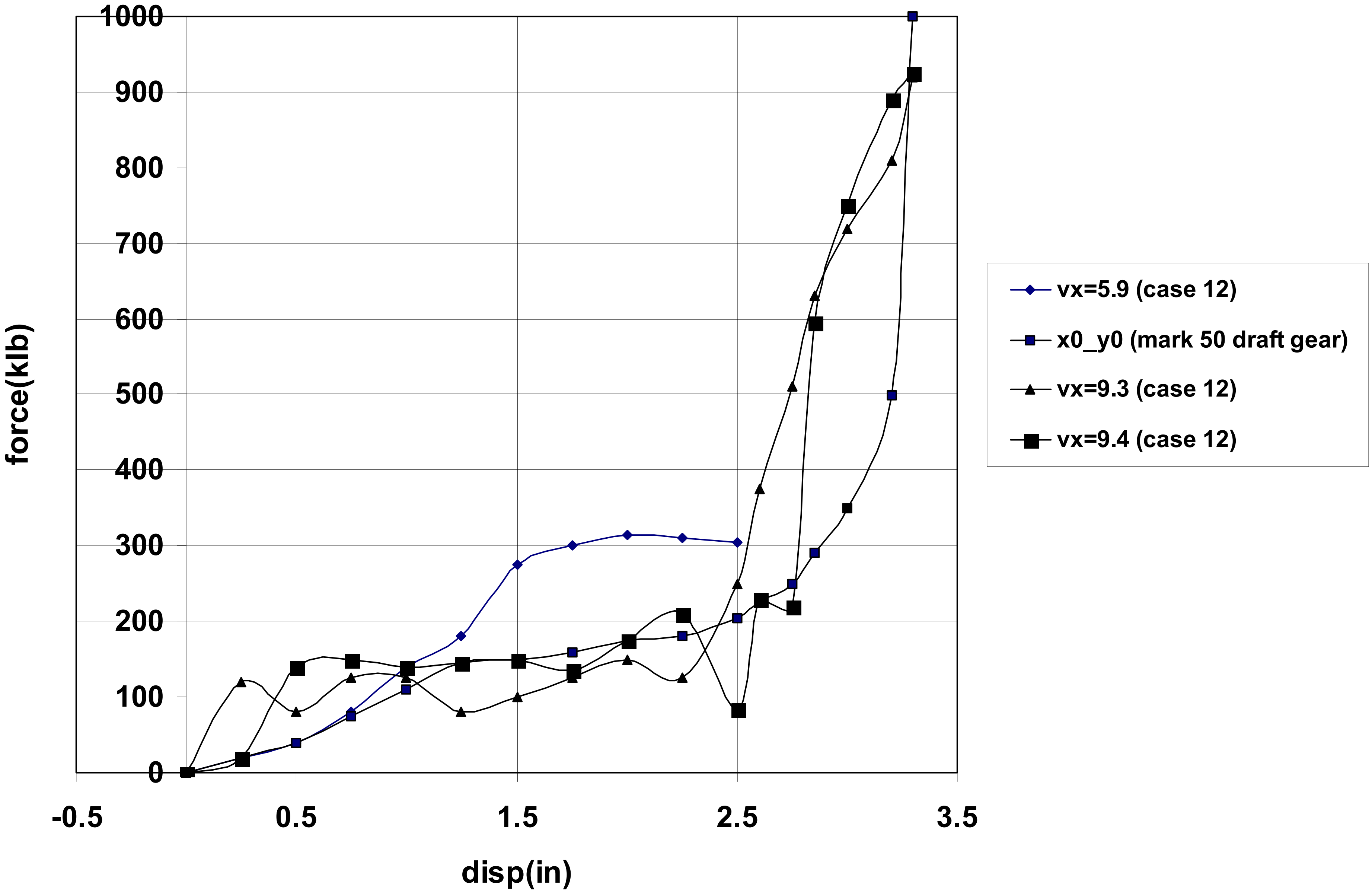
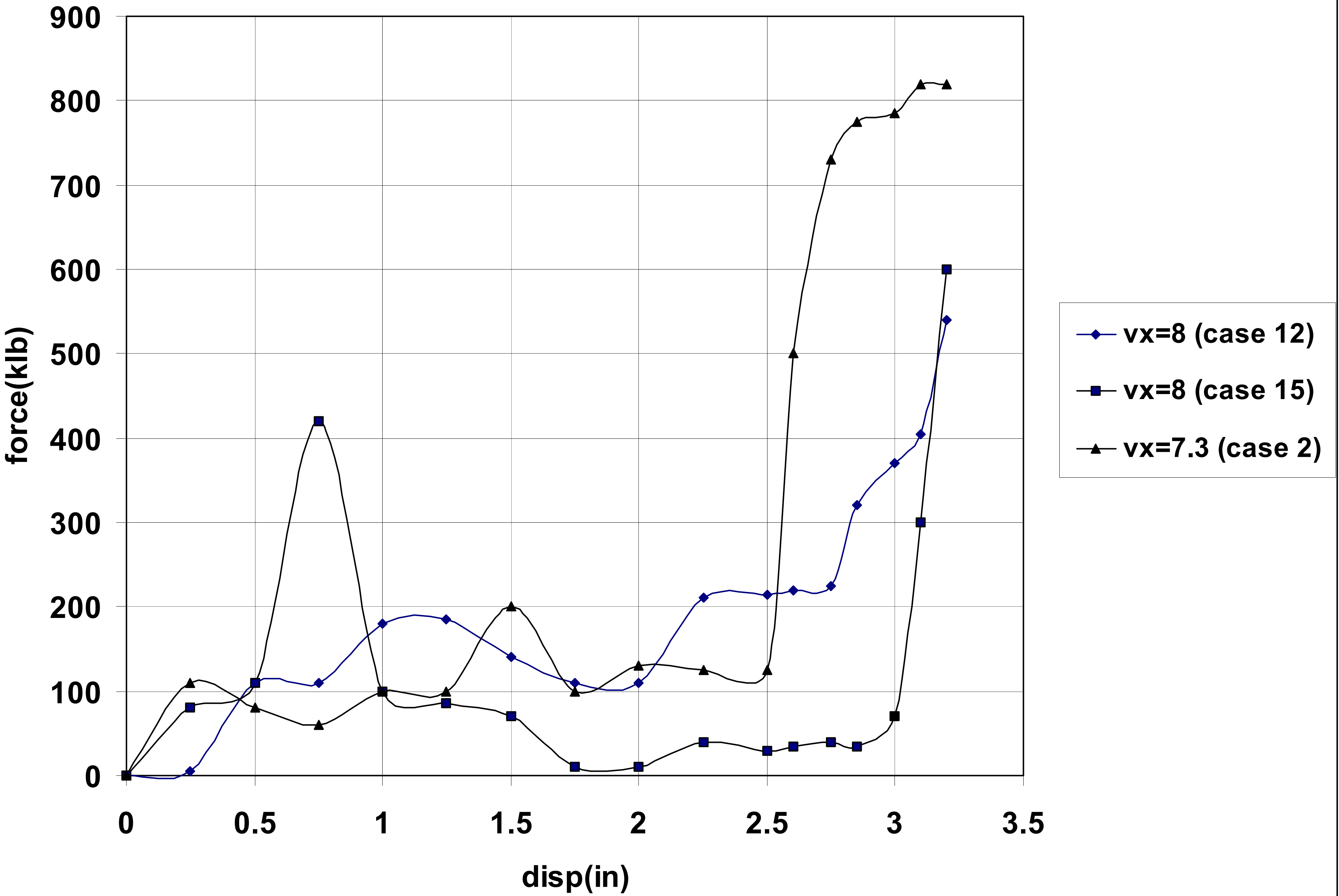


Figure 17: Tank car configurations will change behavior of draft gear



Code	Configuration	(SPLI Curve)
Case 1 1F-(5F)	F F F F F F	1.2Xo-2Yo (Vx<6.5 mph) 1.2Xo-1.1Yo (Vx>6.5 mph)
Case 2 2F-(4F,1C)	F F F F F F	0.75Xo-Yo
Case 3 3F-(4F,1C)	F F F F F F F	0.75Xo-Yo
Case 4 3F-(1F)	F F F F	0.75Xo-Yo
Case 5 3F-(2F)	F F F F F	0.75Xo-Yo
Case 6 3F-(3F)	F F F F F F	0.75Xo-Yo
Case 7 1F-(1F)	F F	1.2Xo-2Yo (Vx<6.5 mph) 1.2Xo-1.1Yo (Vx>6.5 mph)
Case 8 1F-(2F)	F F F	1.2Xo-2Yo (Vx<6.5 mph) 1.2Xo-1.1Yo (Vx>6.5 mph)
Case 9 1F-(3F)	F F F F	1.2Xo-2Yo (Vx<6.5 mph) 1.2Xo-1.1Yo (Vx>6.5 mph)
Case 10 2F,1E-(4F,1C)	F F F F F F	Xo-2Yo (Vx<4.5 mph) 0.75Xo-Yo (Vx>4.5 mph)
Case 11 1E-(5F)	F F F F F	Xo-2Yo (Vx<6.5 mph) 0.75Xo-Yo (Vx>6.5 mph)
Case 12 2E-(5F)	F F F F F	Xo-2Yo (Vx<6.5 mph) 0.75Xo-Yo (Vx>6.5 mph)
Case 13 3E-(5F)	F F F F F	Xo-2Yo (Vx<6.5 mph) 0.75Xo-Yo (Vx>6.5 mph)
Case 14 1F-(1E,4F)	F F F F F	Xo-2Yo (Vx<6.5 mph) 0.75Xo-Yo (Vx>6.5 mph)
Case 15 2F-(1E,4F)	F F F F F F	Xo-2Yo (Vx<4.5 mph) 0.75Xo-Yo (Vx>4.5 mph)

Where: F (Code F) - Liguid-filled Tank Car (98% fill level) (Code E) - Empty Tank Car

(Code C) - Concrete-filled Tank Car Xo-Yo: Mark 50 draft gear curve

Figure 18 Modified X0 - Y0 Curve in ADAMS Models

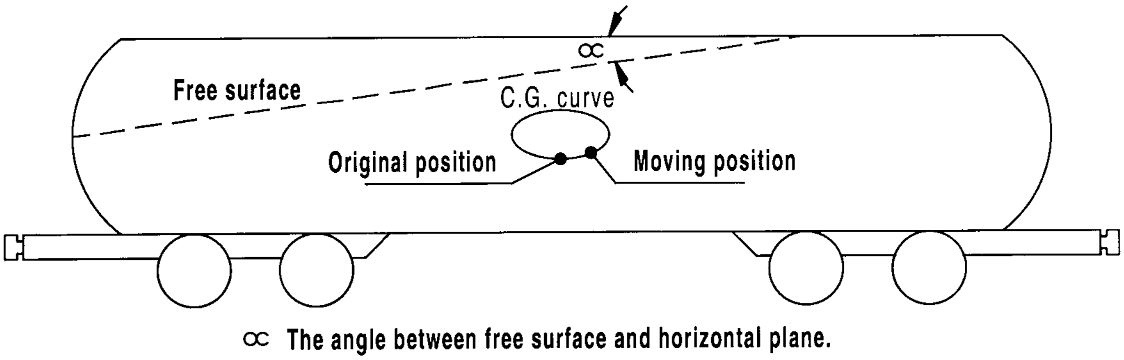


Figure 19 Liquid Model

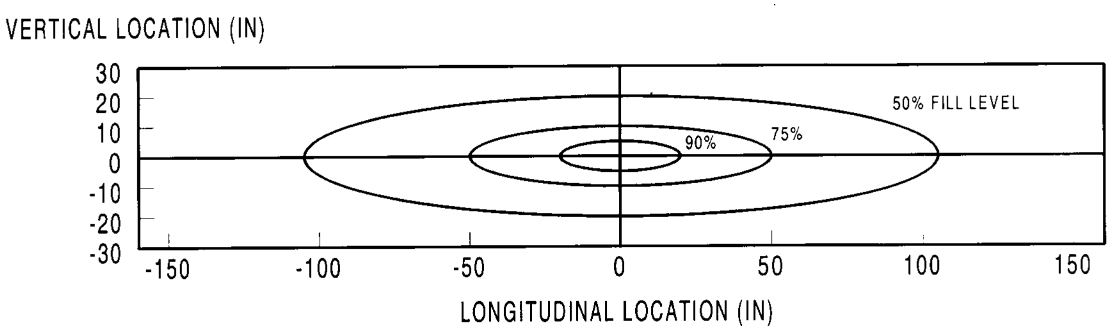


Figure 20 The Trace of Center of Gravity

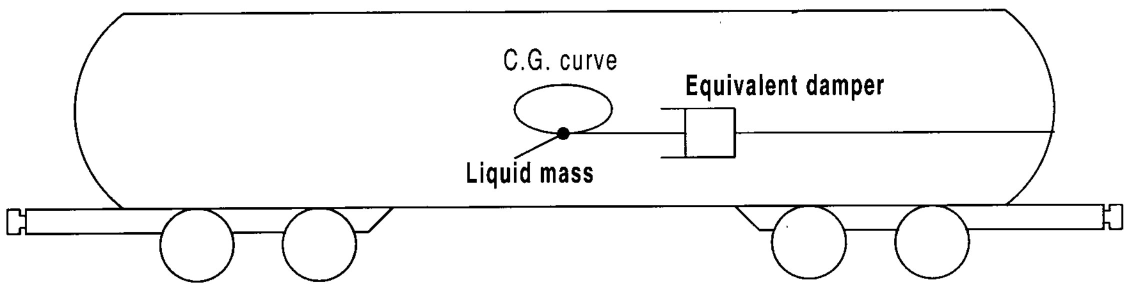


Figure 21 Liquid-vehicle interaction model

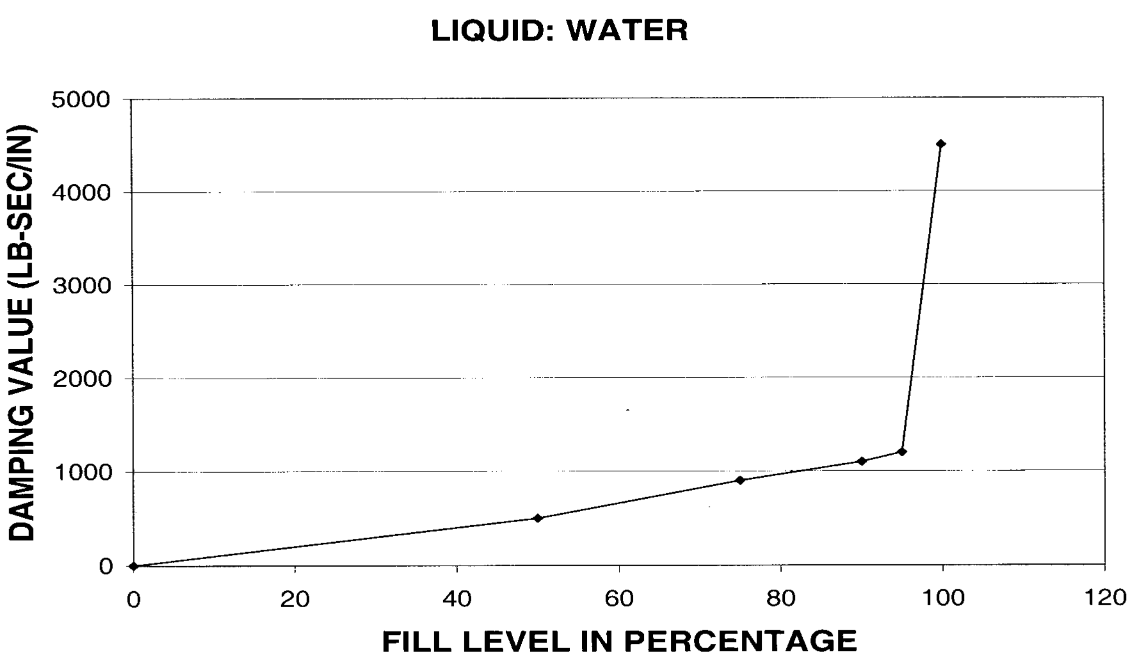
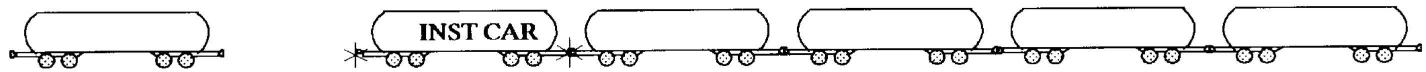


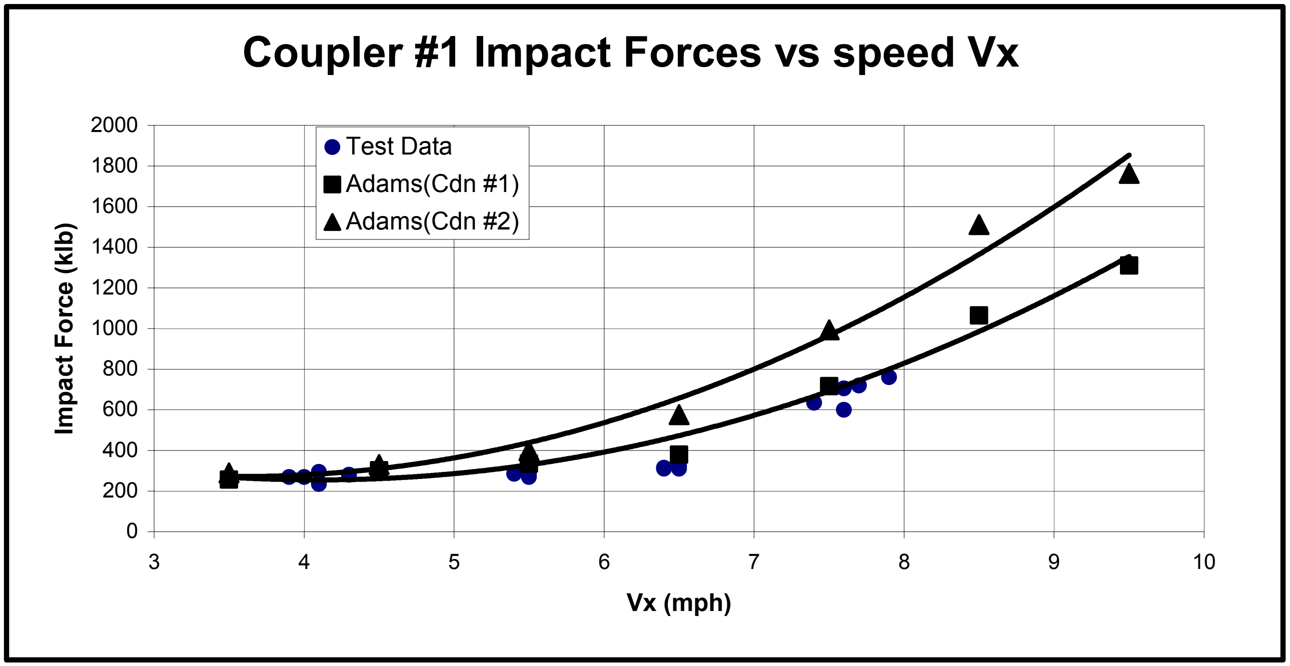
Figure 22 Effects of fill levels on equivalent damping

Case 1

Liquid-filled tank car (98% fill level) **Five liquid-filled tank cars (98% fill level)**



Coupler #1



Test Data

Vx (mph)	Forces Cdn #1 (klb)
3.9 - 4.3	235 - 295
5.4 - 5.5	270 - 295
6.4 - 6.5	310 - 340
7.4 - 7.5	600 - 760

ADAMS Data

Vx (mph)	Forces Cdn #2 (klb)
5	360
6	540
7.5	980
9	1600

Note: Cdn #1: This was the test condition. All tank cars were filled with water (98% fill level).

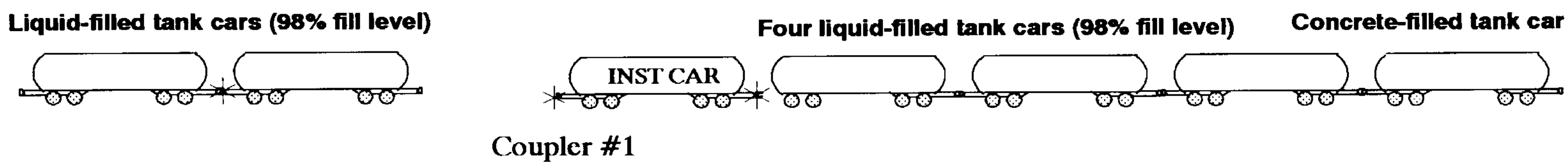
Total weight of each tank car filled with water is 169,000 lb.

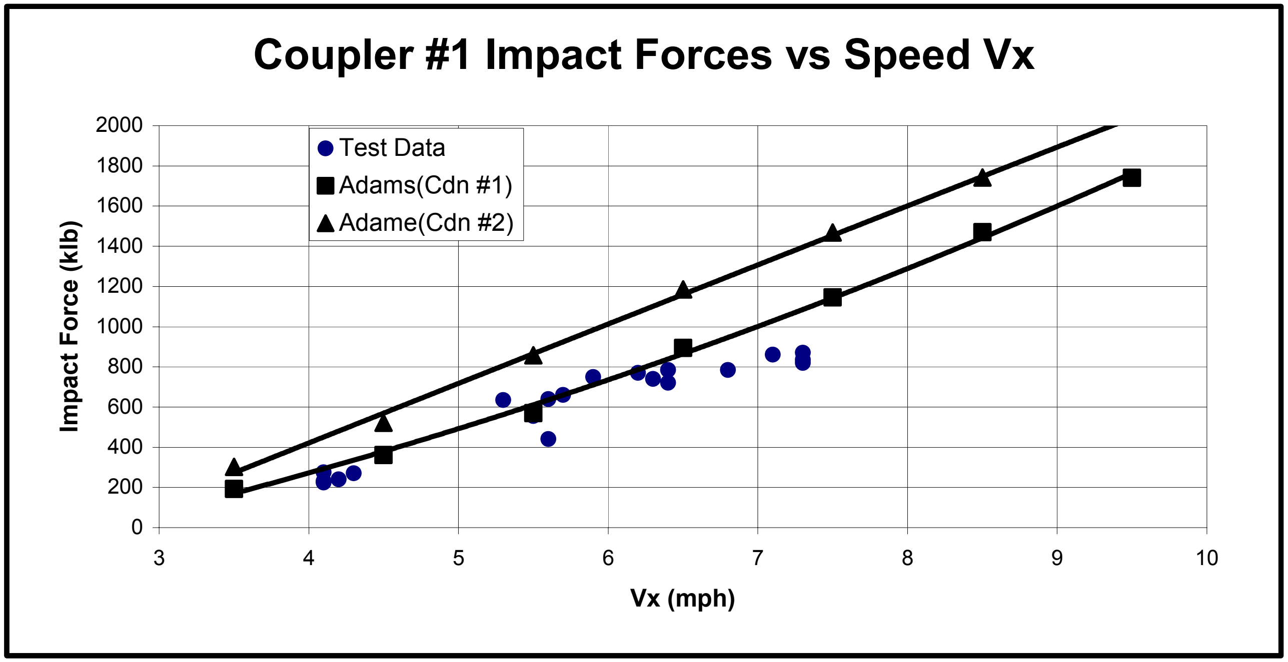
Cdn #2: This was the simulated condition. All tank cars were modeled with acid (98% fill level).

Total weight of each tank car is 263,000 lb.

Figure 23. Case 1 Test and ADAMS data

Case 2





Test Data

Vx (mph)	Forces Cdn #1 (klb)
4.1 - 4.3	225 - 275
5.3 - 5.7	440 - 660
5.9 - 6.4	720 - 785
6.8 - 7.3	785 - 870

ADAMS Data

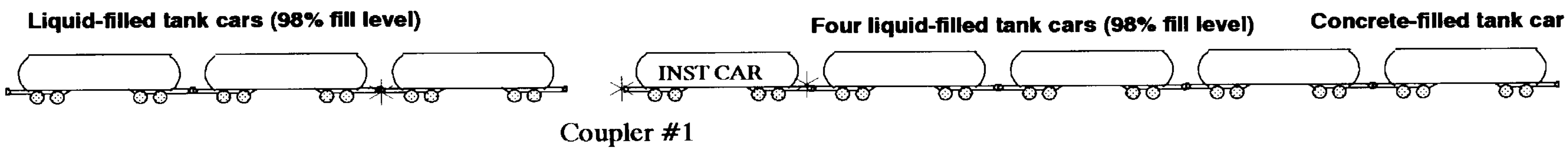
Vx (mph)	Forces Cdn #2 (klb)
5	720
6	1010
7.5	1460
9	1890

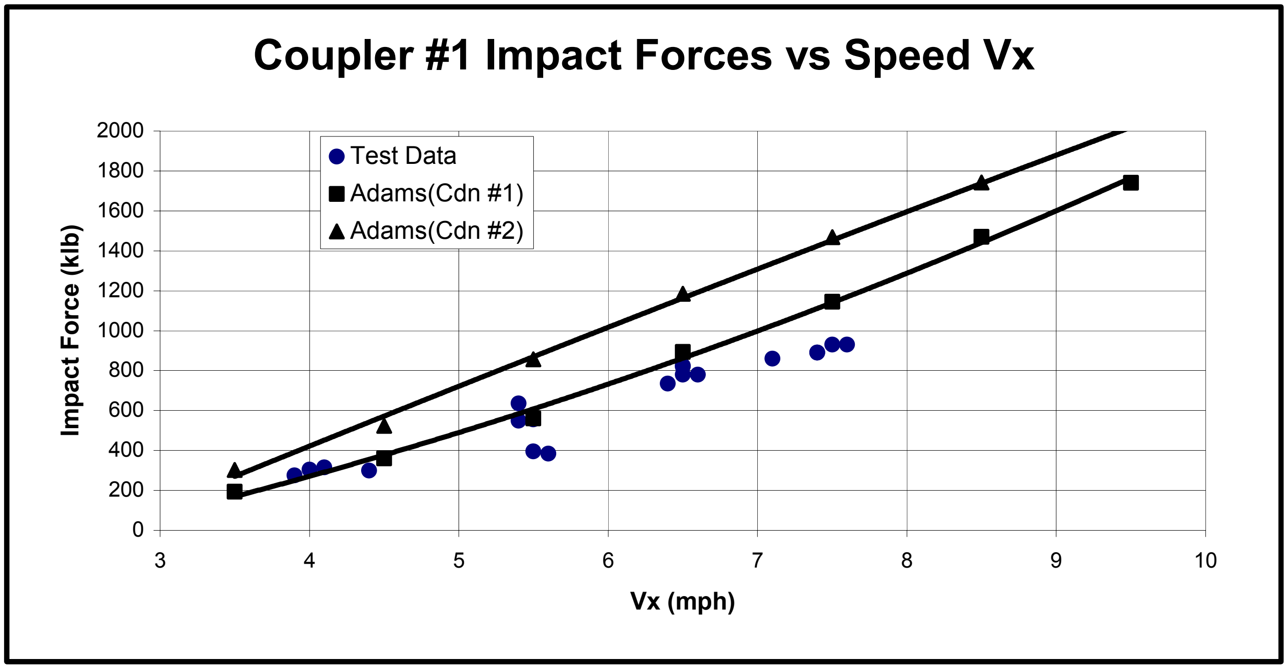
Note: Cdn #1: This was the test condition. Two hammer cars were filled with water. Four anvil cars were filled with water and one anvil car was filled witn concrete. Total weight of each tank car filled with water is 169,000 lb.

Cdn #2: This was the simulated condition. All liquid-filled tank cars were modeled with acid (98% fill level). Total weight of each acid-filled tank car is 263,000 lb. The concrete-filled tank car remained.

Figure 24. Case 2 Test and ADAMS data

Case 3





Test Data

Vx	Forces Cdn #1
(mph)	(klb)
2.9 - 4.4	275 - 315
5.4 - 5.6	385 - 635
6.4 - 6.6	735 - 825
7.1 - 7.6	860 - 930

ADAMS Data

Vx	Forces Cdn #2
(mph)	(klb)
5	720
6	1020
7.5	1460
9	1880

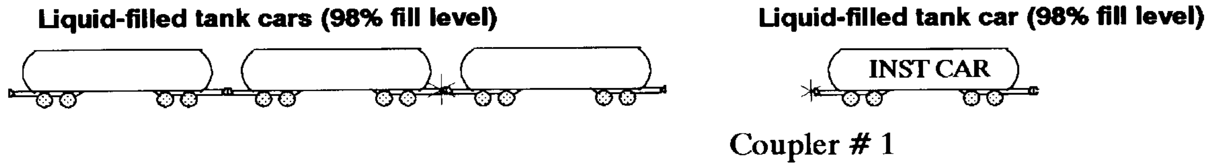
Note: Cdn #1: This was the test condition. Two hammer cars were filled with water. Four anvil cars were filled with water and one anvil car was filled with concrete. Total weight of each tank car filled with water is 169,000 lb.

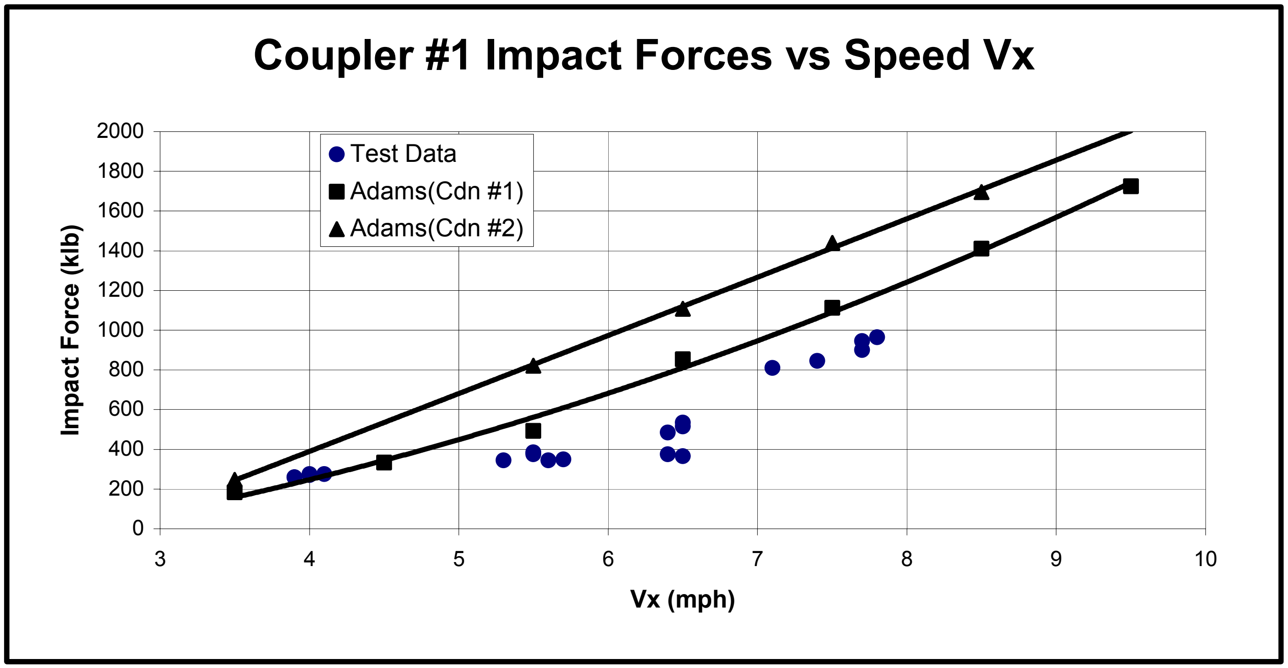
Cdn #2: This was the simulated condition. All liquid-filled tank cars were modeled with acid (98% fill level).

Total weight of each tank car is 263,000 lb. Tne concrete-filled tank car remained.

Figure 25. Case 3 Test and ADAMS data

Case 4





Test Data

Vx (mph)	Forces Cdn #1 (klb)
3.9 - 4.1	260 - 275
5.3 - 5.7	345 - 385
6.4 - 6.5	365 - 535
7.1 - 7.8	810 - 965

ADAMS Data

Vx (mph)	Forces Cdn #2 (klb)
5	680
6	970
7.5	1420
9	1860

Note: Cdn #1: This was the test condition. Three hammer cars were filled with water. One anvil car was filled with water. Total weight of each tank car filled with water is 169,000 lb.

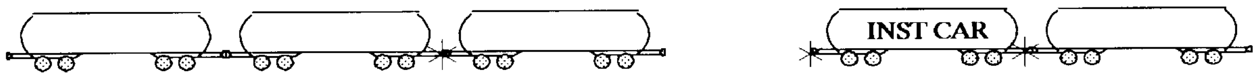
Cdn #2: This was the simulated condition. All liquid-filled tank cars were modeled with acid (98% fill level). Total weight of each tank car is 263,000 lb.

Figure 26. Case 4 Test and ADAMS data

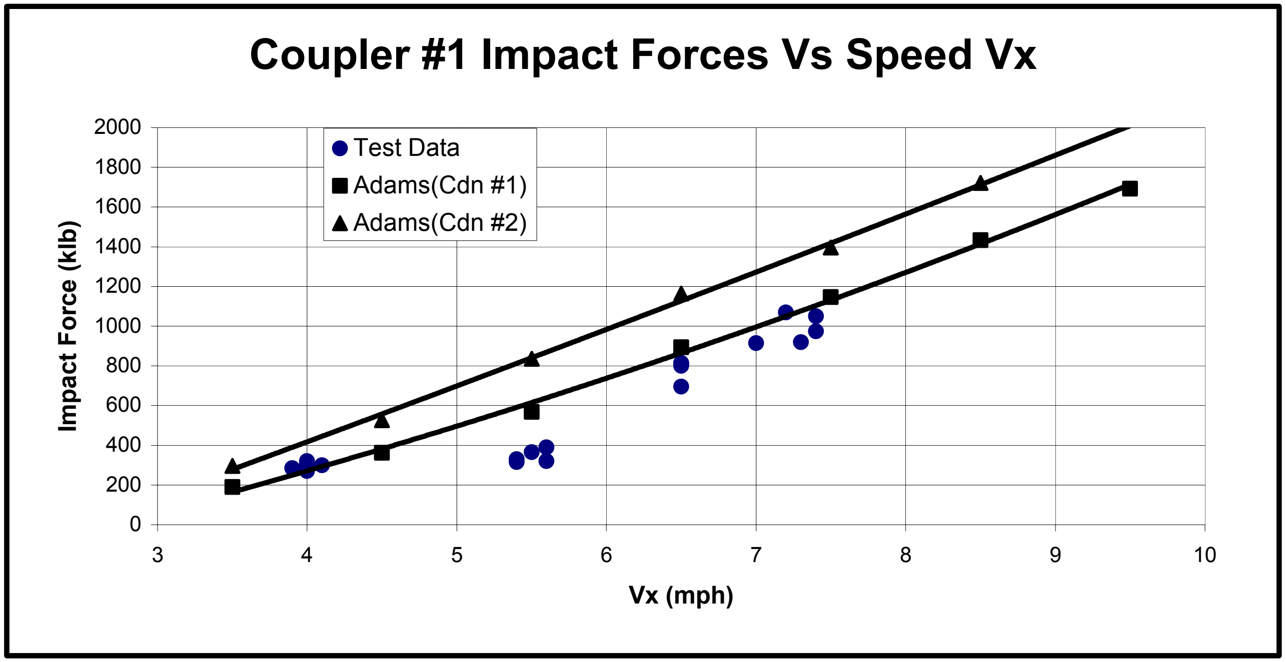
Case 5

Liquid-filled tank cars (98% fill level)

Liquid-filled tank cars (98% fill level)



Coupler # 1



Test Data

Vx (mph)	Forces Cdn #1 (klb)
3.9 - 4.1	270 - 320
5.4 - 5.6	315 - 390
6.5	695 - 815
7.0 - 7.4	915 - 1070

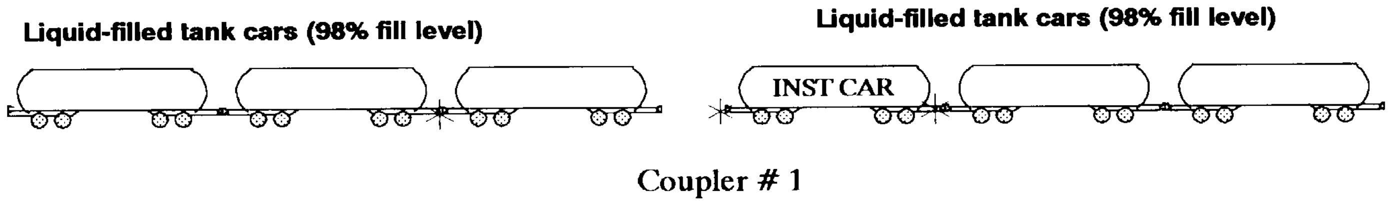
ADAMS Data

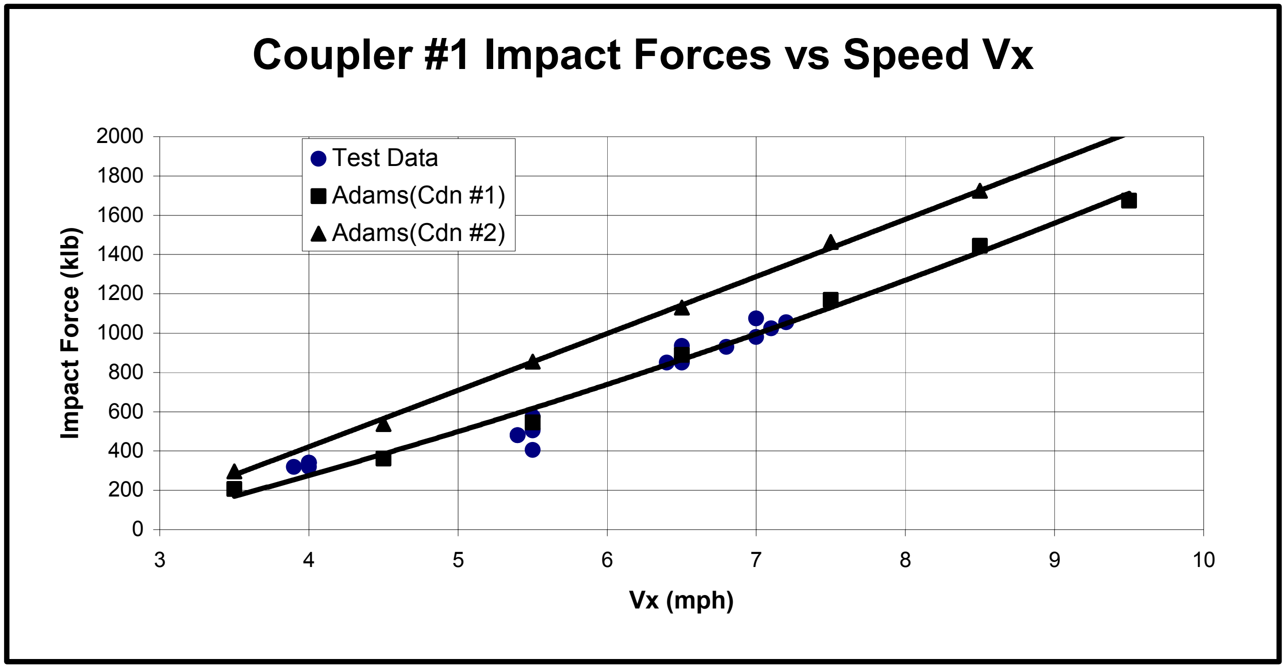
Vx (mph)	Forces Cdn #2 (klb)
5	700
6	990
7.5	1420
9	1860

Note: Cdn #1: This was the test condition. Three hammer cars were filled with water. Two anvil cars were filled with water.
Total weight of each tank car filled with water is 169,000 lb.
Cdn #2: This was the simulated condition. All liquid-filled tank cars were modeled with acid (98% fill level).
Total weight of each tank car is 263,000 lb.

Figure 27. Case 5 Test and ADAMS data

Case 6





Test Data

Vx (mph)	Forces Cdn #1 (klb)
3.9 - 4.0	320 - 340
5.4 - 5.5	405 - 575
6.4 - 6.5	850 - 935
6.8 - 7.2	930 - 1075

ADAMS Data

Vx (mph)	Forces Cdn #2 (klb)
5	710
6	1000
7.5	1440
9	1870

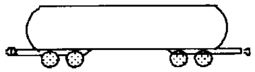
Note: Cdn #1: This was the test condition. Three hammer cars were filled with water. Three anvil cars were filled with water. Total weight of each tank car filled with water is 169,000 lb.

Cdn #2: This was the simulated condition. All liquid-filled tank cars were modeled with acid (98% fill level). Total weight of each tank car is 263,000 lb.

Figure 28. Case 6 Test and ADAMS data

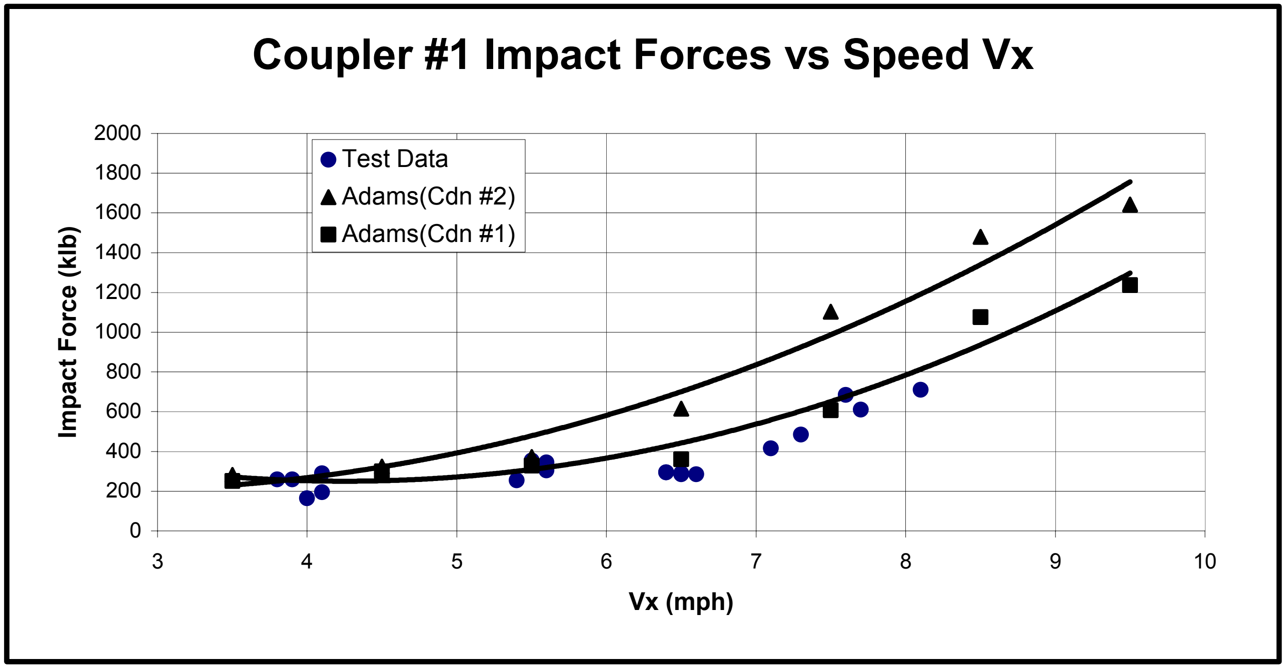
Case 7

Liquid-filled tank car (98% fill level)



Liquid-filled tank car (98% fill level)

Coupler # 1



Test Data

Vx	Forces Cdn #1
(mph)	(klb)
3.8 - 4.1	165 - 290
5.4 - 5.6	255 - 355
6.4 - 6.6	285 - 295
7.1 - 8.1	415 - 710

ADAMS Data

Vx	Forces Cdn #2
(mph)	(klb)
5	400
6	590
7.5	990
9	1530

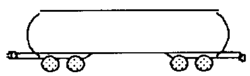
Note: Cdn #1: This was the test condition. One hammer car was filled with water. One anvil car was filled with water.
Total weight of each tank car filled with water is 169,000 lb.

Cdn #2: This was the simulated condition. All liquid-filled tank cars were modeled with acid (98% fill level).
Total weight of each tank car is 263,000 lb.

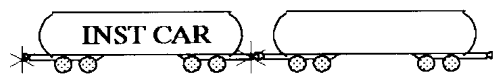
Figure 29. Case 7 Test and ADAMS data

Case 8

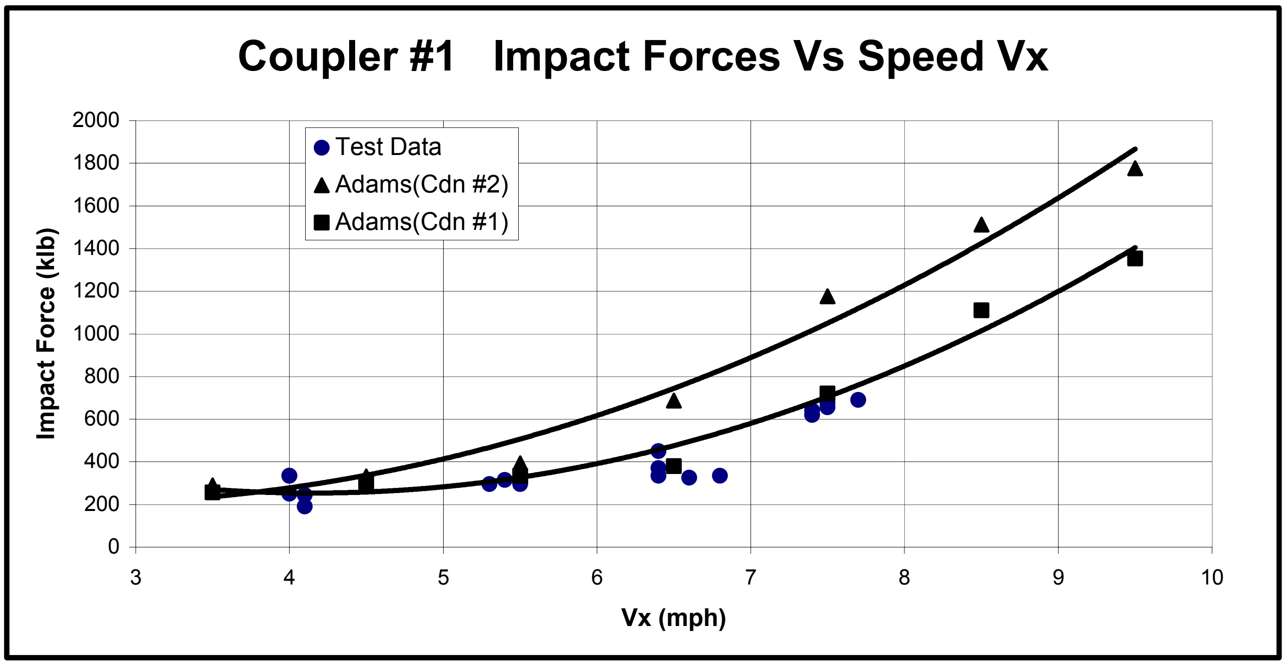
Liquid-filled tank car (98% fill level)



Liquid-filled tank cars (98% fill level)



Coupler # 1



Test Data

Vx (mph)	Forces Cdn #1 (klb)
4.0 - 4.1	190 - 335
5.3 - 5.5	295 - 315
6.4 - 6.8	325 - 450
7.4 - 7.7	620 - 690

ADAMS Data

Vx (mph)	Forces Cdn #2 (klb)
5	410
6	620
7.5	1050
9	1630

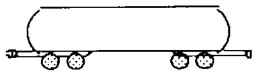
Note: Cdn #1: This was the test condition. One hammer cars was filled with water. Two anvil cars were filled with water. Total weight of each tank car filled with water is 169,000 lb.

Cdn #2: This was the simulated condition. All liquid-filled tank cars were modeled with acid (98% fill level). Total weight of each tank car is 263,000 lb.

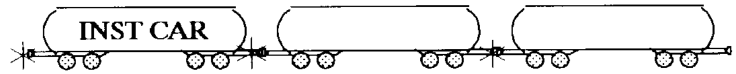
Figure 30. Case 8 Test and ADAMS data

Case 9

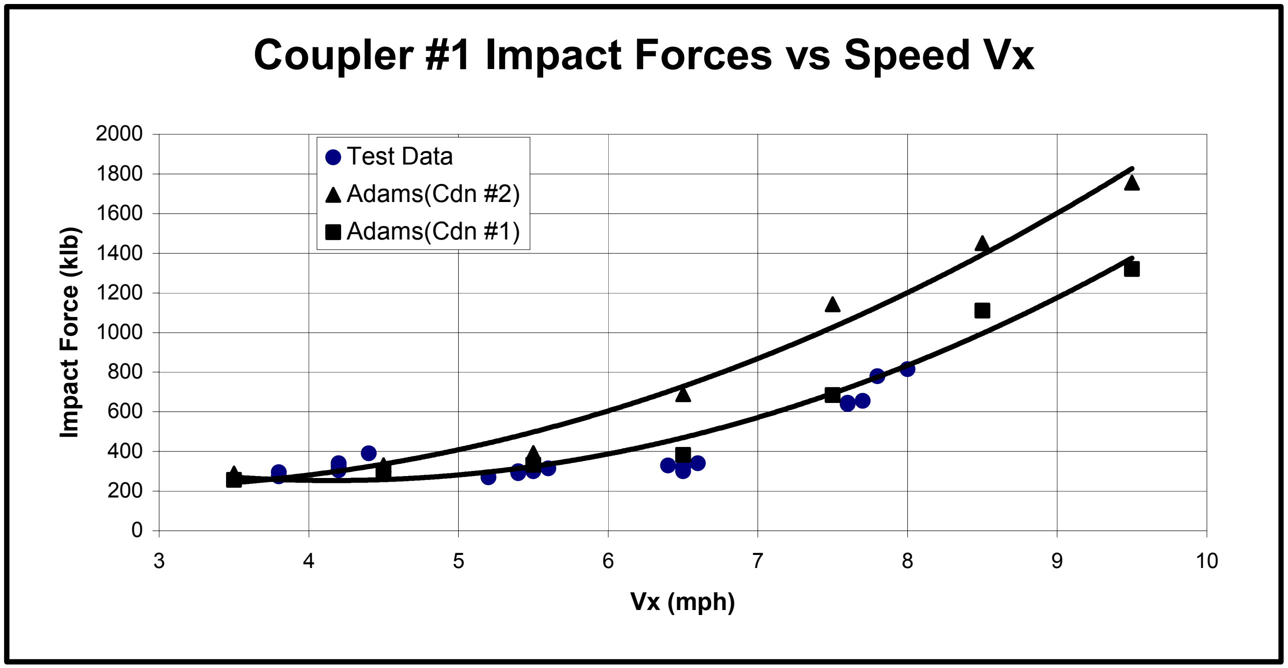
Liquid-filled tank car (98% fill level)



Liquid-filled tank cars (98% fill level)



Coupler # 1



Test Data

Vx (mph)	Forces Cdn #1 (klb)
3.8 - 4.4	275 - 390
5.2 - 5.6	270 - 315
6.4 - 6.6	300 - 340
7.6 - 8.0	640 - 815

ADAMS Data

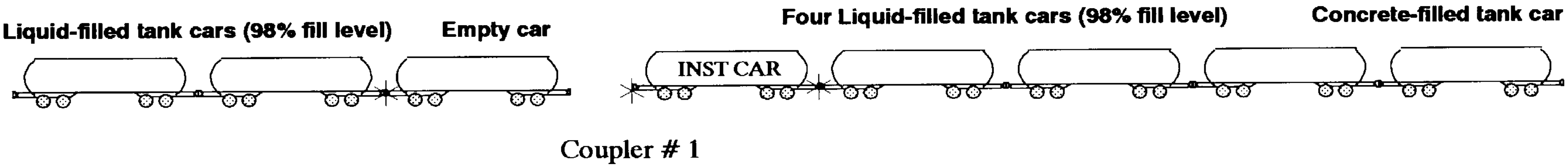
Vx (mph)	Forces Cdn #2 (klb)
5	400
6	600
7.5	1040
9	1600

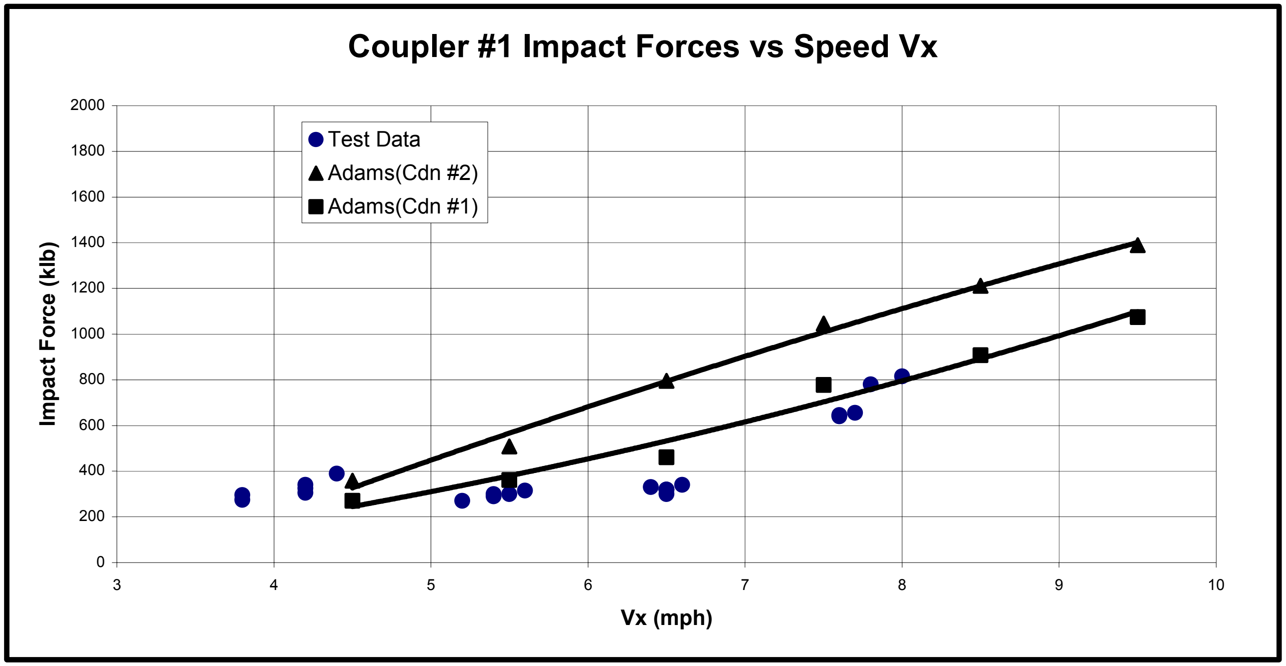
Note: Cdn #1: This was the test condition. One hammer car was filled with water. Three anvill cars were filled with water. Total weight of each tank car filled with water is 169,000 lb.

Cdn #2: This was the simulated condition. All liquid-filled tank cars were modeled with acid (98% fill level). Total weight of each tank car is 263,000 lb.

Figure 31. Case 9 Test and ADAMS data

Case 10





Test Data

Vx	Forces
	Cdn #1
(mph)	(klb)
3.7 - 4.0	320 - 335
4.7 - 5.6	315 - 385
5.8 - 6.8	375 - 645
7.1 - 7.9	695 - 810

ADAMS Data

Vx	Forces
	Cdn #2
(mph)	(klb)
5	450
6	680
7.5	1010
9	1310

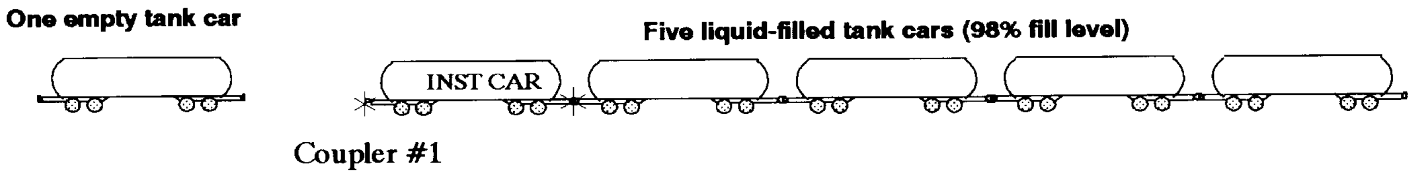
Note: Cdn #1: This was the test condition. There were three hammer cars; one of them was empty and two were filled with water. There were five anvil cars; four of them were filled with water and one was filled with concrete.

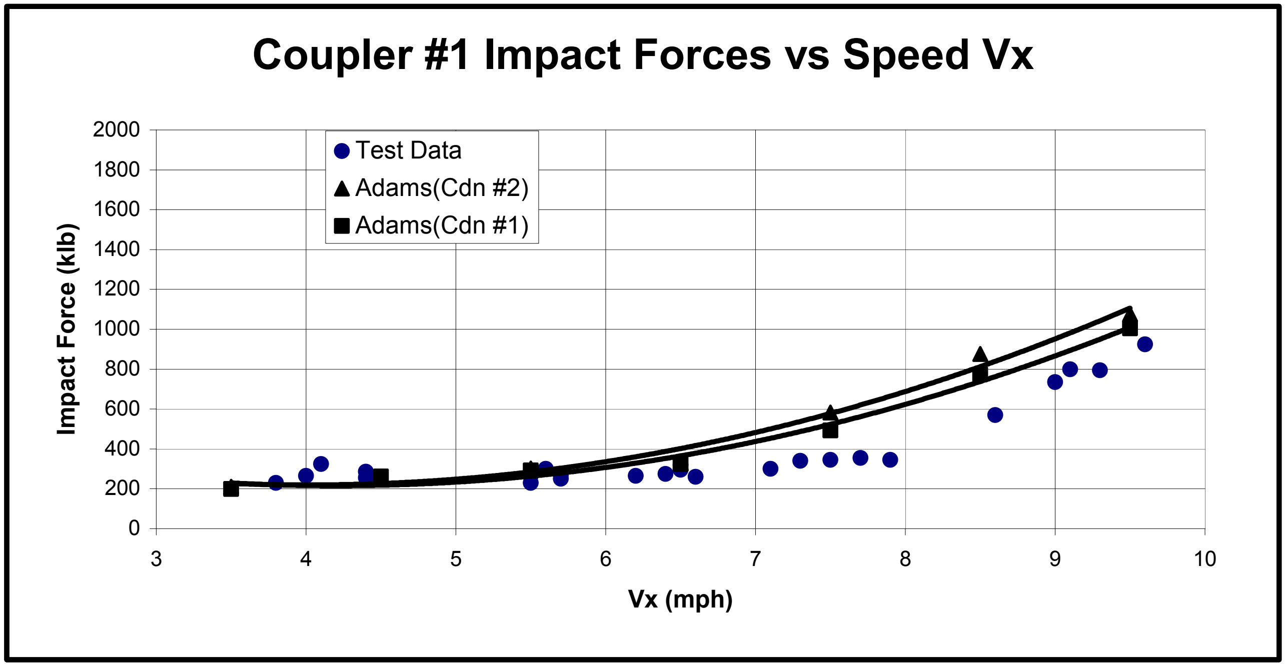
Cdn #2: This was the simulated condition. All liquid-filled tank cars were modeled with acid (98% fill level).

Total weight of each tank car is 263,000 lb. One hammer car remained empty. One anvil car remained filled with concrete.

Figure 32. Case 10 Test and ADAMS data

Case 11





Test Data

Vx	Forces Cdn #1
(mph)	(klb)
3.8 - 4.4	230 - 325
5.5 - 5.7	230 - 300
6.2 - 6.6	260 - 320
7.1 - 7.9	300 - 355
8.6 - 9.6	570 - 925

ADAMS Data

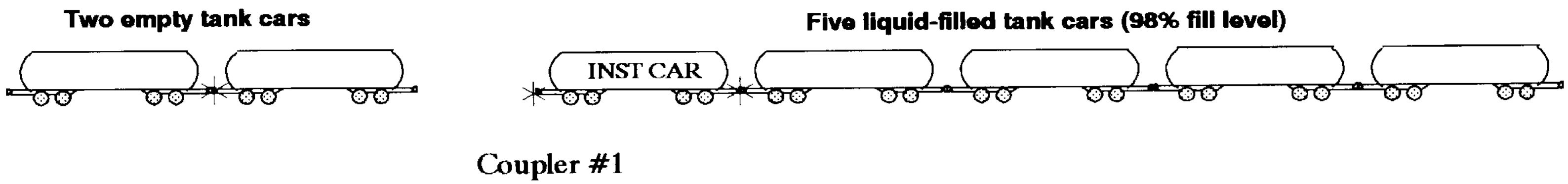
Vx	Forces Cdn #2
(mph)	(klb)
5	250
6	340
7.5	590
9	950

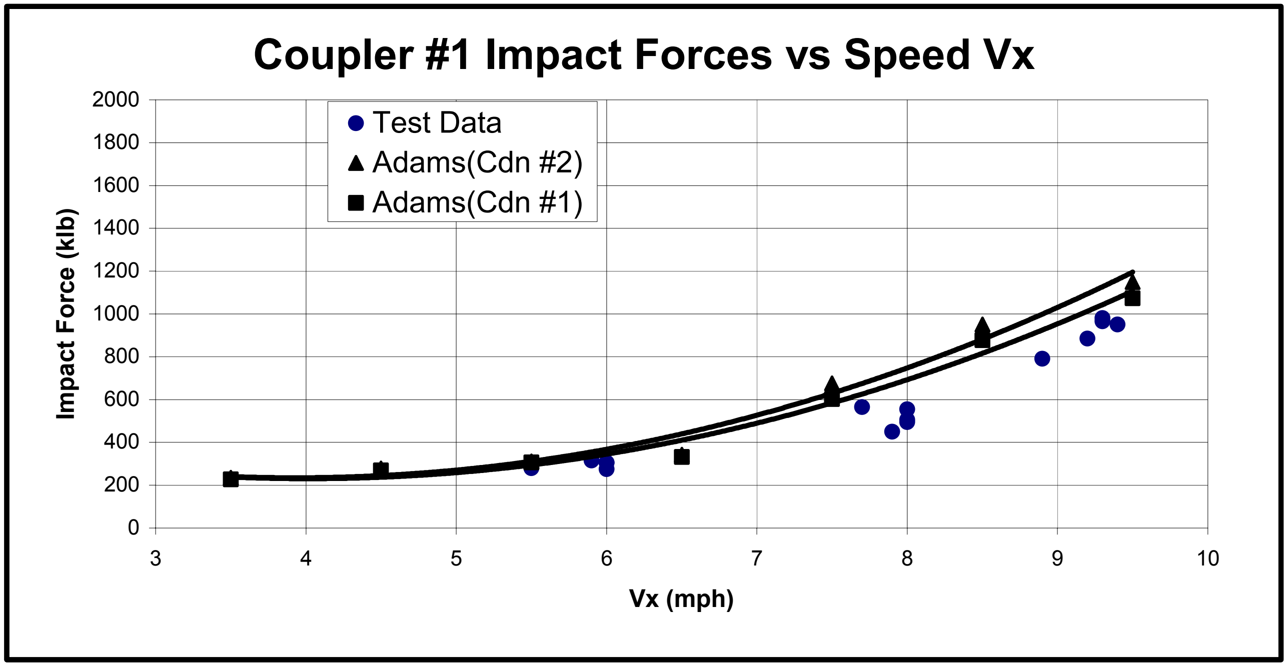
Note: Cdn #1: This was the test condition. One hammer car was empty. Five anvil cars were filled with water. Total weight of each tank car filled with water is 169,000 lb.

Cdn #2: This was the simulated condition. All liquid-filled tank cars were modeled with acid (98% fill level). Total weight of each tank car is 263,000 lb. One hammer car remained empty.

Figure 33. Case 11 Test and ADAMS data

Case 12





Test Data

Vx	Forces Cdn #1
(mph)	(klb)
5.5 - 6.0	275 - 315
7.7 - 8.0	450 - 565
8.9 - 9.4	790 - 980

ADAMS Data

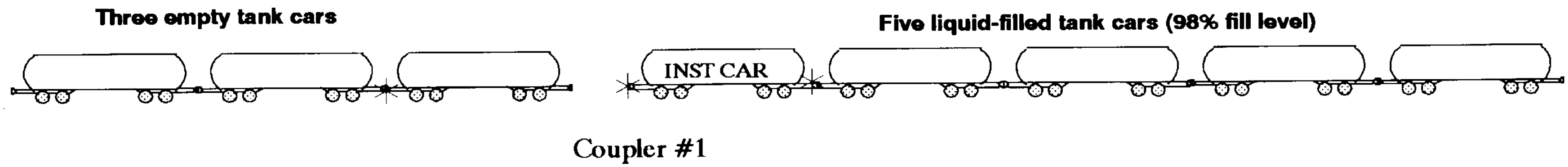
Vx	Forces Cdn #2
(mph)	(klb)
5	270
6	370
7.5	630
9	1030

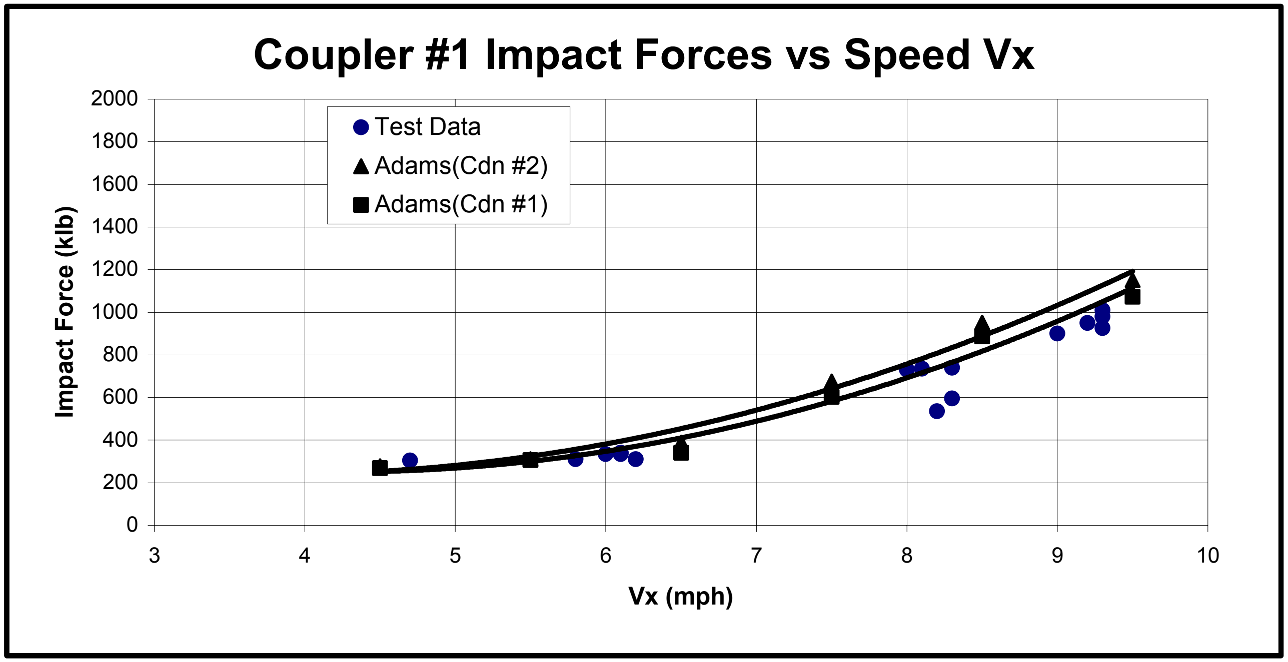
Note: Cdn #1: This was the test condition. Two hammer cars were empty. Five anvil cars were filled with water. Total weight of each tank car filled with water is 169,000 lb.

Cdn #2: This was the simulated condition. All liquid-filled tank cars were modeled with acid (98% fill level). Total weight of each tank car is 263,000 lb. Two hammer cars remained empty.

Figure 34. Case 12 Test and ADAMS data

Case 13





Test Data

Vx (mph)	Forces Cdn #1 (klb)
4.7 - 6.2	305 - 340
8.0 - 8.3	535 - 740
9.0 - 9.3	925 - 1010

ADAMS Data

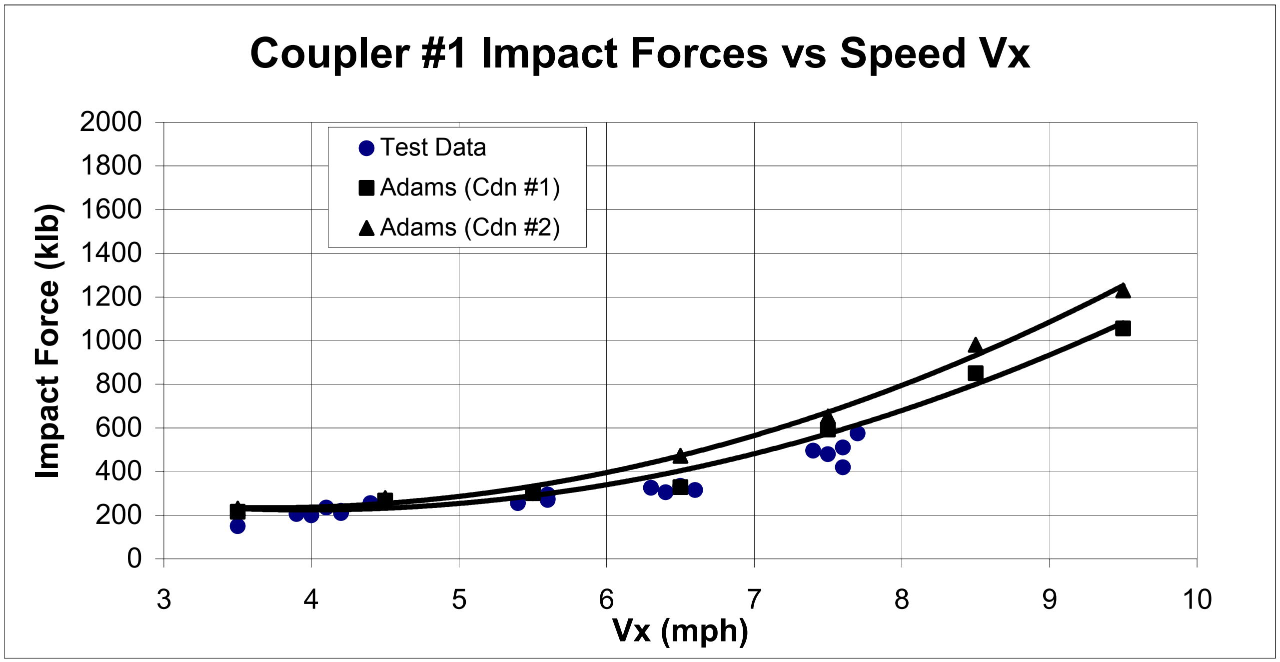
Vx (mph)	Forces Cdn #2 (klb)
5	270
6	380
7.5	640
9	1040

Note: Cdn #1: This was the test condition. Three hammer cars were empty. Five anvil cars were filled with water. Total weight of each tank car filled with water is 169,000 lb.

Cdn #2: This was the simulated condition. All liquid-filled tank cars were modeled with acid (98% fill level). Total weight of each tank car is 263,000 lb. Three hammer cars remained empty.

Figure 35. Case 13 Test and ADAMS data

Case 14



Test Data

Vx (mph)	Forces Cdn #1 (klb)
3.5 - 4.4	150 - 255
5.4 - 5.6	255 - 300
6.3 - 6.6	305 - 335
7.4 - 7.7	420 - 575

ADAMS Data

Vx (mph)	Forces Cdn #2 (klb)
5	290
6	400
7.5	670
9	1090

Note: Cdn #1: This was the test condition. One hammer car was filled with water. There were five anvil cars; four of them were filled with water and one was empty. Total weight of each tank car filled with water is 169,000 lb.

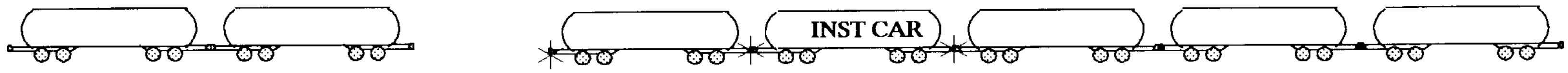
Cdn #2: This was the simulated condition. All liguid-filled tank cars were modeled with acid (98% fill level).

Total weight of each acid-filled tank car is 263,000 lb. One anvil car remained empty.

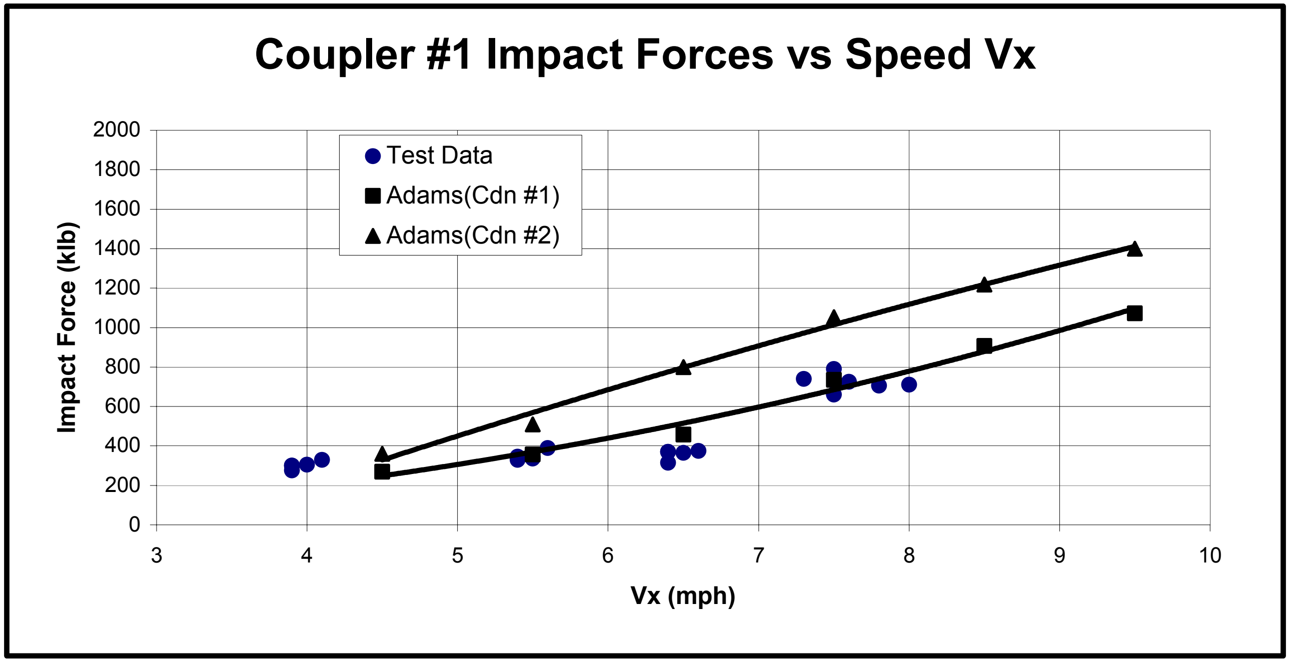
Figure 36. Case 14 Test and ADAMS data

Case 15

Liquid-filled tank cars (98% fill level) **One empty tank car** **Four liquid-filled tank cars (98% fill level)**



Coupler # 1



Test Data

Vx	Forces
	Cdn #1
(mph)	(klb)
3.9 - 4.1	275-330
5.4 - 5.6	335-390
6.4 - 6.6	315-375
7.3 - 8.0	660-790

ADAMS Data

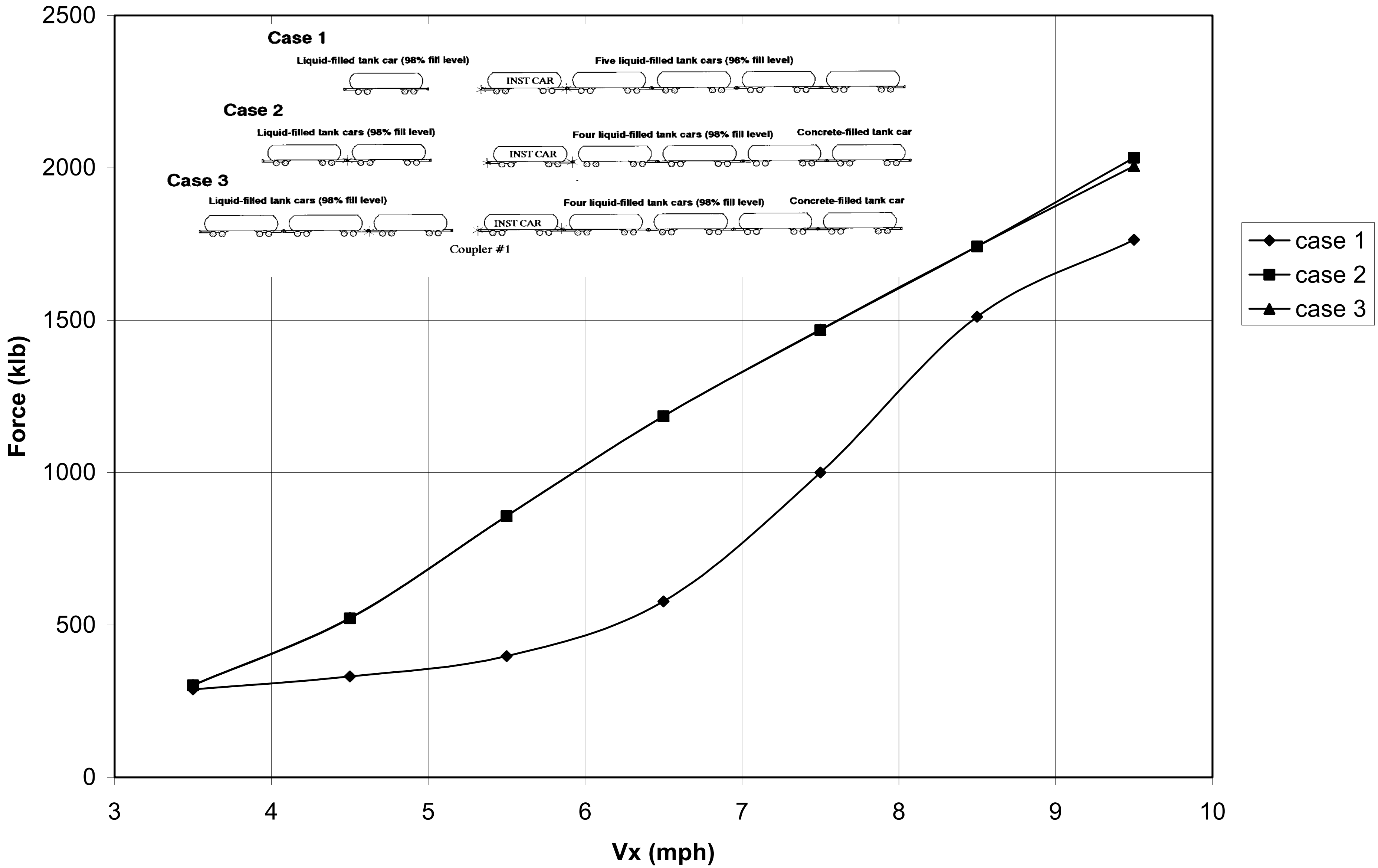
Vx	Forces
	Cdn #2
(mph)	(klb)
5	450
6	680
7.5	1020
9	1320

Note: Cdn #1: This was the test condition. Two hammer cars cars were filled with water. There were five anvil cars; four of them were filled with water and one was empty. Total weight of each tank car filled with water is 169,000 lb.

Cdn #2: This was the simulated condition. All liquid-filled tank cars were modeled with acid (98% fill level). Total weight of each acid-filled tank car is 263,000 lb. One anvil car remained empty.

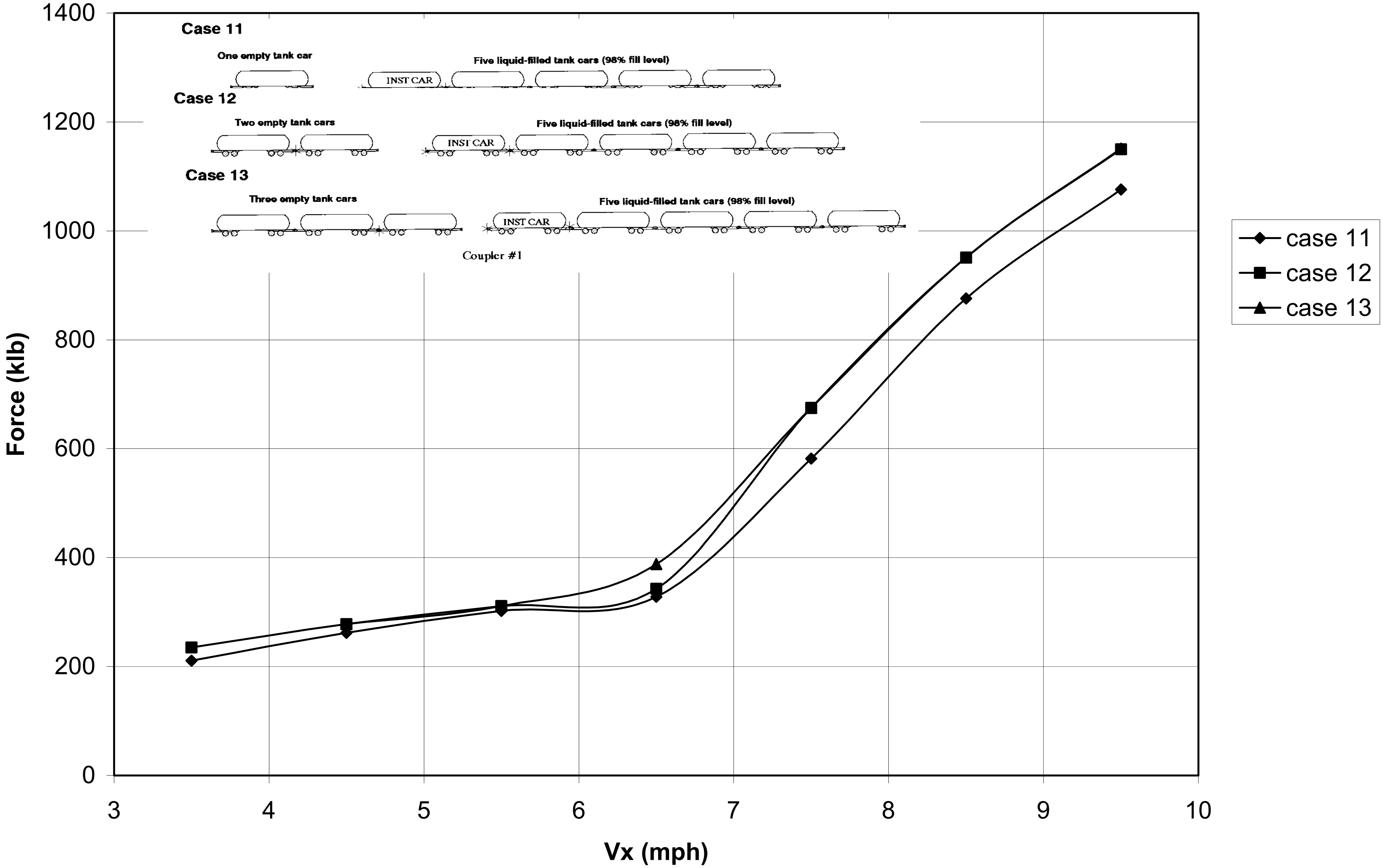
Figure 37. Case 15 Test and ADAMS data

Figure 38: Tank car Impact force (cases 1,2,3) under condition 2



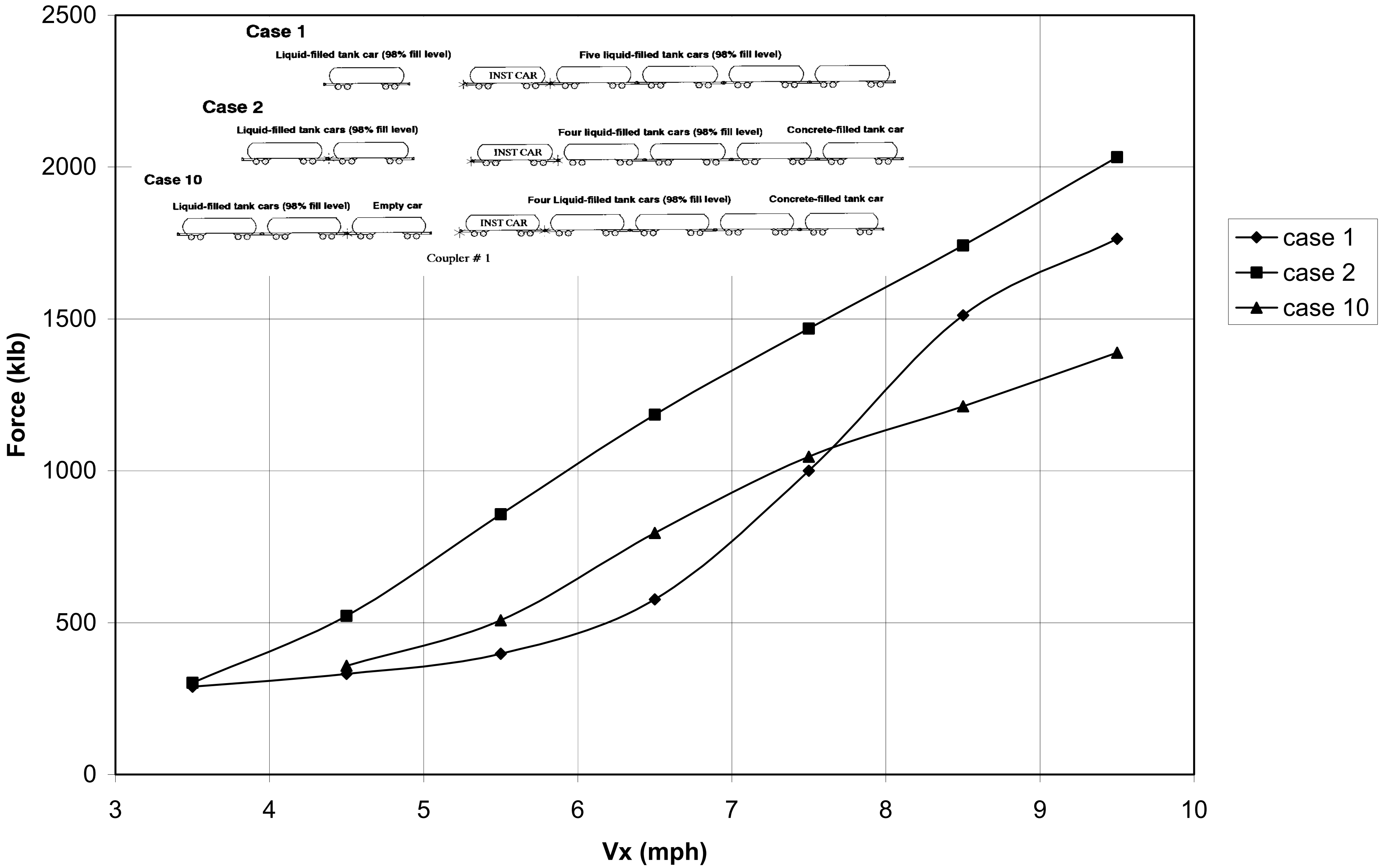
Note: Condition 2: All liguid-filled tank cars were modeled with acid. The loading conditions remained the same for empty and concrete filled tank cars.

Figure 39: Tank car Impact force (cases 11,12,13) under condition 2



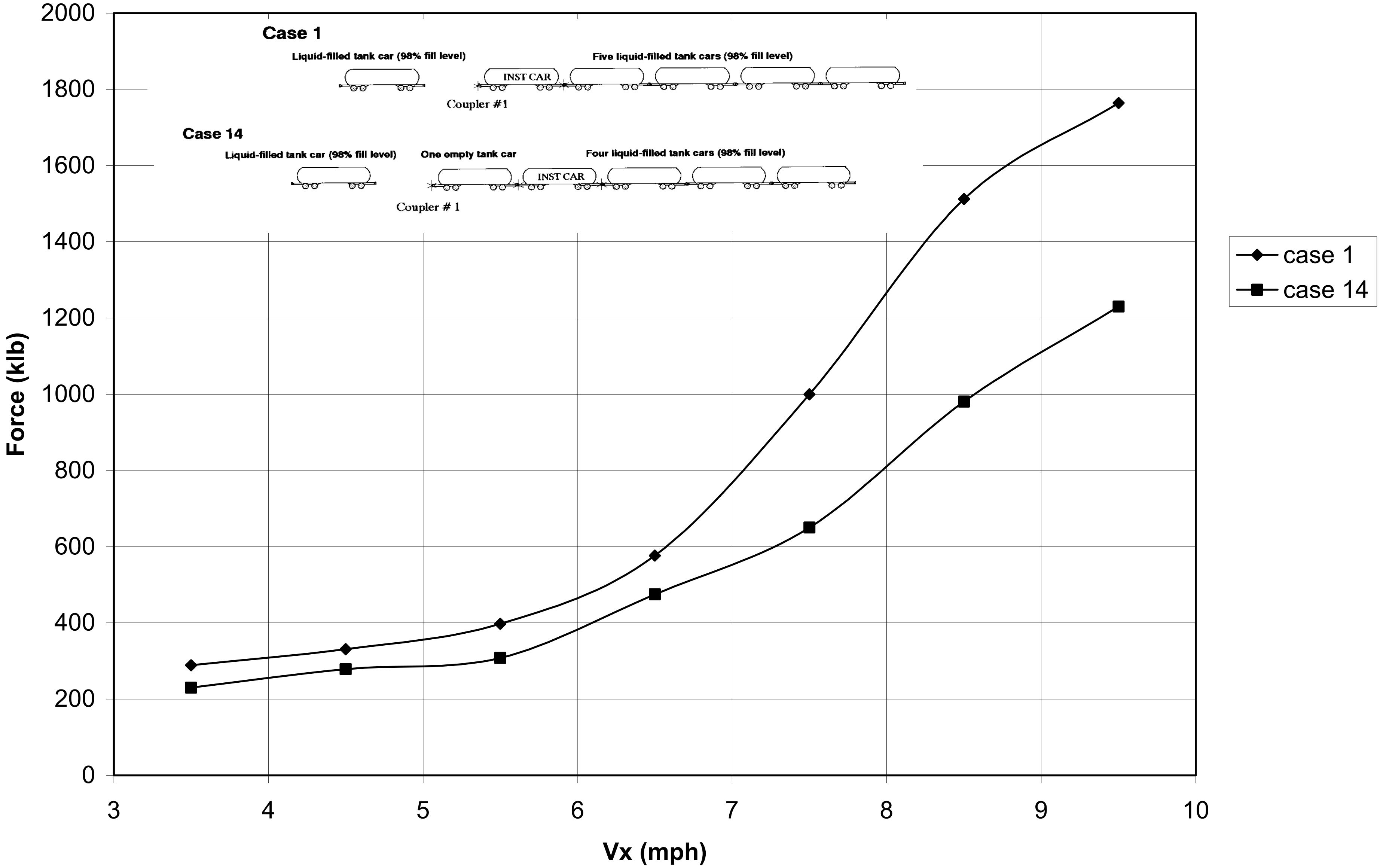
Note: Condition 2: All liguid-filled tank cars were modeled with acid. The loading conditions remained the same for empty and concrete filled tank cars.

Figure 40: Tank car Impact force (cases 1,2,10) under condition 2



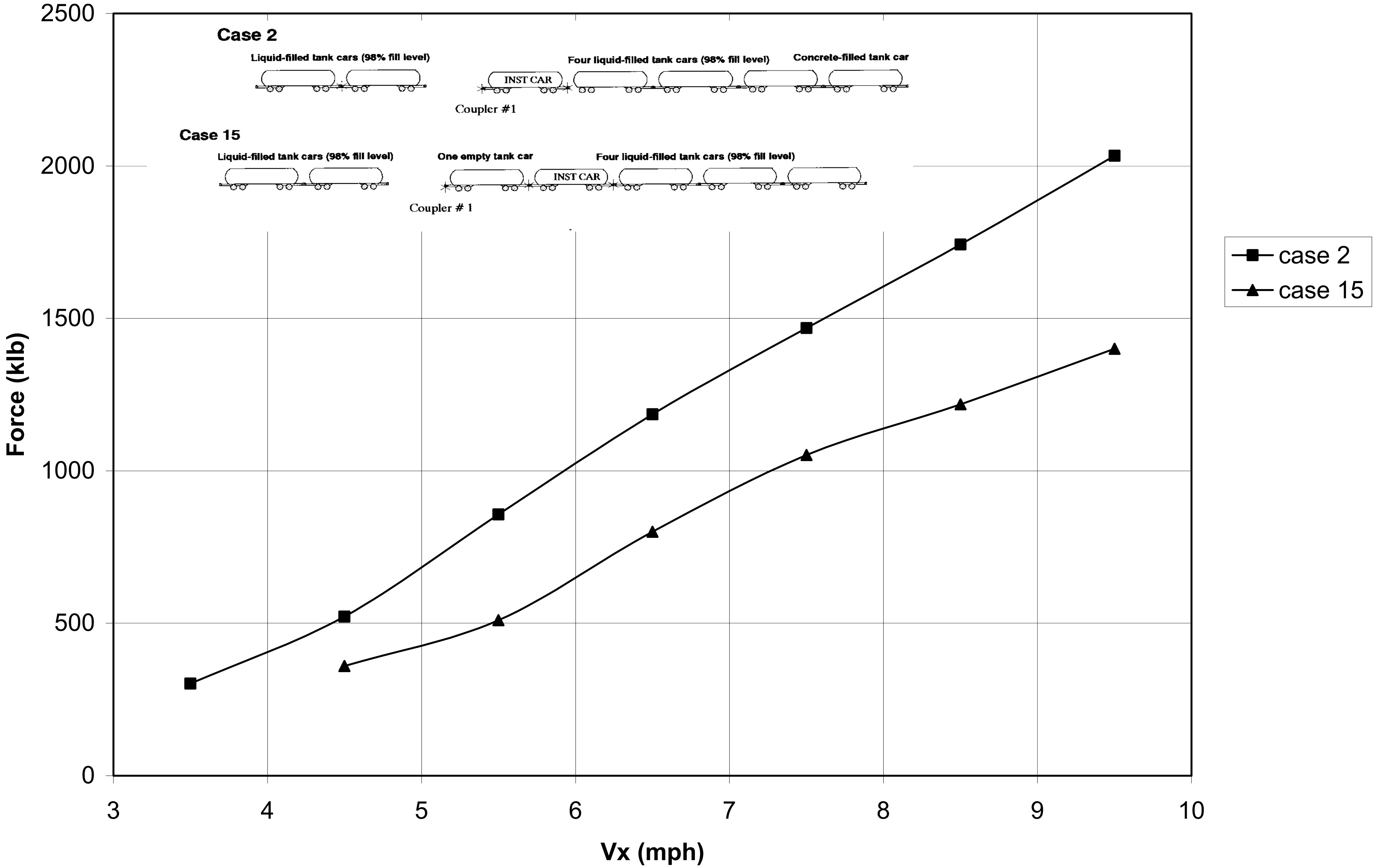
Note: Condition 2: All liguid-filled tank cars were modeled with acid. The loading conditions remained the same for empty and concrete filled tank cars.

Figure 41: Tank car Impact force (cases 1,14) under condition 2



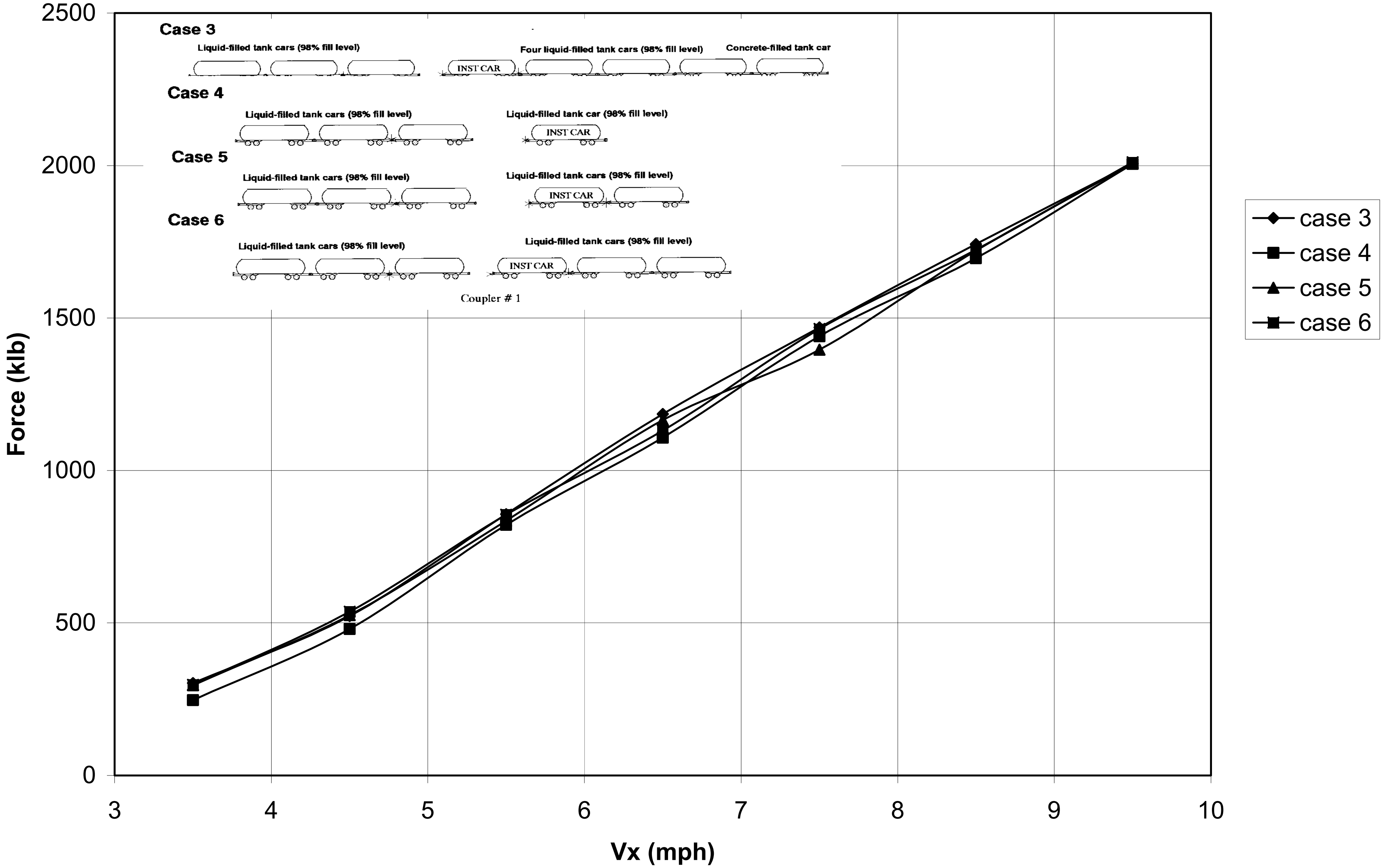
Note: Condition 2: All liguid-filled tank cars were modeled with acid. The loading conditions remained the same for empty and concrete filled tank cars.

Figure 42: Tank car Impact force (cases 2,15) under condition 2



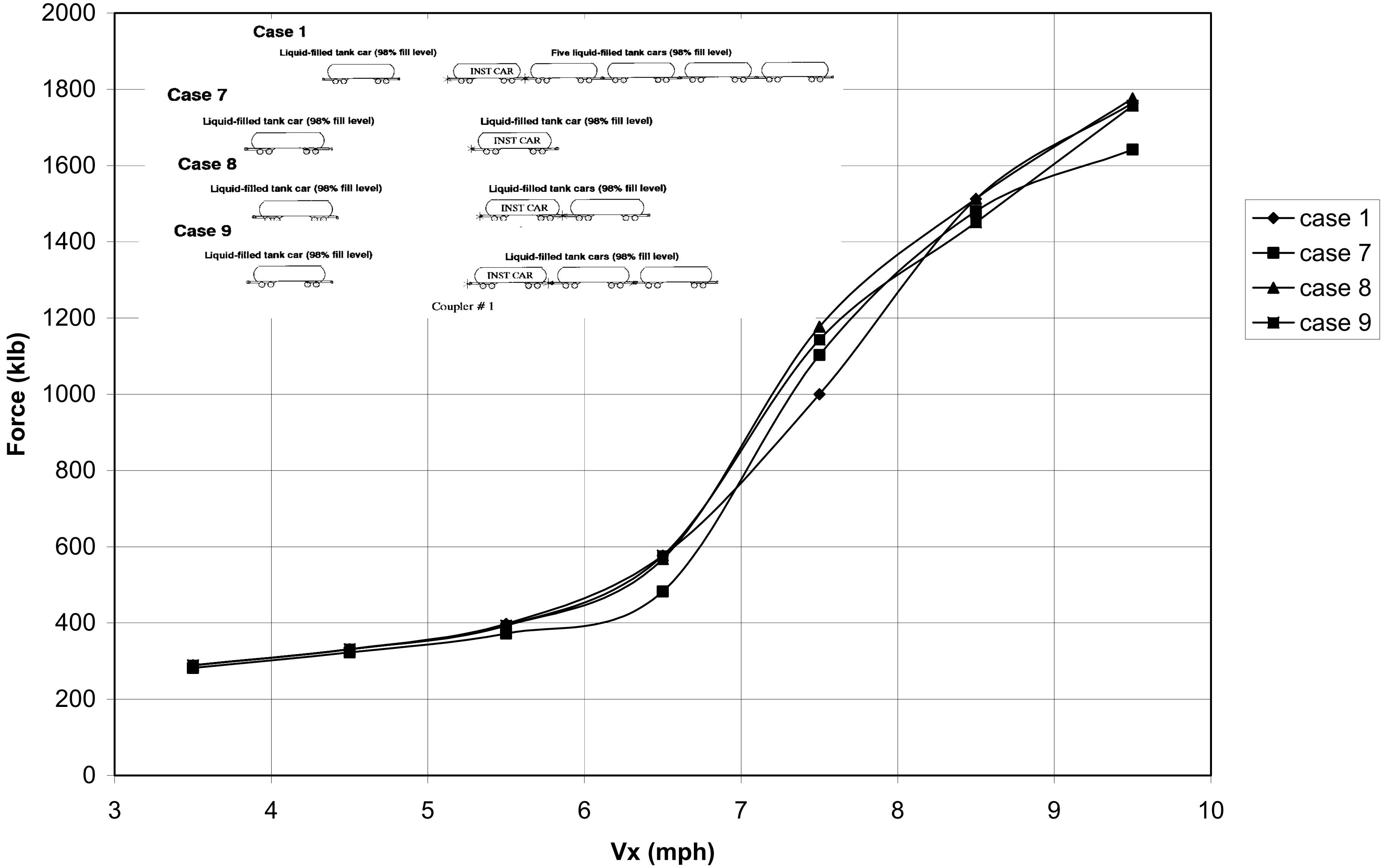
Note: Condition 2: All liguid-filled tank cars were modeled with acid. The loading conditions remained the same for empty and concrete filled tank cars.

Figure 43: Tank car Impact force (cases 3,4,5,6) under condition 2



Note: Condition 2: All liguid-filled tank cars were modeled with acid. The loading conditions remained the same for empty and concrete filled tank cars.

Figure 44: Tank car Impact force (cases 1,7,8,9) under condition 2



Note: Condition 2: All liguid-filled tank cars were modeled with acid. The loading conditions remained the same for empty and concrete filled tank cars.

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Appendix A Tank car configurations in ADAMS models

Figure 1 (appA-1): Tank car configurations in group 1 in ADAMS models

Figure 2 (appA-2): Tank car configurations in group 2 in ADAMS models

Figure 3 (appA-3): Tank car configurations in group 3 in ADAMS models

Figure 4 (appA-4): Tank car configurations in group 4 in ADAMS models

Figure 5 (appA-5): Tank car configurations in group 5 in ADAMS models

Figure 6 (appA-6): Tank car configurations in group 6 in ADAMS models

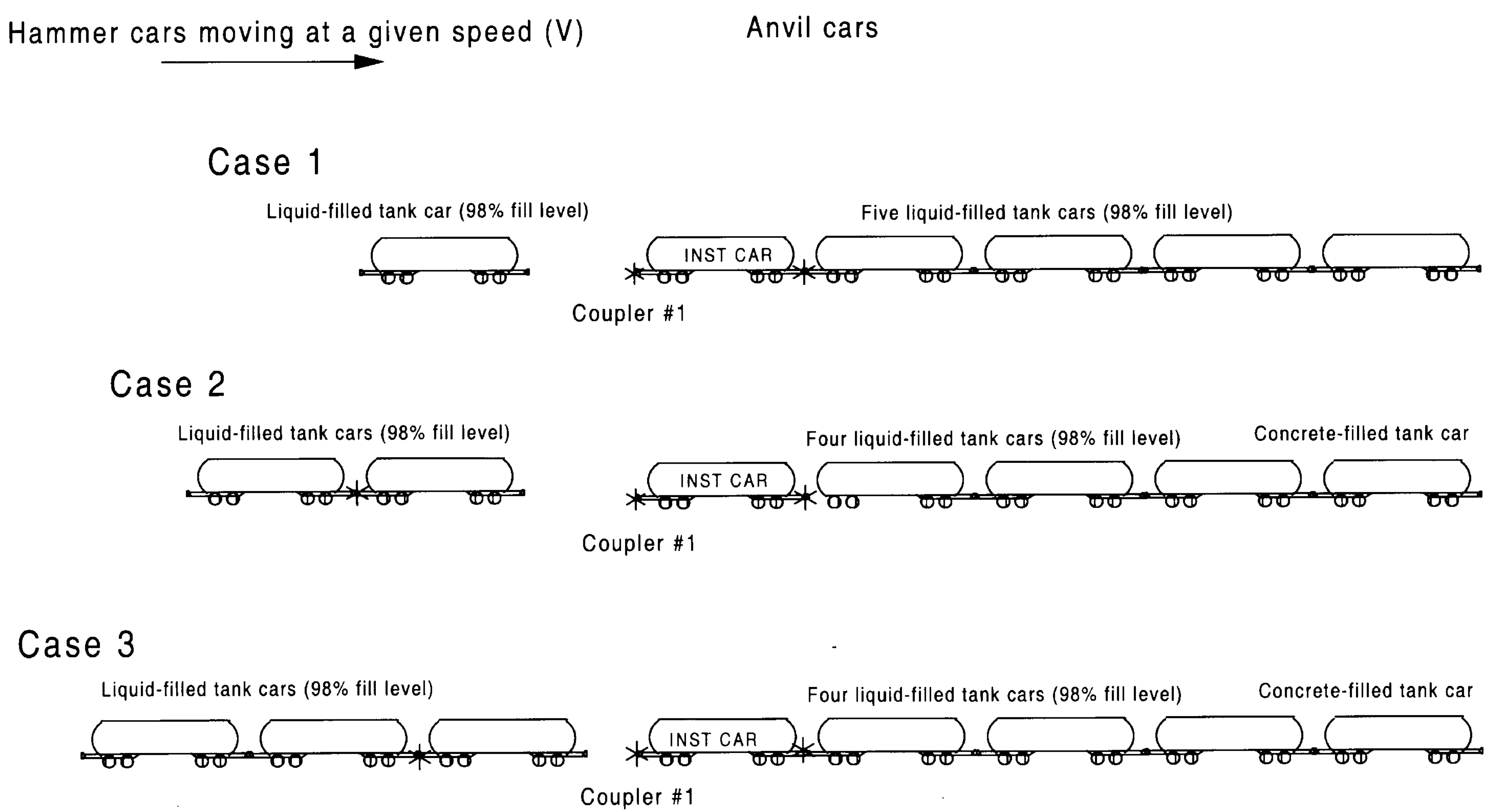

Figure 1 (appA-1)   Tank car configurations in group 1 in ADAMS models

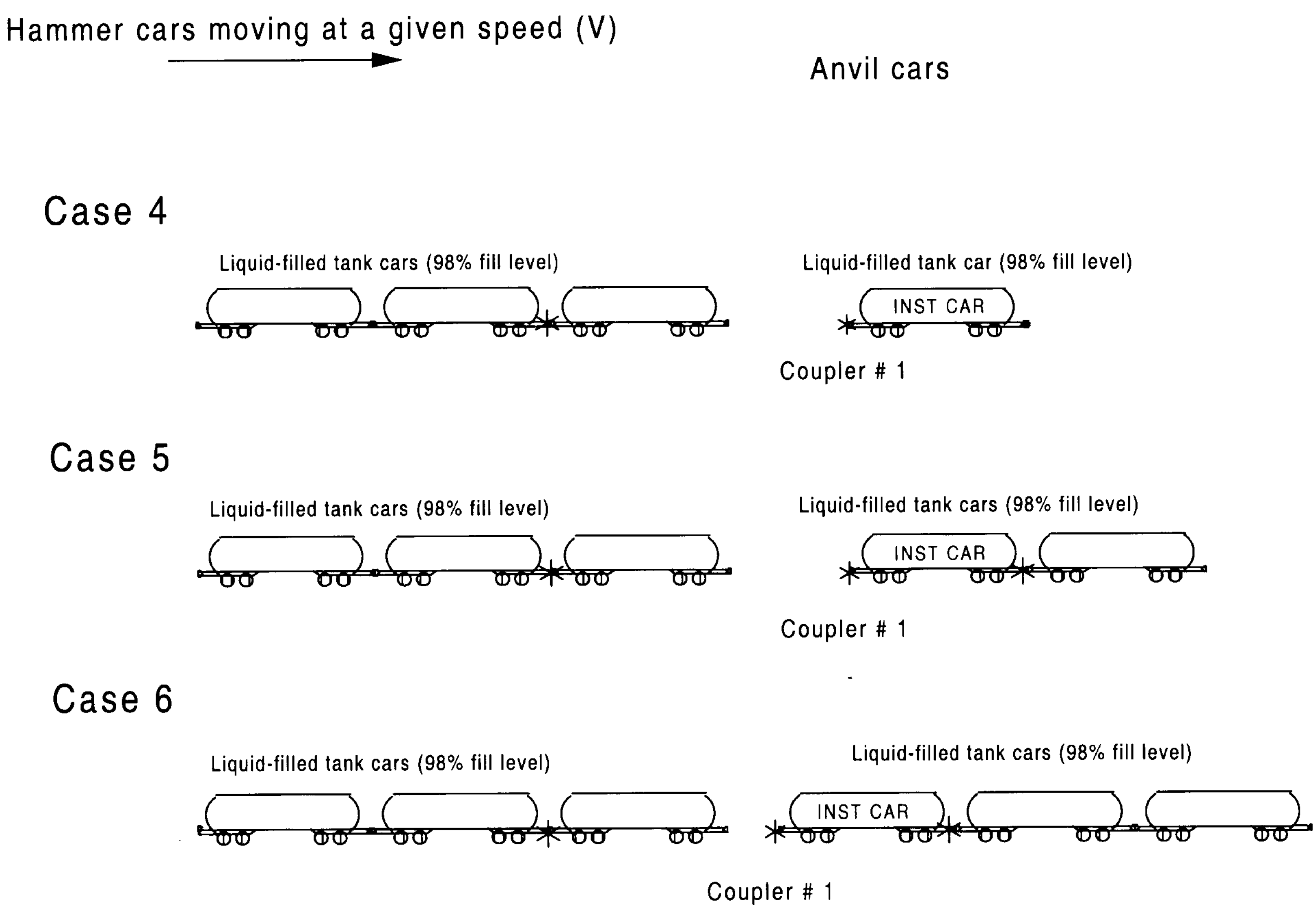

Figure 2 (appA-2) Tank car configurations in group 2 in ADAMS models

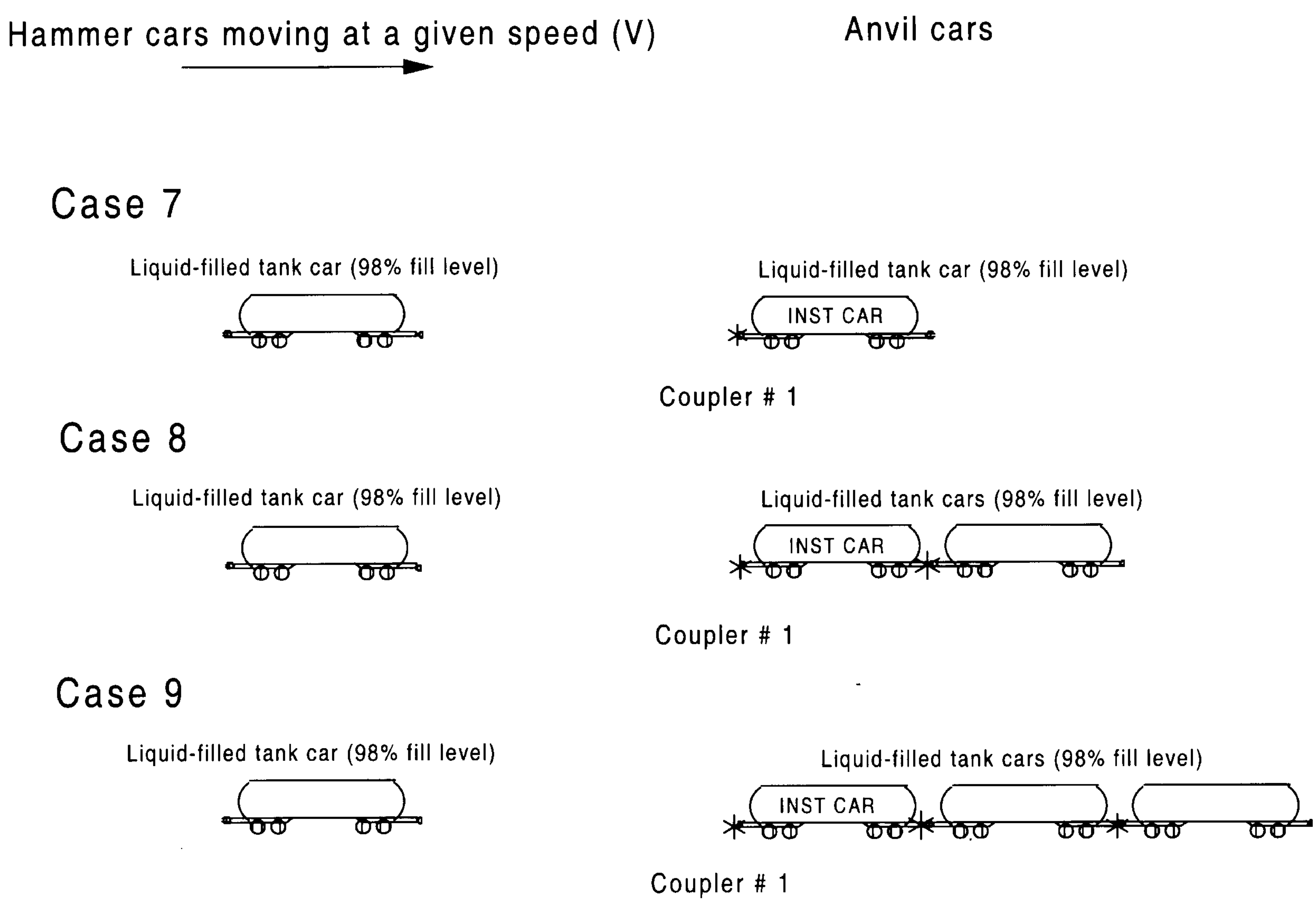

Figure 3 (appA-3) Tank car configurations in group 3 in ADAMS models

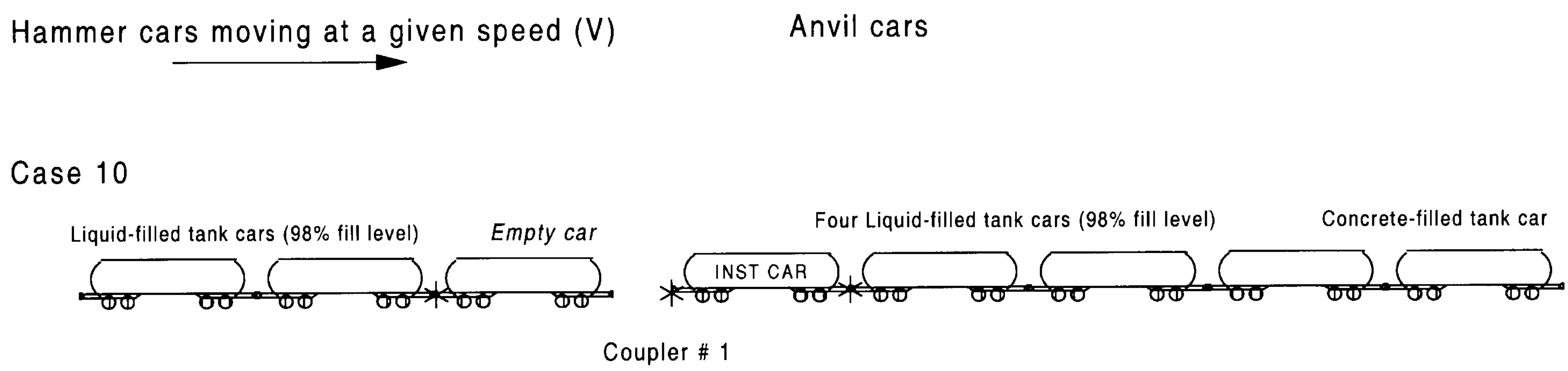

Figure 4 (appA-4) Tank car configurations in group 4 in ADAMS models

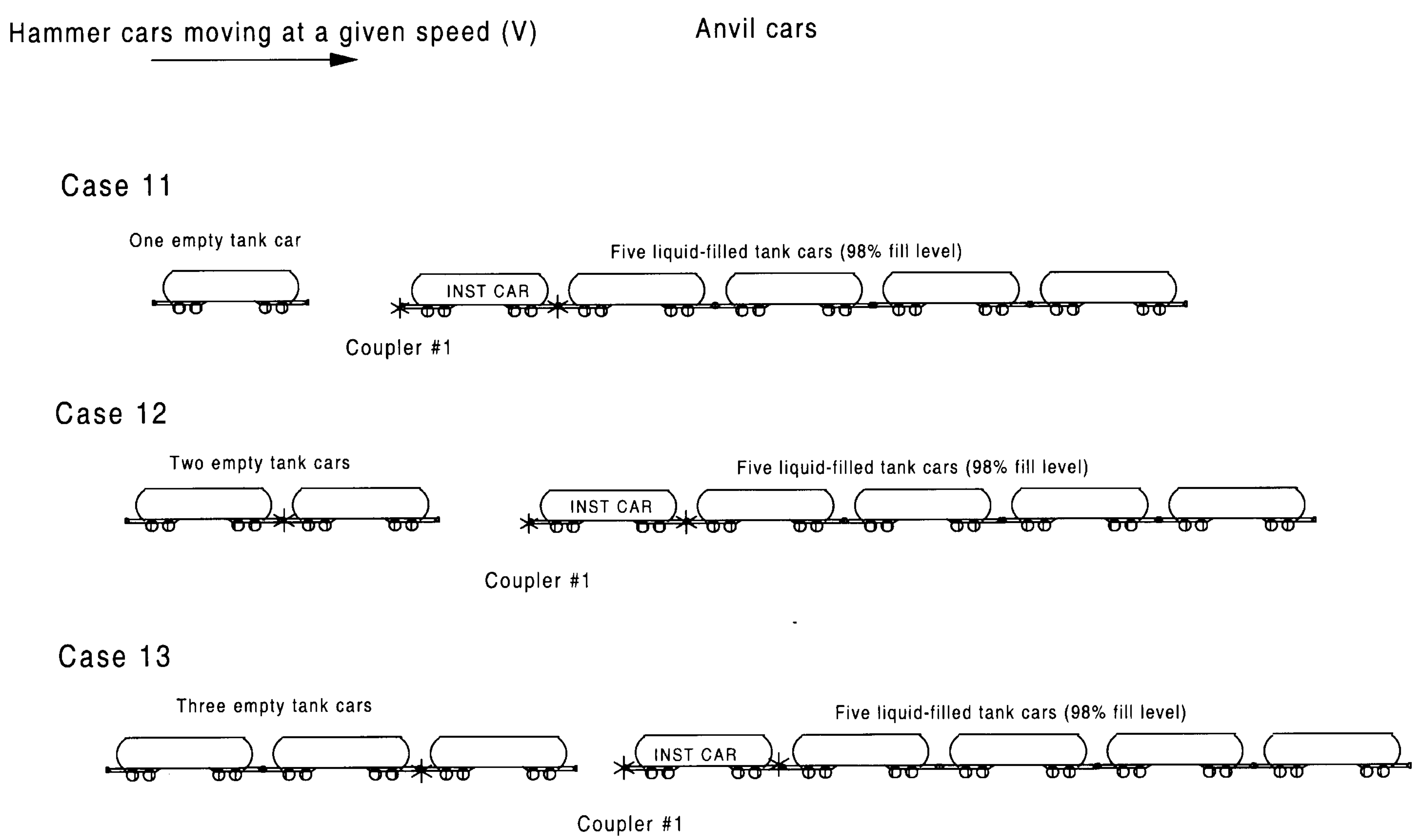

Figure 5 (app-A-5) Tank car configurations in group 5 in ADAMS models

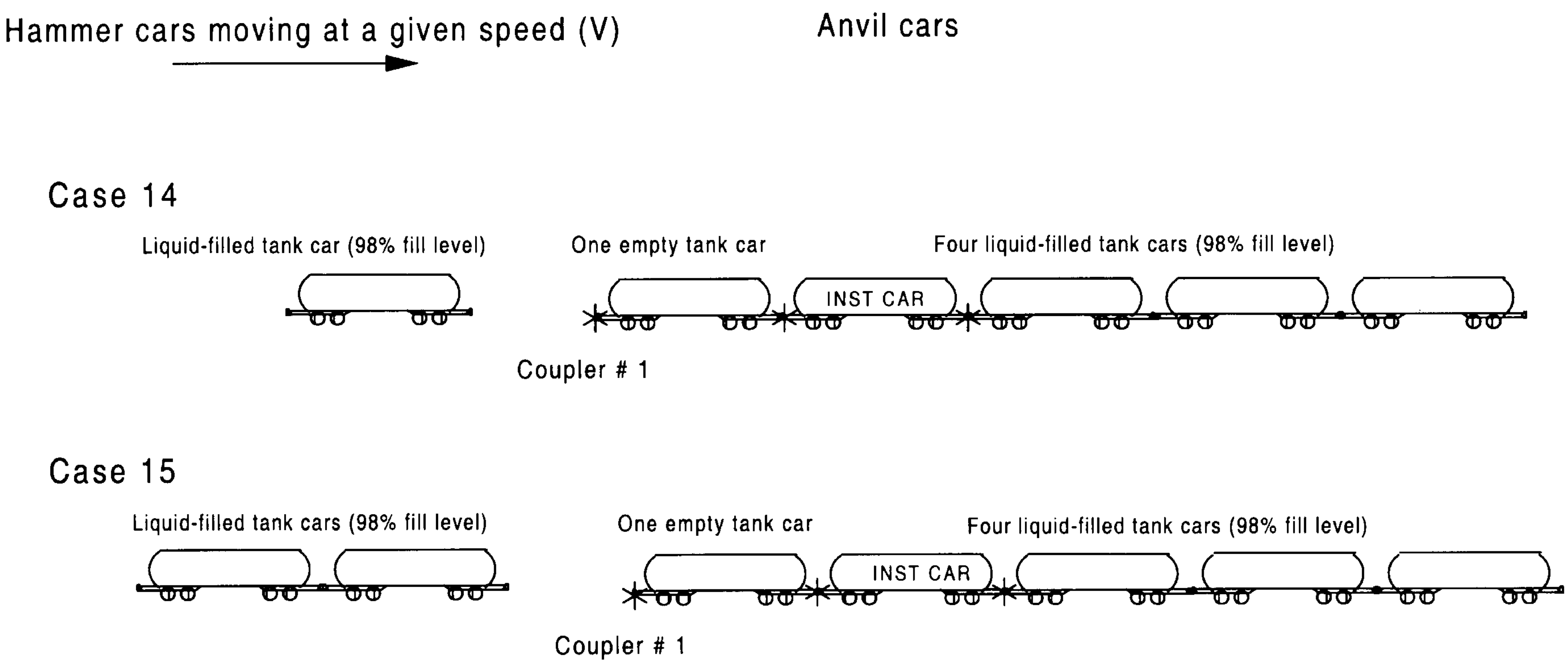

Figure 6 (appA-6) Tank car configurations in group 6 in ADAMS models

APPENDIX B   A SET OF 1F/1F TEST RESULTS PROVIDED BY MINER

Figure 1 (app.B)   Aset of test results provided by Miner/Cardwell-Westinghouse

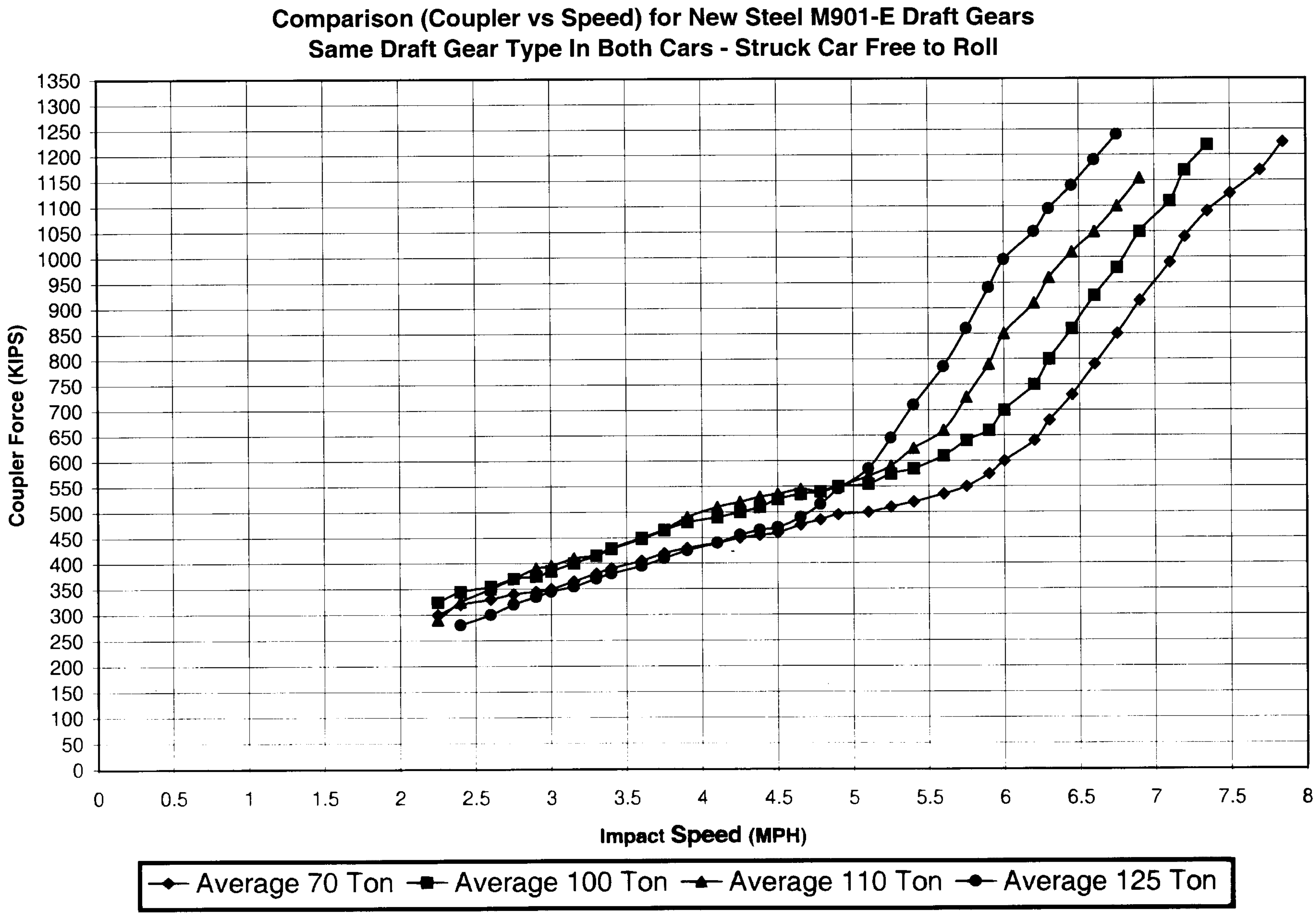

Figure 1 (appB-1) A set of test results provided by Miner/Cardwell-Westinghouse