:alRecovery No. 1310

Final Report

CONVERSION FACTOR STUDY

IN-VEHICLE AND IN-PLACE WASTE DENSITIES

Submitted to:

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NOTE: Legislation (SB 63, Strickland, Chapter 21, Statutes of 2009) signed into law by Gov. Arnold Schwarzenegger eliminated the California Integrated Waste Management Board (CIWMB) and its six-member governing board effective Dec. 31, 2009.

CIWMB programs and oversight responsibilities were retained and reorganized effective Jan. 1, 2010, and merged with the beverage container recycling program previously managed by the California Department of Conservation.

The new entity is known as the Department of Resources Recycling and Recovery (CalRecycle) and is part of the California Natural Resources Agency. It is no longer part of the California Environmental Protection Agency (Cal/EPA).

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IN-VEHICLE AND IN-PLACE WASTE DENSITIES

PREFACE

The California Code of Regulations [Title 14, Division 7, Chapter 9, Article 6.1, Section 18722(f) (1) (A)] requires the California Integrated Waste Management Board to complete a study and compile a list of acceptable conversion factors for each specific solid waste type listed in Section 18722(j) by January 1, 1992. The list of acceptable conversion factors will be used by jurisdictions (cities and counties) to convert quantities of solid waste to the units required in Article 6.1 of the Regulations.

Both the legislation and the regulations implementing the legislation mandate that the quantification be based on weight. One method for calculating waste quantities consists of using volume estimations and appropriate bulk densities to estimate weights of materials. Error of estimation is introduced into the procedure in several forms, including those associated with measuring the volume of materials and those associated with accurately determining and using appropriate bulk densities. This report addresses the important issue of defining densities for a) solid wastes collected and transported in a variety of vehicles, and b) for solid wastes compacted at landfill disposal facilities in California. The bulk densities reported herein can be used to convert volumetric data to weight data or vice versa (i.e., the bulk densities serve as the basis for conversion factors between volume and weight). Important applications of the bulk densities and conversion factors relevant to the State's recycling legislation include estimating volumes or weights of disposed and of diverted wastes.

NOTICE

This report was prepared in fulfillment of California Integrated Waste Management Board Contract No. IWM-C080, for which the total budget was $168,926.

The statements and conclusions of this report are those of the contractor and not necessarily those of the California Integrated Waste Management Board, its employees, or the State of California. The State makes no warranty, express or implied, and assumes no liability for the information contained in the succeeding text.

EXECUTIVE SUMMARY

This report describes models for estimating in-vehicle waste densities and for estimating in-place densities of waste in landfills. The in-vehicle density models can be used to convert volumetric waste quantities to weights for waste delivered by vehicles to solid waste facilities. The in-place density model can be used to estimate the in-place volume of waste compacted under a specified set of conditions.

To our knowledge, this study commissioned by the California Integrated Waste Management Board (CIWMB) is the first effort in the United States to develop sophisticated models for estimating the density of wastes carried in collection vehicles or after compaction by landfill equipment. Heretofore the conventional means of estimating densities was by conducting surveys of weights and volumes for collection vehicles and for compacted wastes in a cell. These data subsequently became "averages" that seldom were checked regularly and almost certainly did not consider the influence of waste composition or operating conditions.

The lack of history of research and of data on compaction of waste is a severe drawback to the solid waste industry regarding the matter of accurately estimating the density of waste under various situations of compaction. The matter is made worse by the fact that solid waste is a mixture of materials and virtually no research has been conducted on the sensitivity of the results of compacting various compositions of a heterogeneous mixture of waste materials under various operating conditions. This study served to extend the fund of knowledge on waste compaction, and to provide important results and a firm basis for further research.

Prior to the development of the models, an extensive literature search and several field tests were conducted in order to provide a base of data for initializing and calibrating the models. The models were develope- based on the results of these early activities, fundamental engineering principles, and other empirical data.

Two models for estimation of in-vehicle densities are presented. The Simple Model estimates in-vehicle waste densities based on type of vehicle (e.g., rear loader), the volumetric capacity of the vehicle, and the estimated percent of full capacity actually occupied by the load. The model was found to be very accurate when tested at two solid waste facilities in California. The model automatically estimates the total tonnage entering a solid waste facility by summing the results of all of the vehicle entries. As its name implies, the model is simple to use and requires data that can be collected relatively easily at the entry point of a solid waste facility.

The second in-vehicle density model, Model-2, is a more sophisticated and therefore, a more complex model than the Simple Model for estimating in-vehicle waste densities and total waste quantities entering a solid waste facility. The model utilizes waste composition as a basic input, as well as volumetric capacity of the vehicles and percent of vehicle capacity utilized. The model was found to be substantially less accurate than the Simple

Model. Consequently, this model requires the exercise of care by the user and verification of the values of the many variables in the model.

The In-Place Density Model estimates the density of waste in a landfill based on three basic parameters: the weight of the compacting vehicle, the number of passes over the waste, and the slope of the working face. The results of the In-Place Density Model can be used to compute the in-place volume for a specified volume of waste delivered to a solid waste facility. The conditions of the compacting process are specified by the user of the model. The In-Place Density Model was found to be very accurate for a reasonable range of operating conditions.

Also presented in the report is a General Model that integrates the more complex in-vehicle density model, i.e., Model-2, with the In-Place Density Model. Combining these two models allows the estimation of in-place density of waste based upon waste composition, as well as the other basic parameters. The General Model is a sophisticated model that requires care in use due to the number of variables used to model the processes. The model was also found to be less accurate than the In-Place Density Model under the conditions studied during the project.

All models are fully described in the report, and examples are presented. The report also includes results of tests conducted to verify the accuracy of the models.

FINDINGS AND RECOMMENDATIONS

IN-VEHICLE DENSITY MODEL

Two models were developed for estimating from volume data the weight of waste carried in different types of vehicles. The simpler of the two models (the Simple Model) was found to be very accurate in terms of levels of accuracy typically achieved in practice for a wide range solid waste operations. The Simple Model was found to be accurate within the range of 8% to 14% based on a program of testing at two solid waste facilities, one in northern and one in southern California. This model is user friendly and should be useful at solid waste facilities around the state. The model is also easily updated to reflect site-specific conditions, such as changes in waste composition, using relatively simple weight surveys of samples from vehicle loads.

The more complex of the models (Model-2), despite substantial analytical work, was found to be only accurate within 30% to 40%. The accuracy of the complex model is low due to lack of test data representing the substantial variations in operating conditions among vehicles and of data reflecting the compaction of various waste compositions under site-specific and controlled conditions. Model-2, however, does reflect the basic principles influencing the compaction of wastes in vehicles (including composition of waste) and therefore is sound fundamentally. Additional research is needed to refine the model and to acquire a large base of data for calibration of the model.

IN-PLACE DENSITY MODEL

A user-friendly model was developed for estimating the density of waste compacted in a landfill. The model was found to be accurate to within about 9% of actual reported values when subjected to verification at 18 landfill facilities in California. An important result found during the study was that waste composition did not appear to substantially impact the accuracy of the model. This finding greatly simplifies the calculational routine and use of the model. This model is appropriate for use for conditions where the compaction equipment weighs in the range of 30,000 to 90,000 lb, the slope of the working face is in the range of 6:1 to 2:1, and the number of passes over the waste is in the range of 2 to 9.

A General Model was also developed which incorporates the composition of the waste as a variable and incorporates the more complex in-vehicle density model (Model-2). This model was found to be less accurate than the simple in-place density model under the conditions investigated during the project. The inaccuracy of the General Model is a consequence of the compounding of the inaccuracy of Model-2 and that of the in-place model. Consequently, the General Model should not be used without verification of the values of the variables and constants for the specific case under consideration. Additionally, further research is recommended to determine the value of constants in the model and the parameters that influence them.

The General Model serves to model the density of waste from the point of collection until the point of burial. This concept of integration was a development of the study and, to our knowledge, represents the first attempt at such an integration. While the accuracy of the

General Model may be less than desired, the fundamental principles have been identified and encoded in the model. Further research and field testing would serve to improve the accuracy and utility of the model.

Section 1

IN-VEHICLE DENSITIES

INTRODUCTION

Densities of solid waste hauled in various types of refuse collection and self-haul vehicles are reported in this study. For the purpose of this study, such densities are termed "in-truck" or "in-vehicle" densities. In-truck densities were identified from the solid waste literature, from a canvassing of various solid waste jurisdictions and collection vehicle manufacturers in the U.S., and from the conduct of field investigations.

CalRecovery developed lists of vehicle manufacturers, haulers, and other potential sources from which to gather as many reliable data as possible within the constraints of the time schedule and the budget for the study. The lists were composed of contacts obtained from CalRecovery files, from industry publications such as Waste Age, and from professional rosters. The gathering of information did not take the form of a survey with a specified population. Rather, the focus was on identifying the best possible data either directly from contacts or from further leads provided by the primary contacts.

Information is discussed in some cases in terms of primary data and secondary data. Primary data, for the purpose of this study, are defined as measured data reported by an investigator or measured data reported by a third party. CalRecovery exercised judgement in forming opinions of what constituted primary data as opposed to secondary data. Secondary data are defined as data of lesser quality than primary data, such as data reported with inadequate information or a lack of reference to test conditions. In keeping with the standard industry convention, all density data are reported in lb/cu yd.

Primary data were gathered from field studies and a review of available literature. The sample data from the very few available field studies yielded averages. Many references reported data in the form of a range. The mean (i.e., average) of the sample data reported in some of these studies was not reported.

The purpose of gathering data from field studies and available literature was to generate as large a base of reasonable data as possible so that useful summary inferences could be made regarding in-vehicle densities by waste type and vehicle type.

The midpoints of the ranges obtained from the literature search were close in most cases to the sample averages identified in the field studies. For this reason, and due to the low number of available studies that reported primary data, the sample averages and the midpoints of the ranges obtained from the literature were averaged.

To the extent that it was available, the information obtained accounts for the sources of waste from various types of waste generators. These sources of waste are categorized as "residential," "commercial," "industrial," and "self-haul," using the definitions established by the California Integrated Waste Management Board (CIWMB) in Title 14, Chapter 9, Article 3, Section 18720(a).

LITERATURE REVIEW AND FIELD DATA ANALYSES

As required by the Scope Of Work, a comprehensive review of the literature was conducted to determine the existence of primary and secondary data regarding in-vehicle densities of solid waste. Information on in-vehicle densities was collected for several types of trucks and for wastes collected from residential, commercial, industrial, and self-haul sources.

Based on the review, it was found that although there are considerable secondary data available, reliable primary data are few in number. Only the primary data will be reported here. The secondary data are generally within the range of reported values obtained from primary sources, and are viewed as background data only.

Information was collected from California sources as well as from non-California sources. The non-California data generally were similar to the California data as reflected in a comparison among the data. California and non-California in-truck density information was collected to provide a universe of data that would encompass all the types of vehicles and waste sources that could be expected currently or in the next 5 to 10 years in California. In cases where California-specific data are available, these data are used for in-truck analyses. However, since the definition of every waste generator and every vehicle manufacturer and model is outside of the Scope Of Work of the study, non-California data are presented as a resource to draw upon for reasonable estimates of in-truck waste densities where a jurisdiction lacks its own vehicle fleet information or encounters a situation not specifically covered in this report.

Residential Sector

Residential waste is delivered to solid waste facilities (e.g., landfills) primarily in rear loaders, side loaders, or in self-haul vehicles (see Self-Haul). Currently, the predominant vehicle type in California collecting residential waste is the rear loader.

<u>Rear Loaders</u>

Based on information provided by more than 10 manufacturers of rear loaders (see Table 1-1), in-truck densities range from 600 lb/cu yd to 1200 lb/cu yd. The average of the values reported by the manufacturers is 860 lb/cu yd. Half of these values were between 800 and 900 lb/cu yd. Generally, the information is test data that were gathered in two primary ways. First, several manufacturers reported data that had been gathered through direct observation by research staff from the companies. Second, other manufacturers reported data that had been gathered in the field by users of the equipment. This categorization of how the data were gathered is for the sake of differentiation among sources of data; no differentiation exists between research staff or users in terms of reliability of the reported data. This categorization is also utilized in later sections of the report. The manufacturers that provided information were selected from a list of equipment manufacturers as discussed in the Introduction.

Table 1-1. In-Truck Densities (lb/cu yd): Residential Rear Loaders (Manufacturers)

Company	Density[1]
Capital Disposal Equipment, Inc.[2]	1050 and 700
Crane Carrier Company*[3]	1000
Dempster, Inc.*[3]	900
G & H Manufacturing, Inc.[3]	up to 800
The Heil Company*[3]	up to 1000 and up to 800
Jaeger Canada Equipment Co. Ltd.[2]	1000-1200 and 800-1000 and 800-1000
Leach*[3]	600-1000
Loadmaster Corporation[3]	1000 and 950-1000 and 700-750
McNeilus Truck & Mfg.*[2]	up to 1000
Peabody Galion/E-Z Pack*[3]	up to 1000 and 900 and 800
Peabody Galion/E-Z Pack*[3]	600
Scranton Manufacturing Co., Inc.*[3]	700-800
Wayne Engineering Corporation*[2]	850 and 800 and 700

*Vehicle known to be sold in California.

1 Reported densities are national averages; manufacturers could not provide a breakdown of densities by region (e.g., California, non-California).

2 Source: Field data provided by manufacturers in telephone calls, September and October 1991.

3 Source: Literature data obtained from Waste Age, June 1991.

California Data

Four studies conducted in California during the past ten years identified statistically significant sample averages of in-truck densities ranging from approximately 420 lb/cu yd to 680 lb/cu yd (see Table 1-2). The overall average of these averages is approximately 530 lb/cu yd. The sample average from rural Kings County, California (520 lb/cu yd) is within 2% of the overall average of the California studies (both rural and urban) identified in Table 1-2.

The compaction capability of rear loaders has increased considerably since 1970. The most pronounced shift occurred in the period between 1973 and 1978, when several manufacturers introduced high compaction models. This shift was made in response to the post-1973 rise in oil prices, and became a means to reduce the increase in collection costs. The potential influence of the year a rear loader was manufactured on the in-truck density of mixed residential waste is shown in Figure 1-1 using data from field studies conducted in California.

Non-California Data

Based on primary information provided by three non-California local governments or their consultants (see Table 1-3), in-truck densities range from 410 lb/cu yd to 1200 lb/cu yd.

Based on information provided by six waste haulers (see Table 1-4), in-truck densities range from 810 lb/cu yd to 1000 lb/cu yd. The average of the midpoints of the individually reported ranges is 890 lb/cu yd. Nearly all of the reported ranges cover this average. The process used to select these haulers is discussed in the Introduction.

Side Loaders

Based on information furnished by more than fifteen manufacturers of side loaders that were chosen randomly (see Table 1-5), in-truck densities range from 300 lb/cu yd to 825 lb/cu yd. The average of the values reported by the manufacturers is 590 lb/cu yd. Approximately half of these values were between 550 and 650 lb/cu yd. Generally, the information is test data that were gathered in two primary ways. First, several manufacturers reported data that had been gathered through direct observation by research staff from the companies. Second, other manufacturers reported data that had been gathered in the field by users of the equipment. The manufacturers that provided information were selected from a list of equipment manufacturers, as discussed in the Introduction.

California Data

In a field study conducted in 1991 by CalRecovery, the average in-truck density for side loaders operating in Marin County, California, was 464 lb/cu yd. This result is based on 4 samples, and has a 13.8% error.

Table 1-2. In-Truck Densities (lb/cu yd): Residential Rear Loaders
California Local Government Field Studies

Location	Sample Average	% Error	Number of Samples	Demographics	Source
Alameda County[1]	675	5.0	15	Urban	Cal Recovery Systems, Inc. (1989)
Kings County[2]	521	8.6	8	Rural	Cal Recovery Systems, Inc. (1990)
Marin County	579	6.5	78	Suburban	CalRecovery, Inc. (1991)
Santa Clara County[3]	439	20.4	6	Urban/Suburban	Cal Recovery Systems, Inc. (1983-84)
Santa Clara County[3]	417	30.1	3	Urban/Suburban	Cal Recovery Systems, Inc. (1983-84)
Average	526 [a)]				

a) rounded to 525 lb/yd^3

[1] Aggregate of three vehicle types.

[2] Side-loader used in residential pick-up.

[3] From different vehicles.

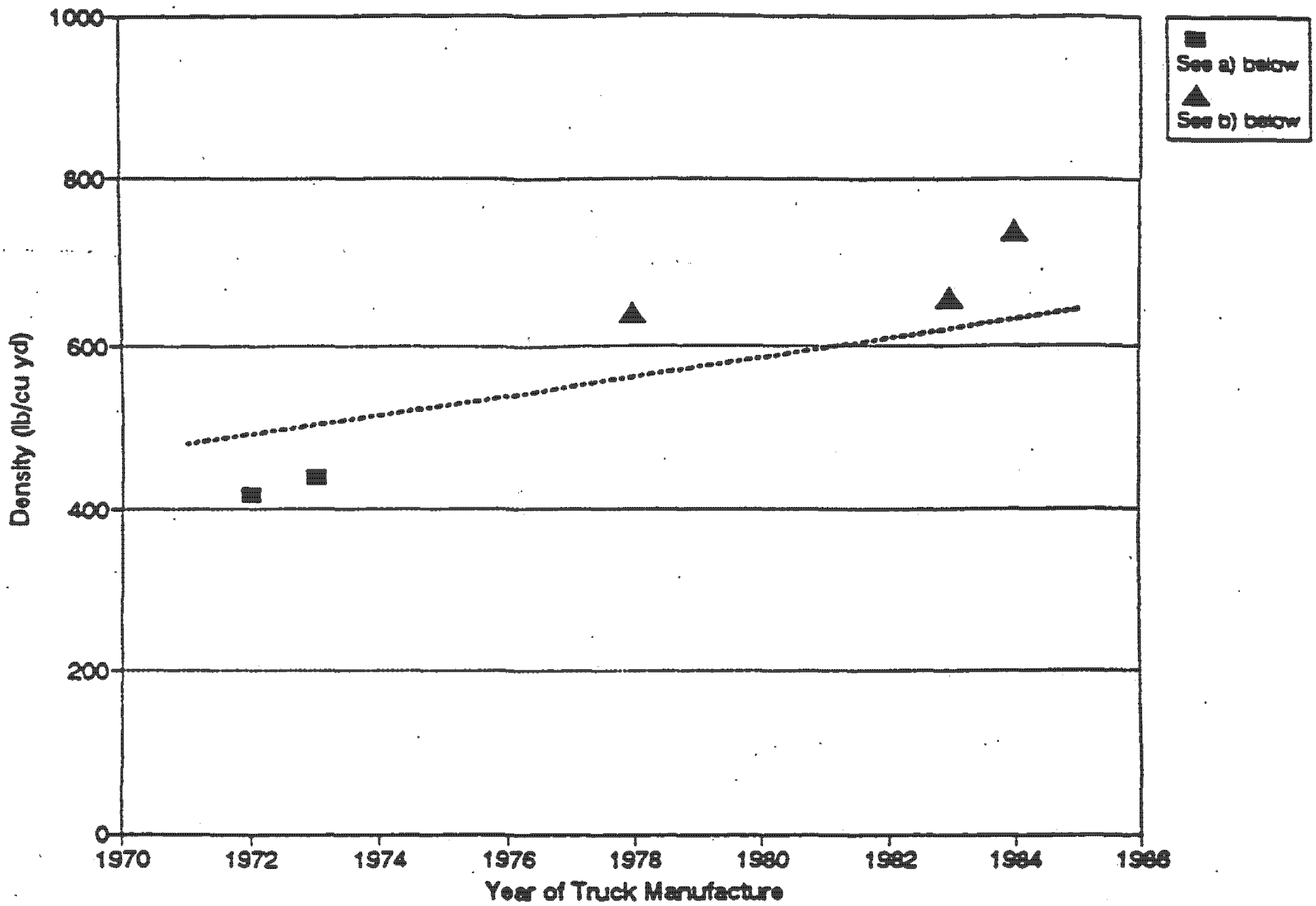


Figure 1-1. In-Truck Density of Mixed Residential Waste vs. Year of Truck Manufacture – Rear Loader

a) Based on vehicle data gathered as part of a 1983-84 comprehensive waste characterization study for North Santa Clara County conducted by Cal Recovery Systems, Inc.

b) Cal Recovery Systems, Inc., Waste Characterization Study for Berkeley, California: First Sampling Period, January, 1989.

Table 1-3. In-Truck Densities (lb/cu yd): Residential Rear Loaders
Non-California Local Government Studies

Location	Range	Midpoint of Range[1]	Demographics	Source
Dakota County, MN (1987)	410-630	520	Rural	Pope-Reid Associates, Inc.
Anoka County, MN (1985)	590-810	700	Suburban	Pope-Reid Associates, Inc.
New York, NY	1000-1200	1100	Urban	City of New York (1991)

[1] Information on the distribution of data points within the range was unavailable.

Table 1-4. In-Truck Densities (lb/cu yd): Residential Rear Loaders
Non-California Haulers

Range	Midpoint of Range	Source[1]
770-900	840	BFI—Cambridge, MA (1991)
n/a	810	Vining Disposal (1991)
770-1030	900	Lyons Corporation (1991)
900-970	940	Atlantic Waste (1991)
650-1030	840	Sherman Disposal (1991)
840-1160	1000	Dooley Disposal (1991)

Table 1-5. In-Truck Densities (lb/cu yd): Residential Side Loaders
(Manufacturers)

Company	Density[2]
Able Body Company, Inc.*[3]	550-800
Amertek, Inc.*[4]	600-800
Athey Products Corporation[4]	750
Crane Carrier Company*[3]	700-800
G & H Manufacturing, Inc.[3]	600-700
Haul-All Equipment Systems*	300-350
The Heil Company*[3]	up to 650
Labrie Equipment Ltd.*[4]	600-700
Lodal, Inc.*[3]	700-825
Martco, Inc.	300-500
Peabody Galion/E-Z Pack*[3]	500-700
Peerless Corporation*[4]	600-800
Rapid Rail Systems*[4]	635-700
Scranton Manufacturing Co., Inc.*[3]	500 and 400-600
Wayne Engineering Corporation*[4]	700
Wayne Engineering Corporation*[4]	330-350 and 530
Wittke Iron Works Company, Ltd.*[4]	475 and 450

*Vehicle known to be sold in California.

1 Estimated ranges obtained during telephone conversations with respective haulers. Whether results are based on sample data could not be confirmed.

2 Reported densities are national averages; manufacturers could not provide a breakdown of densities by region (e.g., California, non-California).

3 Source: Field data provided by manufacturers in telephone calls, 9-10/91.

4 Source: Literature data obtained from Waste Age, June 1991.

Commercial Sector

Commercial waste is normally delivered to solid waste facilities in front loaders. Rear loaders are sometimes used to service commercial generators, e.g., when such generators are dispersed among residential generators or in those cases where small collection vehicles are required due to route limitations. Some commercial waste is delivered to solid waste facilities in roll-off compactors as well.

Front Loaders

In-truck densities for front loaders were provided by approximately 10 equipment manufacturers (see Table 1-6). Based on this information, in-truck densities range from 400 lb/cu yd to 1000 lb/cu yd. The average of the values reported by the manufacturers is 730 lb/cu yd. Approximately half of these values were between 650 and 750 lb/cu yd. Generally, the information is test data that were gathered in two primary ways. First, several manufacturers reported data that had been gathered through direct observation by research staff from the companies. Second, other manufacturers reported data that had been gathered in the field by users of the equipment. The manufacturers that provided information were selected from a list of equipment manufacturers, as discussed in the Introduction.

California Data

Four studies conducted in California during the past ten years identified statistically significant sample averages of in-truck densities ranging from approximately 370 lb/cu yd to 630 lb/cu yd. The overall average of these averages is approximately 480 lb/cu yd (see Table 1-7). This average is similar to that found outside California, as described below. The sample average from rural Kings County, California, (approximately 520 lb/cu yd) is within 8% of the overall average of the California studies (both rural and urban) identified in Table 1-7.

Non-California Data

Based on primary information gathered from two non-California local governments or their consultants (see Table 1-8), in-truck densities range from 280 lb/cu yd to 730 lb/cu yd. The average of the midpoints of the individually reported ranges is 520 lb/cu yd. Each of the reported individual ranges covers this average value. The midpoint of the range reported for rural Dakota County, Minnesota, is within 2% of the average of the midpoints for non-California studies (both suburban and rural) identified in Table 1-8.

One waste hauler reported an in-truck density of 370 to 420 lb/cu yd (A-1 Container, Rehoboth, MA, 1991).

Rear Loaders

In-truck densities for rear loaders that haul commercial waste were obtained from three waste haulers (see Table 1-9). Based on this information, in-truck densities range from 320 lb/cu yd to 970 lb/cu yd. The average of the midpoints of the individually reported ranges is approximately 740 lb/cu yd. These data are estimated to be representative of the range

Table 1-6. In-Truck Densities (lb/cu yd): Commercial Front Loaders (Manufacturers)

Company	Density[1]
Able Body Company, Inc.*[2]	500-800
Amrep, Inc.*[3]	700
Capital Disposal Equipment, Inc.[3]	800
Crane Carrier Company*[2]	700-1000
Dempster, Inc.*[2]	850 and 700
The Heil Company*[2]	up to 1000
The Heil Company*[2] models)	up to 1000 (all
Lodal, Inc.*[2]	400-500 and 500-600
Lodal, Inc.*[2]	700 and 800
Peabody Galion/E-Z Pack*[2]	600 and 700 and 500
Univ. Handling Equipment Co. Ltd.[2]	650 and 925
Wittke Iron Works Company, Ltd.*[3]	700

*Vehicle known to be sold in California.

1 Reported densities are national averages; manufacturers could not provide a breakdown of densities by region (e.g., California, non-California).

2 Source: Field data provided by manufacturers in telephone calls, 9-10/91.

3 Source: Literature data obtained from Waste Age, June 1991.

Table 1-7. In-Truck Densities (lb/cu yd): Commercial Front Loaders
California Local Government Field Studies

Location	Sample Average	% Error	Number of Samples	Demographics	Source
Alameda County	631	4.3	22	Urban	Cal Recovery Systems, Inc. (1989)
Kings County	516	11.5	9	Rural	Cal Recovery Systems, Inc. (1990)
Santa Clara County 84)	365	9.2	15	Urban/Suburban	Cal Recovery Systems, Inc. (1983-
Santa Clara County	400	10.5	20	Urban/Suburban	Cal Recovery Systems, Inc. (1988)
Average	478 [a]				

a) rounded to 480 lb/cu yd for use in Table 1-18

Table 1-8. In-Truck Densities (lb/cu yd): Commercial Front Loaders
Non-California Local Government Studies

Location	Range	Midpoint of Range[1]	Demographics	Source
Dakota County, MN (1987)	280-730	510	Rural	Pope-Reid Associates, Inc.
Anoka County, MN (1985)	420-640	540	Suburban	Pope-Reid Associates, Inc.

[1] Information on the distribution of data points within the range was unavailable.

of densities of commercial wastes collected by rear loaders in California. A wide range of densities for commercial collection rear loaders is to be expected given the examples cited previously. Densities for specific locations can vary within the range given in Table 1-9, and site specific data should be used whenever possible.

Roll-Off Compactors

In-truck densities were reported for a few specific commercial sub-sectors. As illustrated in Table 1-10, densities can vary greatly by sub-sector. These densities are judged to be representative of those for similar commercial sub-sectors in California since the loads are relatively homogeneous, i.e., predominantly of one or two waste types.

Industrial Sector

California Data

Industrial waste is delivered to solid waste facilities primarily in roll-off or debris boxes. In a field study conducted in 1991 by CalRecovery, the sample average found in Marin County, California, was 402 lb/cu yd, based on 58 samples. This information is also presented in Table 1-11.

Non-California Data

Based on information gathered from local and state governments or their consultants in two states other than California (see Table 1-12), in-truck densities range from 190 lb/cu yd to 500 lb/cu yd. The midpoint of the reported ranges is 400 lb/cu yd. This midpoint is nearly identical to the sample average found in Marin County, as discussed previously.

Information on in-truck densities was gathered from four waste haulers (see Table 1-13). Reported densities range from 250 lb/cu yd to 690 lb/cu yd. The average of the midpoint of the reported ranges is approximately 410 lb/cu yd. The process used to select haulers is discussed in the Introduction.

Construction and Demolition Materials

Separate information was gathered from six waste haulers on construction and demolition (C&D) materials. This information is presented in Table 1-14. Much of industrial waste consists of C&D materials separated from other waste. The process used to select haulers is discussed in the Introduction.

The average densities reported range from 300 lb/cu yd to 2000 lb/cu yd. This wide range is affected by the type of material being hauled. For example, the density of concrete was reported at 2000 lb/cu yd, while the density of loose wooden boards was reported at 330 lb/cu yd. The overall average for the reported densities is 810 lb/cu yd. Because of the similarity in C&D materials nationwide, these results are judged by CalRecovery to be representative for California as well as for non-California locations.

Table 1-9. In-Truck Densities (lb/cu yd): Commercial Rear Loaders
Non-California Haulers

Range	Midpoint of Range[1]	Source
n/a	970	Vining Disposal (1991)
770-900	840	Atlantic Waste (1991)
320-520	420	Sherman Disposal
(1991)		

Table 1-10. In-Truck Densities (lb/cu yd): Commercial Roll-Off Compactors
Non-California Haulers

Sub-Sector	Range	Midpoint of Range[2]	Source
Restaurants	800-930	870	E.L. Harvey and Sons (1991)
Grocery Stores[3]	1000-1330	1170	E.L. Harvey and Sons (1991)
Computer Company	150-200	180	E.L. Harvey and Sons (1991)
Tourist/Recreation	n/a	500	E.L. Harvey and Sons (1991)
	Average	680[4]	

Table 1-11. In-Truck Densities (lb/cu yd): Industrial Roll-Offs
California Studies

Location	Sample Average	Percent of Error	Number of Samples	Source
Marin County	402[5]	22.1	58	CalRecovery, Inc. (1991)

1 Information on the distribution of data points within the range was unavailable.

2 Information on the distribution of data points within the range was unavailable.

3 Corrugated cardboard removed from measured load.

4 Value used in Table 1-18

5 Rounded to 400 lb/cu yd for use in Table 1-18

Table 1-12. In-Truck Densities (lb/cu yd): Industrial Roll-Offs
Non-California State and Local Government Studies

State	Range	Midpoint of Range	Source
Minnesota (1991)	190-500	350	Minnesota Pollution Control Agency
Maine	n/a	440	State of Maine (1991)

Table 1-13. In-Truck Densities (lb/cu yd): Industrial Roll-Offs
Non-California Haulers

Vehicle Type	Range	Midpoint of Range	Source
Roll-off compactor	n/a	690	Vining Disposal
Roll-off	n/a	450	Vining Disposal
Roll-off compactor	270-330	300	Sherman Disposal
Roll-off compactor	n/a	250	A-1 Container
Roll-off compactor	290-480	380	Reliable

Table 1-14. In-Truck Densities (lb/cu yd): Construction & Demolition (C&D) Materials Non-California Haulers

Materials	Average	Source
C & D, no rock, dirt, brick	360	Vining Disposal
C & D, with rock, dirt, brick	600	Vining Disposal
C & D, with rock	1330	Lyons
C & D	300	Anytime
C & D	330	Sherman
C & D	1250	Grant
Concrete	2000	Harvey
Boards	330	Harvey

Table 1-15. As-Delivered Densities (lb/cu yd): Self-Haul Vehicles California Field Study - Kings County, Spring 1990

Vehicle Type	Average Volume of Load[1]	Sample Average[2]	Number of Samples
Pick-up	2.3 cubic yards	261	60
Small trailers	3.3 cubic yards	267	44

Source: Cal Recovery Systems, Inc. 1990.

1 Based on data from a week-long sampling of self-haul vehicle types by visual estimation.

2 Based on an average wt/vehicle as weighed in a week-long scale-house sampling program.

Self-Haul

California Field Studies

Self-haul waste is delivered to solid waste facilities in small, private vehicles, such as automobiles, pick-up trucks, and small trailers. In one rural county in California, self-haul waste has been determined to have an average density of approximately 260 lb/cu yd, as described in Table 1-15. In suburban Marin County, a field study determined the average density of self-haul waste to be approximately 430 lb/cu yd. This region receives considerably more precipitation than rural Kings County. It is presumed that the different densities in these two studies can be attributed in part to the effect of moisture content on in-vehicle density. These different densities can also be attributed in part to differences in waste composition and to the effect of seasonality. The study in Marin County was conducted in the fall, while the one in Kings County was conducted during the spring. Generally, the organic fraction of the waste stream is higher (and wetter) during the fall.

Average densities of self-haul waste were determined through a field study conducted at the Marin Recycling and Resource Recovery Facility. The test plan and data forms for the study are included as Appendix A of this report. Based on the results of this field study, the breakdown of densities for a variety of vehicle types and material categories is given in Table 1-16.

The average density of self-haul waste, based on results from these studies conducted in California, is similar to results from outside California, as described below.

Non-California Studies

A consultant for one non-California local government (Anoka County, MN) reported a range of 340 to 440 lb/cu yd for average density of self-haul waste (Pope-Reid Associates, 1985).

Mixed Solid Waste

Transfer Trailers

California Studies

In those cases where sources of waste generation are remote to disposal sites, mixed solid waste sometimes is transported in transfer trailers to landfills and other ultimate solid waste disposal facilities. In a field study conducted at the Marin Recycling and Resource Recovery Facility, the average density of mixed waste loaded loosely into transfer trailers was determined to be 431 lb/cu yd (4.9% error), based on a sampling of 14 loaded transfer trailers.

Summary

Information presented in Table 1-17 summarizes all of the California and non-California in-truck density data for residential, commercial, industrial, and self-haul wastes. The data are reported on the basis of three types of primary sources: local governments or their consultants; equipment manufacturers; and waste haulers.

Table 1-16. Marin County, California Field Study: Density Values for Self-Haul Vehicles

Type of Hauler	Waste Category	Vehicle Type	Sample Size	Average Density lb/cuyd	% Error (a)
Residential	Yard Waste	Mini-pickup	5	273.5	57.5
	Misc.	Mini-pickup	16	244.8	19.3
	Yard Waste	Full Size Pickup	7	193.3	35.2
	Misc.	Full Size Pickup	8	742.1	49.3
Commercial	Misc.	Van	4	376.7	31.5
	Yard Waste	Mini-pickup	16	293.7	27.0
	Misc.	Mini-pickup	6	533.3	39.1
	C & D	Mini-pickup	5	574.4	33.8
	Yard Waste	Full Size Pickup	24	315.6	22.0
	Misc.	Full Size Pickup	9	295.0	39.9
	Dirt/Rubble	Full Size Pickup	8	2660.9	26.1
	C & D	Full Size Pickup	9	472.7	31.3
	Yard Waste	Flat Bed	4	354.0	93.2
	Misc.	Flat Bed	5	683.2	90.4
	C & D	Flat Bed	5	498.4	50.7
	Yard Waste	Dump truck	12	355.9	43.7
	Misc.	Dump truck	4	298.3	65.7
	Dirt/Rubble	Dump truck	3	1083.1	16.0
	C & D	Dump truck	4	623.6	111.2

a) at 90% confidence

Table 1-17. Summary of In-Truck Density Data (lb/cu yd): Combined California and Non-California Sources

Waste Source	Vehicle Type	Range	Average[1]	Reporter
Residential	Rear loader	600-1200	860	Manufacturers
Residential	Rear loader	410-1200	620	Local Governments/Consultants
Residential	Rear loader	810-1000	890	Haulers
Residential	Side loader	300-825	590	Manufacturers
Residential	Side loader	400-530	460	Local Governments/Consultants
Commercial	Front loader	400-1000	730	Manufacturers
Commercial	Front loader	280-730	500	Local Governments/Consultants
Commercial	Front loader	370-420	400	Haulers
Commercial	Rear loader	320-970	740	Haulers
Commercial	Roll-off compactor	170-1170[2]	n/a	Haulers
Industrial	Roll-off	90-980	400	State/Local Governments/Consultants
Industrial	Roll-off	250-690	410	Haulers
Industrial (Construction & Demolition)	Roll-off	300-2000[3]	n/a	Haulers
Self-haul	Car/Pick-up	260-440	360	Local Governments/Consultants
Mixed	Transfer trailer	n/a	430	Consultants

1 "Average" includes: a) average of reported values; or b) average of the midpoints of reported ranges.

2 Varies by sub-sector (see Table 1-10).

3 Varies by primary material (see Table 1-14).

The recommended densities for use as the basis of estimating mixed waste quantities delivered in refuse collection vehicles in California are summarized in Table 1-18. The densities in Table 1-18 can be used in conjunction with waste volume estimates to formulate a simple but accurate predictive model for estimating waste quantities delivered to solid waste facilities.

Recommended densities for self-haul vehicles are shown in Tables 1-15 and 1-16 for rural and urban areas, respectively. No one value for self-haul vehicles is recommended since the bulk density of the wastes vary substantially depending on type of vehicle and waste composition. For purposes of volume-to-weight conversion for self-haul waste, jurisdictions should select the value or values from the tables that reflect their specific situation.

For those jurisdictions having vehicle types and waste sources not listed in Table 1-18, the jurisdictions can select the in-vehicle density values from Table 1-17 that most closely reflect the vehicle types and waste sources under consideration. For example, if a jurisdiction desires an in-truck waste density for residential side loaders, the average of the two average values listed in Table 1-17, i.e., 525 lb/cu yd, is a good estimation.

INFLUENCE OF COMPACTION PRESSURE

In addition to developing and collecting in-truck density data for compaction vehicles, CalRecovery examined the fundamental principles that potentially govern compaction of waste in order to identify variables heretofore not analyzed in the context of in-truck density estimation. Factors that impact the degree of compaction in compaction vehicles include waste composition, moisture content of the waste, and pressure applied to the wastes inside of the vehicle compartment. Of the above factors, the impact of waste composition and moisture content has been demonstrated by the range and average densities reported earlier in this report for residential, commercial, and industrial wastes. The third factor, pressure applied to the load, is an obvious target as a fundamental variable. However, there is a paucity of data available in the literature relating to density and any measure of compaction pressure as it exists in compaction vehicles.

With the above realization, CalRecovery investigated the type and extent of information on the compressive forces and pressures available from manufacturers of compaction vehicles. The intent of the investigation was to identify what, if any, applicable information existed on the forces and pressures applied to waste within the vehicle compartment. Confounding any analysis of the conditions inside a compaction vehicle are the complex mechanical systems that apply the compressive force to the load. For example, multiple stages of compaction in terms of applied pressure and its direction of application on the wastes inside the compartment virtually eliminate the potential of identifying and quantifying a single parameter that represents the magnitude and direction of the applied compressive pressure. In fact, the compressive pressure and thus the density of wastes within the compartment likely varies as a function of locations of the waste in the compartment, even if the mixture is homogeneous. One reason for the variation is the effect of wall resistance (e.g., sidewalls, floor, etc.) on the force applied to the load.

Table 1-18. Recommended In-Truck Density Values for Key Waste Sources and Truck Types in California

Waste Source/Truck Type	In-Truck Density (lb/cu yd)
Residential Rear Loaders	525
Commercial Front Loaders	480
Commercial Roll-Off Compactor	680
Industrial Roll-Off	400

Our survey of manufacturers resulted in the identification and quantification of a pressure parameter, i.e., the pressure exerted by a compactor blade at one end of the load. The manufacturers provided an estimate of the compacted density, compaction ratio, and applied pressure. Compaction ratio is defined as the initial volume of a given mass of wastes divided by the final volume. Taken collectively, the data show a general trend indicating in-truck density increases with applied pressure and compaction ratio. The relationships are illustrated in Figures 1-2 and 1-3, respectively. The trend of the data correlates with the fundamental engineering principle that the density of a mixture increases with applied pressure. This information is also presented in tabular form in Tables 1-19 and 1-20, respectively. The tables and figures presented in this section illustrate the influence of fundamental parameters on in-truck compacted densities. In the future, these data may be used to develop fundamental governing equations for waste compaction in vehicles. However, models can be formulated that are of sufficient accuracy without resorting at present to defining equations of state.

MODELING

The following text describes the development and utilization of the models for estimating quantities of waste delivered to solid waste facilities. Further discussion and examples of use are given in Appendix B.

A simple method to convert data from a volume basis to a weight basis regarding loads of solid waste that are transported to solid waste disposal facilities would allow the CIWMB and local jurisdictions to evaluate local and regional solid waste management trends and issues more comprehensively than is currently possible. A simple model to estimate the weight of a vehicle load is given by the following equation:

Weight (tons) of load per vehicle	=	(in-vehicle density)[1] x (rated volume of vehicle compartment) x (% full volumetric capacity)/100
	=	(lb/cu yd x ton/2000 lb) x cu yd x (% of full volumetric capacity)/100

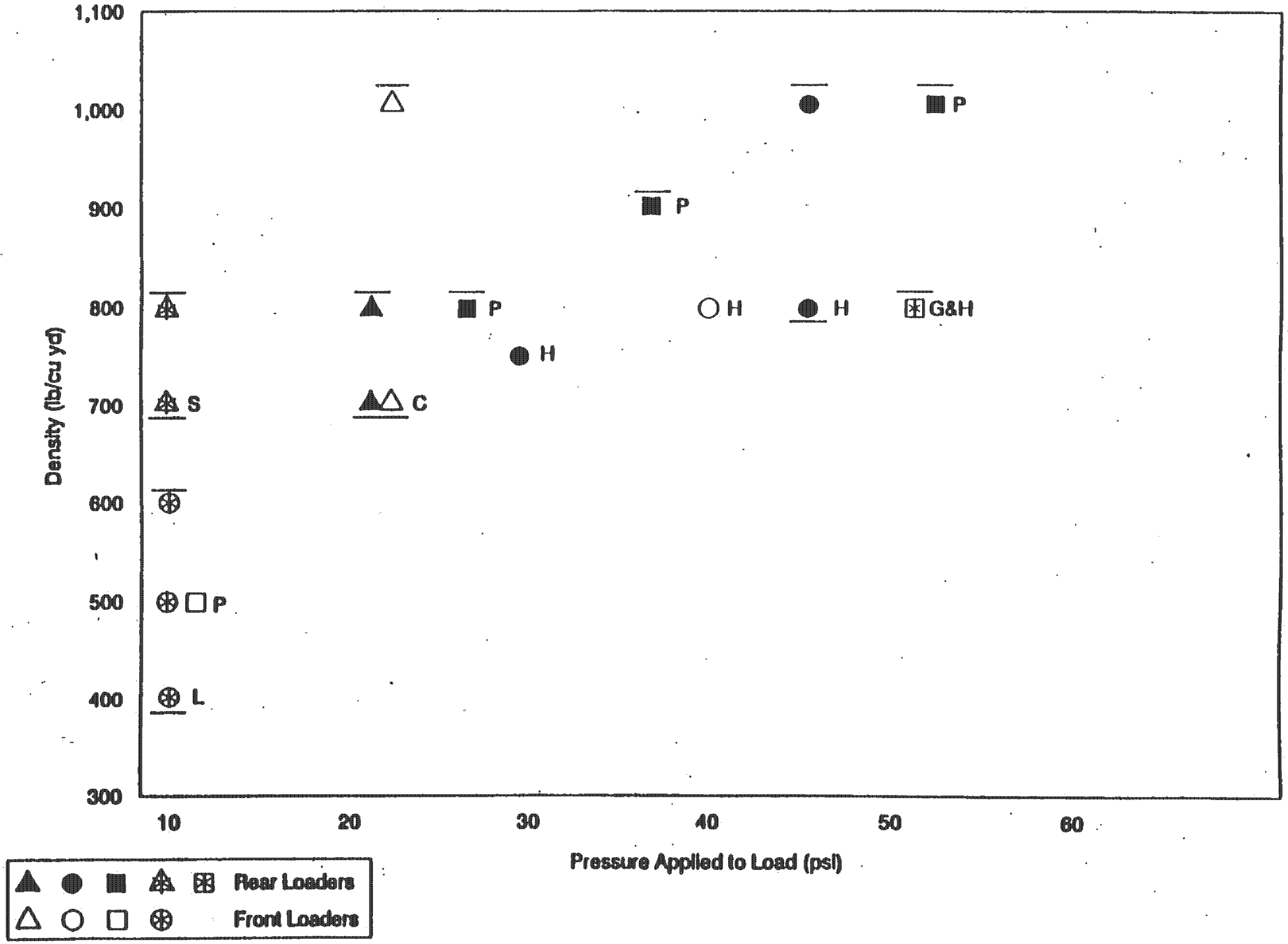
To make the conversion from volume of material in a vehicle to weight, utilizing the above equation, the following information must be entered:

- The source of the waste
- The type of vehicle
- The volumetric capacity (cu yd) of the vehicle
- The percentage of full capacity occupied by the load

The calculated weight of each load is then summed over all of the vehicles in order to arrive at a total delivered weight of waste.

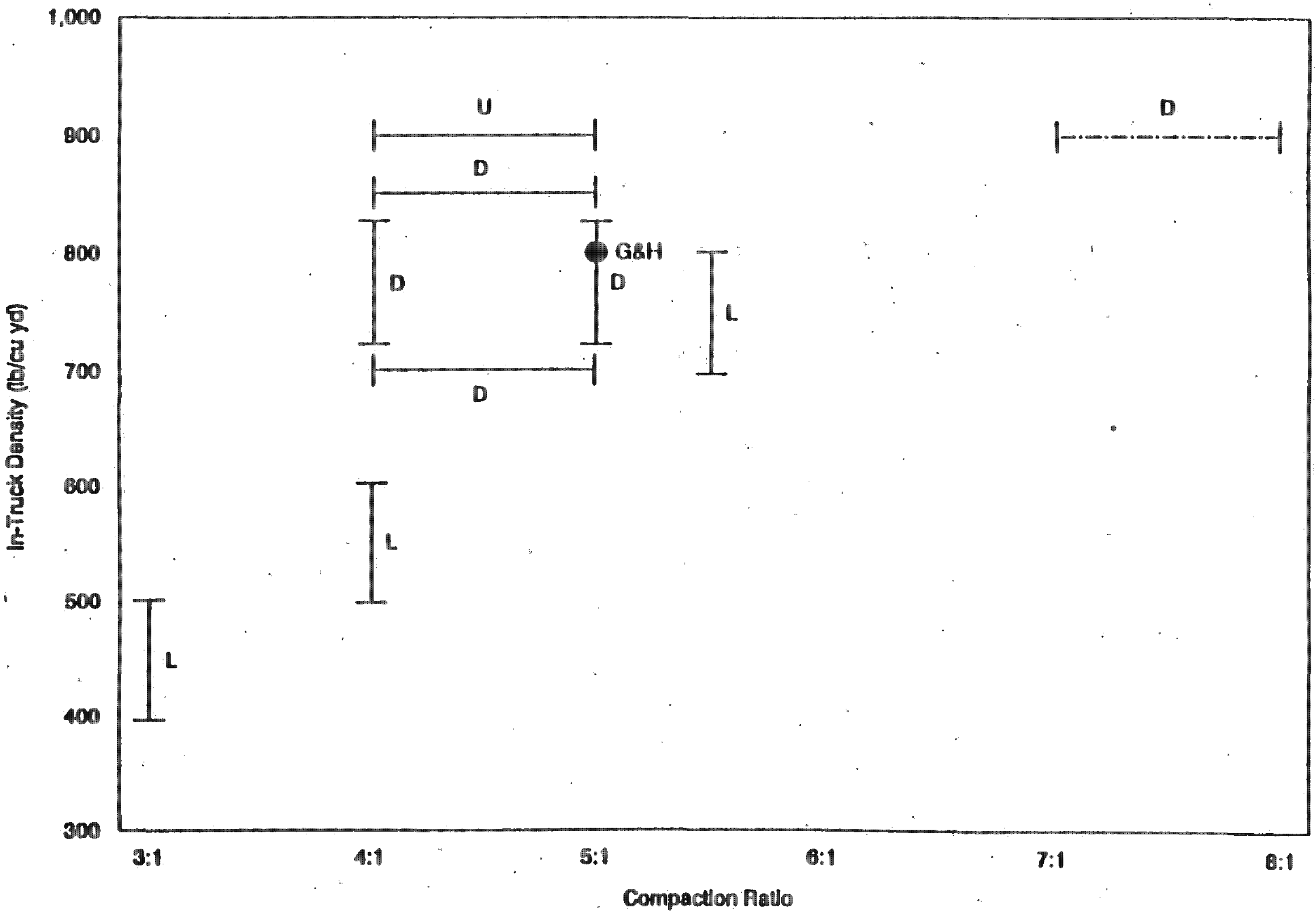
[1] The in-vehicle density factor is based on: A) waste source (i.e., residential, commercial, industrial, and self-haul); and B) vehicle type (e.g., rear loader, front loader).

Figure 1-2. Influence of Applied Pressure on In-Truck Material Density



a) Refer to Table 1-19 for data and manufacturer associated with the letters H, C, L, P, S, and G&H.

Figure 1-3. Influence of Compaction Ratios on In-Truck Material Density



Solid Line - Front Loaders
Dotted Line and Dot - Rear Loaders

a) Refer to Table 1-20 for data and manufactuer associated with the letters L,'D, U, and G&H.

Table 1-19. In-Truck Densities and Applied Pressure on Loads

Front Loaders

Manufacturer	Model	Density (lb/cu yd)	Packing Blade Force (lb)	Packing Blade Force (psi)
Peabody	FL80E	600	125,000	NA
	FLHC80D	700	148,000	NA
	FLSC	500	85,000	12
Lodal	TC or TF-826/1026	400-500/500-600	74,000*	10*
	TC or TF-830/1030	400-500/500-600	74,000*	10*
	TC or TF-834/1034	400-500/500-600	74,000*	10*
	TC or TF-1038/HC	700/800	NA	NA
Dempster	XHD 33/88 / ULTIL40T	700/850	122,000	NA
Heil	HP4-(D)(E)-LW-STD	800	103,000	40
Crane	IFL	700-1000	157,000	22

Rear Loaders

Manufacturer	Model	Density (lb/cu yd)	Packing Blade Force (lb)	Packing Blade Force (psi)
Peabody	GL370	up to 1000	120,000	53
	A300	up to 900	80,000	36
	C200E	up to 800	70,000	26
G&H	R90(20)(25)(70)	up to 800	132,000	51
Scranton Manufacturing Company	NewWay RL	700-800	58,000	8
Crane Carrier	ISL**	700-800	157,000	22
Heil	5000	800-1000	NA	45
	4000	750	NA	28

* Average of 4 stages of compaction.
** Side loader.

Table 1-20. In-Truck Compaction Ratios and Densities

Front Loaders

Manufacturer	Model	Compaction Ratio	Density (lb/cu yd)
Dempster	XHD33/38 / ULTIL40T	4:1 - 5:1	700/850
Lodal	TC or TF-826/1026	3:1/4:1	400-500/500-600
	TC or TF-830/1030	3:1/4:1	400-500/500-600
	TC or TF-834/1034	3:1/4:1	400-500/500-600
	TC or TF-1038/HC	5.5:1	700/800
Universal Handling Equipment	80/40	4:1 - 5:1	900

Rear Loaders

Manufacturer	Model	Compaction Ratio	Density (lb/cu yd)
G&H	R90(20)25)(30)	5:1	up to 800
Dempster	DRK II 20/25/32	7:1 - 8:1	900

A post-model validation study was conducted at the Redwood Landfill in Marin County, California, to show that the data presented in this report are representative of field results in California. The study was conducted over two consecutive days in December 1991. This field study was commissioned to test the validity of the simple in-vehicle density model described above against field data collected in California. The field results demonstrate how that the model estimate is within approximately 8% of the quantities measured at the landfill over the two periods. An error of 8% is an acceptable level of error given the fact that previous mass balance studies conducted by CalRecovery under controlled conditions at solid waste facilities yield levels of error of at least 20%.

The results of the validation study are presented in Appendix B. An additional model test was conducted for data collected at the Bee Canyon Landfill. In this case, the results were slightly less favorable with an approximate error of 14%. The results of both of these validation studies are presented in full in the test results section of Appendix B.

The results of the validation studies demonstrate that large fluctuations in densities are inherent in the types of wastes hauled in open top roll-off boxes (OTR). Since these types of wastes can vary substantially from jurisdiction to jurisdiction, short-term surveys should be conducted to establish whether or not the default density selected as a consequence of this study for OTR waste (i.e., 400 lb/cu yd) is applicable to a particular jurisdiction.

Complex Model Description

Several models were developed to incorporate waste composition into the calculation of in-truck compacted density. These models are substantially more complex than the simple model described in the previous section.

The first model, termed the "first order model" assumes that each waste type compacts similarly whether it is being compacted alone or as part of a mixture of waste types. In mathematical notation, let:

i = subscript denoting waste type

d_i = uncompacted density of waste type i (before compaction process)

c_i = compacted density of waste type i (after compaction process)

p_i = percentage by weight of waste type i in mixed waste batch

Then the first order complex model assumes that overall compacted density of a mixture of waste types is the sum of the weighted average of the individual material compacted densities, i.e.,

(1) $D = 1/(R_i\ p_i/c_i)$

Field tests demonstrated that the first order model somewhat overstates compaction; that is, based on equation (1), predictions of compacted density for mixtures of waste types are greater than the measured bulk density of the mixture. One common observation concerning mixed waste compaction is that glass containers are cushioned by other materials, and glass breakage is less than in the case of compaction of glass only. Compaction of a load of glass containers in a packer truck typically breaks most or all containers, leading to a high compacted density.

These observations concerning the behavior of glass containers undergoing compaction in a matrix of other waste types suggest an extension of the first order model to a second order model. For each waste material, define the "zero compaction percentage" as:

z_i = maximum value of p_i at which no compaction of material i occurs in mixed waste

Based on observation in the field, a value of $z_i = .3$ (i.e., 30%) for glass containers, and 0 for other materials is deemed accurate.

For a waste type such as glass containers, c_i, the compacted density of the homogeneous waste type, does not accurately reflect the compacted density of glass in mixed waste. Instead, when $p_i < z_i$, the uncompacted density d_i is the accurate density value (cushioning is complete, and no compaction occurs). When $p_i > z_i$, the compacted density increases toward a limit of c_i when $p_i = 1$. For $z_i < p_i < 1$, the compacted density is a weighted average of d_i and c_i.

To express this relationship, a scaling variable is defined and is used only for those material types that behave like glass under compression, i.e., the variable ranges from 0 at $p_i = z_i$ to 1 at $p_i = 1$.

$$q_i = \begin{cases} 0 & \text{if } p_i < z_i \\ (p_i - z_i) / (1 - z_i) & \text{if } p_i \geq z_i \end{cases}$$

The parameter q_i designates the fraction of possible compaction of glass (or other materials with $z_i > 0$) which occurs in a given load of mixed waste.

Defining the mixed-compaction density m_i of waste type i in a a mixed waste batch,

$$\text{(2)} \quad m_i = \begin{cases} c_i & \text{if } z_i = 0 \quad \textit{(use compacted density except for glass)} \\ (1 - q_i)d_i + q_i c_i & \text{if } z_i > 0 \quad \textit{(for glass, use weighted average of compacted, uncompacted densities)} \end{cases}$$

Finally, substitution into equation (1) yields,

$$\text{(3)} \quad D = 1/ (R_i \, p_i/m_i)$$

Equation (3) differs from (1) only for those wastes for which $z_i > 0$. In those cases, the compacted density of material type i, c_i, is replaced by a weighted average of c_i and the uncompacted density d_i; q_i, as defined above, is the fraction of the complete compaction of waste type i. A high value of z_i, through its influence on q_i, implies a high degree of cushioning, and a relatively low degree of compaction, of waste type i in a mixture of waste types.

Data Collection and Model Testing

The second order in-truck density model presented above predicts a compacted density of 688 lb/cu yd for a California default waste composition and material densities which are presented in the test results section of Appendix B. The California default waste composition and material densities are given in Appendix B. The California default listing of waste types includes most of the waste types given in AB 939. The exceptions and the waste types that include them are: refillable glass beverage containers and California redemption value glass in recyclable glass; bimetal containers and tin cans in ferrous; food waste, agricultural crop residue and manure in other bio-organic waste; and tires and rubber products in other nonbio-organic waste.

To obtain data on in-truck density of solid waste, 30 California landfills were contacted. Redwood Landfill in Novato (Marin County) agreed to provide truck weight and volume data. In testing the model, historical waste composition data for Marin County were analyzed, and the model estimated an in-truck compacted density of 724 lb/cu yd, as appears in Table 1-21. Weight survey data collected from approximately 100 truckloads of waste received at Redwood Landfill on December 11 and 12, 1991 were used to establish the level of accuracy of the complex in-truck density model. The data are tabulated in Appendix B-3. On average, the predictions of the complex in-truck density model for the default waste stream were in the range of 30% to 40% greater than the actual weights. The sensitivity of the model predictions to waste composition is evident from this comparison and indicate that site-specific waste characteristics and vehicle weight data must be collected together.

One striking characteristic of the reported data is the wide range of densities, from 30 to 1841 lb/cu yd. Of the 103 truck loads, 14 had reported densities under 300 lb/cu yd, suggesting either specialized loads of light-weight materials, little or no compaction, and/or reporting errors. At the other extreme, 11 truck loads reported densities over 900 lb/cu yd, suggesting unusually heavy materials, unusually high compaction, and/or reporting errors. Of the 11 truck loads reporting over 900 lb/cu yd, 9 reported that the truck was 75% or less full; most other trucks were reported as 80% or more full. If weight is reported correctly, but the percent of full volumetric capacity is understated, the density will be correspondingly overstated. Thus it is possible that some of the highest reported densities might reflect errors in estimation of the percent of full load. Deletion of suspect data would result in an error of less than the 30% to 40% range mentioned above.

The second order complex in-truck density model is relatively insensitive to waste composition for the majority of waste types within the range of compositions that can be reasonably expected. However, the predictions of the model are particularly sensitive to at least three waste types that typically exhibit relatively large variances in composition and in bulk density. These waste types are inert solids, other bio-organic waste (which includes

Table 1-21

IN-TRUCK DENSITY MODEL — Estimated density (lb/cu yd): 724

Marin County

Material Type	Waste stream Percent by weight	Density uncompacted (lb/cu yd)	Density compacted (lb/cu yd)	Zero Compaction Percentage	Intermediate calculations		
	p	d	c	z	q	m	p*m
Paper:							
Corrugated Containers	5.90%	33	360		0.06	359.75	21
Mixed Paper	4.40%	484	613		0.04	612.50	27
Newspaper	1.30%	323	552		0.01	551.50	7
High Grade Ledger	9.40%	364	644		0.09	644.00	61
Other Paper	9.70%	570	635		0.10	635.00	62
Plastics:							
HDPE	0.30%	35	264		0.00	263.75	1
PET	0.20%	39	182		0.00	182.00	0
Film Plastics	4.00%	23	226		0.04	226.00	9
Other Plastics	4.00%	50	372		0.04	371.62	15
Glass:							
Recyclable	2.90%	455	1258	30%		455.38	13
Non-recyclable	0.20%	566	1258	30%		566.00	1
Metals:							
Aluminum Cans	0.30%	91	399		0.00	399.00	1
Ferrous	2.50%	141	501		0.03	501.00	13
Non-Ferrous	0.60%	1248	1248		0.01	1248.32	7
White Goods		255	255			255.40	
Organics:							
Yardwaste	17.00%	292	584		0.17	584.20	99
Other Bio-organic	11.60%	1013	1080		0.12	1080.00	125
Other Nonbio-organic	6.15%	540	648		0.06	648.00	40
Textiles	1.20%	247	540		0.01	540.00	6
Leather	1.20%	380	759		0.01	759.30	9
Woodwaste	6.80%	333	333		0.07	332.65	23
Other Waste:							
Inert Solids	7.80%	1975	1975		0.08	1974.85	154
HHW	0.40%	1523	1523		0.00	1522.70	6
Special Wastes:							
Sewage Sludge		1294	1294			1293.75	
Ash	1.70%	1350	1350		0.02	1350.00	23
Auto Shredder Waste		800	800			800.00	
Dewatered Sludge		1615	1615			1614.60	
Tannery Sludge		NA					
Drilling Mud		NA					
Mine Tailings		NA					
TOTAL	99.55%			TOTAL COMPACTED DENSITY			724

Source: Marin County Solid Waste Management Plan, Beck & Assoc. Table 2.4, 8/91.

food waste), and yard wastes. Additionally, the categories of other bio-organics and of inerts have very large bulk densities relative to the other waste categories. These conditions are likely one of the primary reasons that the inaccuracy of the second order complex model can be relatively large (e.g., 30% to 40%) in some cases as illustrated by the examples in Appendix B-3. Therefore, validation of the waste composition and of the default values of loose and compacted densities should be undertaken if the predicted results of second order complex model are not sufficiently accurate for the particular application under consideration. For example, in those cases where unusual waste characteristics can be expected, e.g., very wet waste or waste containing large percentages of inert fines, verification of model predictions is strongly advised.

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Section 2

IN-PLACE DENSITY MODEL

INTRODUCTION

General

This section of the report presents the methodology used to produce a mathematical model of in-place landfill density using primarily density data available from field studies. The development of the model is based on empiricism as well as certain fundamental governing principles. The model is presented both graphically and in terms of mathematical formulations. The impact of varying several landfill operating parameters is also discussed.

This model can be applied to predict the in-place volume of a known quantity (tonnage) of waste on the basis of fundamental parameters of weight of landfill compaction equipment, number of passes, and slope of the landfill working face. The model can also be used to estimate delivered quantity from the change in landfill volume over a known period as a function of the aforementioned parameters.

In-place landfill density has been reported by various investigators. Reports have included information on the density of mixed solid waste in landfills based on one of two principal estimating techniques:

- Annual change in topographic contours of the landfill and annual tonnage delivered.
- Specific tests designed to determine density, which usually include one to three days' landfilling operation with survey of final contours and test tonnage.

Based on previous studies and a literature review, the fundamental parameters that govern in-place solid waste density were initially identified as including variables grouped according to the following list:

A. MSW related parameters, including:

- weight of waste delivered
- composition
- moisture content

B. Landform of the waste pile, including:

- slope
- waste depth

C. Equipment-related parameters, including:

- compaction method
- type of compaction equipment
- number of equipment passes
- equipment weight
- pressure at the point of contact

MSW-Related Parameters

Of the MSW factors, most previous studies report the composition of the waste under consideration in only the most general terms. For example, Collord's December 1979 Orange County tests indicate that the test was conducted with "Group 2 wastes."[1] Two years later, at Stanislaus County, Collord reports commercially-collected "Group 2 wastes" with minor amounts of "Group 3" but with construction and demolition, tires, woody yard waste, septage, drilling muds, and cannery waste excluded. No water was added in any of the tests conducted by Collord.

In addition to the data reported by Collord, more recent data from studies conducted in Connecticut, Rhode Island, and Vermont are less specific with respect to composition. Waste is reported as "mixed waste, residential waste, or commercial waste" only.

Landform Parameters

Of the landform or topographic factors, isolation of the degree to which slope and waste depth affect in-place density has not been reported with great care in the previous investigations. Where slope has been reported, it has most commonly referred to the maximum slope that the inclined sides of the waste pile are permitted to achieve. Thus, in cases where the in-place density has been reported on the basis of annual data, as in New Milford, Connecticut and J[illegible]nston, Rhode Island, the slope should be understood to reflect the general sideslopes of the fill and not the density achieved by compacting directly on such a slope.

Based on in-house information and discussions with landfill managers, waste depth appears to influence compacted density in two ways. Waste that is compacted against the base of a landfill may achieve a slightly higher density upon initial compaction relative to upper lifts. Two factors may contribute to this effect: the unyielding nature of the prepared landfill base and the absence of voids that remain in waste after compaction. Thus, a difference could be expected between the data from test cells (i.e., Vermont and Collord) and annual data from Rhode Island and Connecticut. This potential difference is discussed further in a later subsection.

A second influence of waste depth on density is the consolidation of the lower levels of waste that occurs over time as additional upper lifts are added. The effect of the additional

[1] The category "Group 2 wastes," as defined by the California Solid Waste Management Board, the predecessor agency to the CIWMB, includes mixed municipal solid wastes.

weight that is added to the landfill can be substantial. For example, a large, privately operated New Jersey landfill that is currently more than 100 ft high has periodically shown only 5 ft of elevation change after the completion of a 10-ft lift because of consolidation of the lower waste layers. Since, however, the Board's stated objective in this study is the determination of waste density in the upper layers of landfills, no further consideration has been given to consolidation of lower landfill layers.

Equipment-Related Parameters

Of the equipment related parameters cited above, compaction method and type of equipment affects density most directly. Thus, landfills that place and compact waste using bulldozer-type tracked equipment typically achieve the lowest in-place density because of the low bearing pressure exerted by the equipment. This observation is supported by reference to the design of tracked equipment in general, i.e., that it is designed to float on the surface of soft soils to avoid sinking that would result from compression of the soils. Alternatively, landfills that employ specially designed compactors generally achieve higher in-place densities than do those using dozers. Wheeled compactors (designed to achieve high bearing pressures) are usually equipped with steel wheels with cleats. Cleats are advertised as creators of high pressure at the point of contact with the waste.

Equipment weight is most obviously the critical variable once equipment type is selected. As shown in a later subsection of this report, within certain limits, increasing machine weight results in higher densities. For each generic machine type (i.e., landfill compactor), a value can be determined that represents the upper limit of density that can be achieved.

The number of passes of the equipment over a given section of waste has been shown in the literature to affect density up to approximately five passes. Beyond five passes, it is likely that the impact and the cost of the passes by the equipment is not offset by the incremental increases in in-place density.

The following section presents the mathematical relationship of the variables to in-place densities of wastes compacted in a landfill.

IN-PLACE DENSITY MODEL

In this section we present a mathematical model combining three of the most important, easily quantified influences on the in-place density of landfilled waste: weight of the compacting equipment, surface slope, and number of passes made by the compacting equipment. (Model parameters are estimated based on previously published quantitative field test data.) All three factors influencing in-place density are combined in a single equation at the end of this subsection, and are presented in an easy-to-use spreadsheet model. The following text describes the development and utilization of the models. Further discussion and examples of use are given in Appendix B.

Model Description

Machine Weight

Figure 2-1 and Table 2-1 present the available information relating the weight of compacting equipment to the in-place density. The data are based on five passes by the vehicle over waste on a horizontal surface, i.e., zero slope. The data point at a machine weight of zero represents the uncompacted in-place density of 325 lb/cu yd, as reported in the literature (Diaz, Savage, Golueke, 1982).

As shown in Figure 2-1, in-place density initially rises rapidly with machine weight; however, the rate of increase tapers off, and around 60,000 lb a plateau is reached. Such saturation effects are often modeled in the scientific literature by a logistic curve of the form

(4) $Y = a / (1 + be^{-cX})$

where a, b, and c are positive constants, and e = 2.718... is the base of natural logarithms. As X becomes very large, Y approaches a. At X = 0, Y = a/(1+b). The third parameter, c, affects the curvature of the graph.

A logistic curve fitted to the data presented in Table 2-1 is also presented in Figure 2-1, with a = 1450, b = 3.5, and c = 6.3×10^{-5}. That is, if Y is in-place density and X is vehicle weight in pounds,

(5) $Y = 1450 / (1 + 3.5 \times e^{-0.000063 \times X})$

This suggests that as vehicle weight becomes large, in-place density (assuming five passes and zero slope) approaches 1450 lb/cu yd. Values for other vehicle weights can be calculated from equation (5) with a scientific calculator; equation (5) is also incorporated in the complete model presented below and in the accompanying spreadsheet model.

Slope

Either compacting waste on a sloping ground surface, or compacting to a sloping finished grade, results in a lower in-place density than compaction on a level surface. Modeling of the effect of slope is a simple matter of physics. On a level surface compaction depends on vehicle weight, as described above. However, on a slope, the effective weight of the compacting vehicle is reduced.

Compaction depends to a large degree on the weight that is exerted in a direction perpendicular to the working face of the landfill. If the surface is sloped at an angle A to the horizontal, then

(6)Effective weight perpendicular to surface = cos(A) x machine weight

where cos(A), the cosine function of trigonometry, is equal to 1 when A=0. A schematic representing the compaction conditions on a sloped surface is shown in Figure 2-2. Values of cos(A) are shown for a number of angles in Table 2-2.

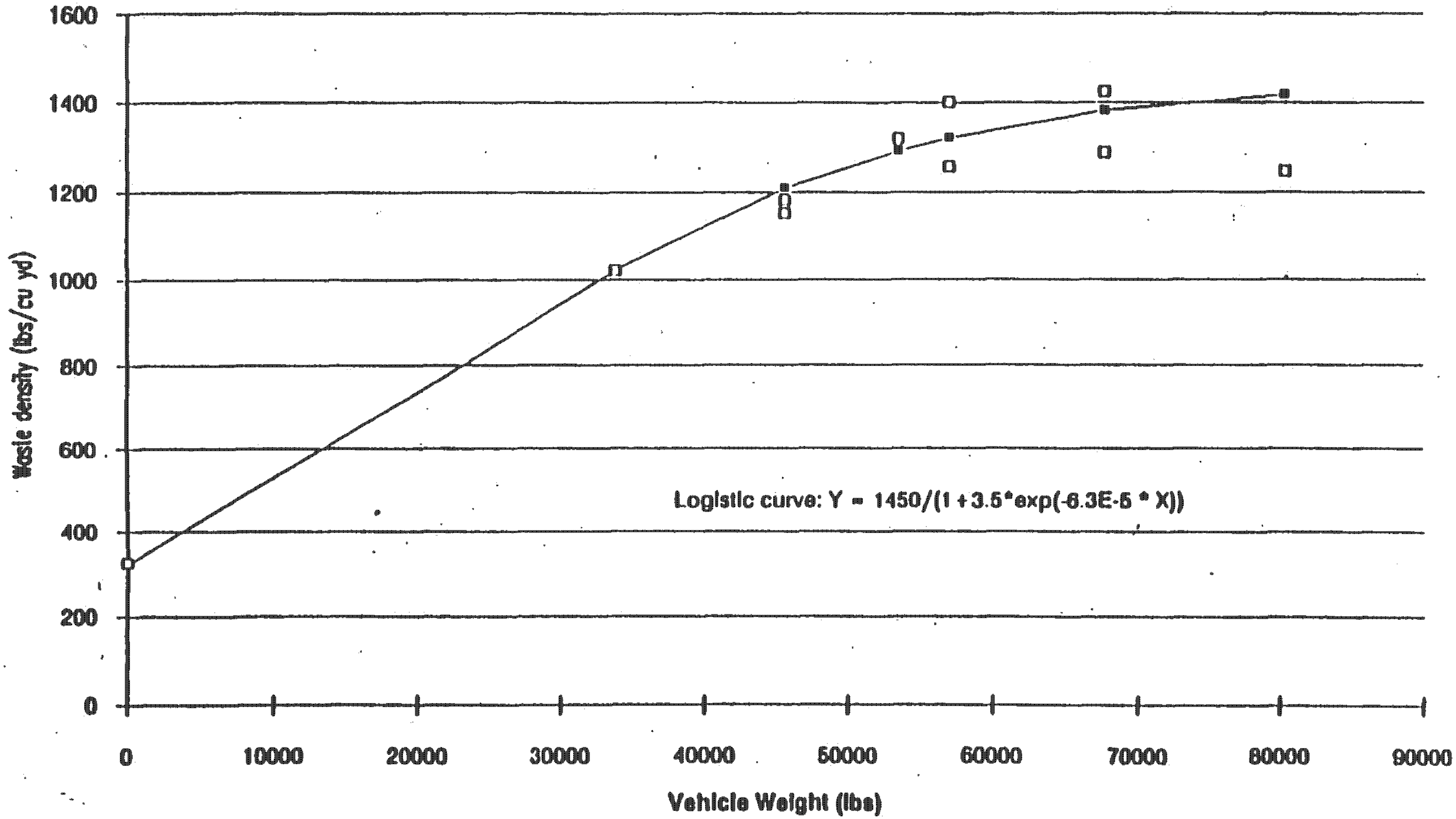

Figure 2.1 Machine Weight vs. In-Place Density, Model (Predicted) Data and Field (Observed) Data

Table 2-1. Machine Weight and Density Data

Machine	Machine Weight lb	Density lb/cu yd	Notes	Reference
Slope: Flat Number of Passes: 5[a]				
Deere JD646-C	33746	1020.8		Collord, 1980a
Cat816B	45477	1151.1	Cat Blades	Collord, 1981
Cat816B	45477	1180.05	Caron Teeth	Collord, 1981
Rexnord 3-70	57000	1255.63		Collord, 1979
Rexnord 3-70	57000	1398.77		Collord, 1979
Cat826C	67670	1287.58		Collord, 1980b
Cat826C	67670	1423.57		Collord, 1980b
BomagK701	80325	1246.77		Collord, 1980b
Cat966	53490	1318		New Milford, Waste Management, Inc.1991

[a] Assumed to be five passes based on analysis of data.

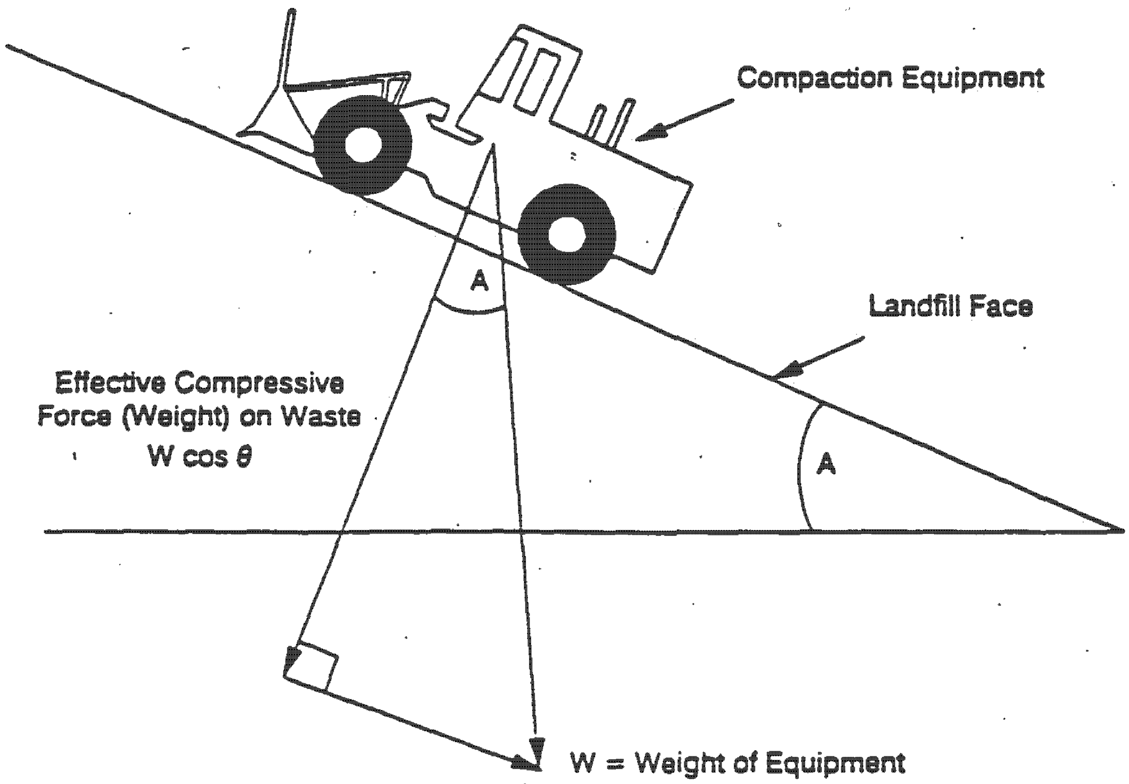

Figure 2-2. Compaction of Waste on a Sloped Surface

Table 2-2. Machine Weight Conversion Factors For Various Landfill Slopes

Slope	Conversion Factor (cos (A))
1%	1.00
5%	1.00
10%	1.00
5:1	0.98
4:1	0.97
3:1	0.95
2:1	0.89

At large angles, slippage of equipment on the surface will occur. This reduces the force exerted by the equipment on the surface by even more than equation (6) indicates. However, lacking empirical data on equipment slippage, equation (6) is used in the model. The implication of equation (6) is that vehicle weight, as used for example in equation (5), should be replaced by an effective weight = cos(A) x actual weight.

Number of Passes

Based on the literature (Waste Age, 1981), the number of passes made by landfill compacting equipment over waste affects its in-place density in a pronounced manner. Table 2-3 and Figure 2-3 illustrate this impact. As the number of passes increases, in-place density at first increases rapidly.

This relationship again suggests a logistic curve, based on equation (4). A logistic curve fitted to the data in Figure 2-2, with Y = index of in-place density (5-pass density = 100), and X = number of passes yields the equation:

(7) $$Y = 116 / (1 + 3 \times e^{-0.6 \times X})$$

The limit as the number of passes becomes large is 116% of the 5-pass density. As with equation (5), this can be estimated with a calculator; it is also incorporated into the general model presented in Section 3 and is included in the spreadsheet formulation.

Combining equations (5) and (7) and re-defining the set of parameters as:

D = in-place density in lb/cu yd

P = number of passes

W = weight of vehicle in pounds

A = slope angle of the surface or finished grade

the equation for in-place density becomes:

(8) $$D = 1680 / [(1 + 3.5 \times e^{-0.000063 \times W \times \cos(A)})(1 + 3 \times e^{-0.6 \times P})]$$

The numerator, 1680, is the estimated maximum achievable density via vehicle compaction alone. It is the product of 1450, the limit for 5 passes with heavy vehicles according to equation (5), multiplied by 116%, the maximum increase over the 5-pass density achievable with repeated passes according to equation (7).

Equation (8) does not hold in a physical sense in the limit where either W or P is zero, i.e., if there is no vehicle or number of passes is equal to zero. Equation (8) holds for positive values of W and P. In general equation (8) should apply to those situations where the number of passes is in the range of 2 to 9, the weight of the compaction equipment is 30,000 lb to 90,000 lb, and the slope of the working face is in the range of 6:1 to 2:1.

Table 2-3. Effect of Equipment Passes Over Waste on In-Place Density (Flat Slope)

Number of Passes (p)	Density at Pass (p) D(p) (lb/cy)	Change in Density D(p) - D(p-1) (lb/cy)
0	350	
1	565	215
2	775	210
3	970	195
4	1125	155
5	1225	100
6	1300	75
7	1350	50
8	1375	25
9	1395	20
10	1405	10

Reference: Waste Age, September 1981, Page 66.

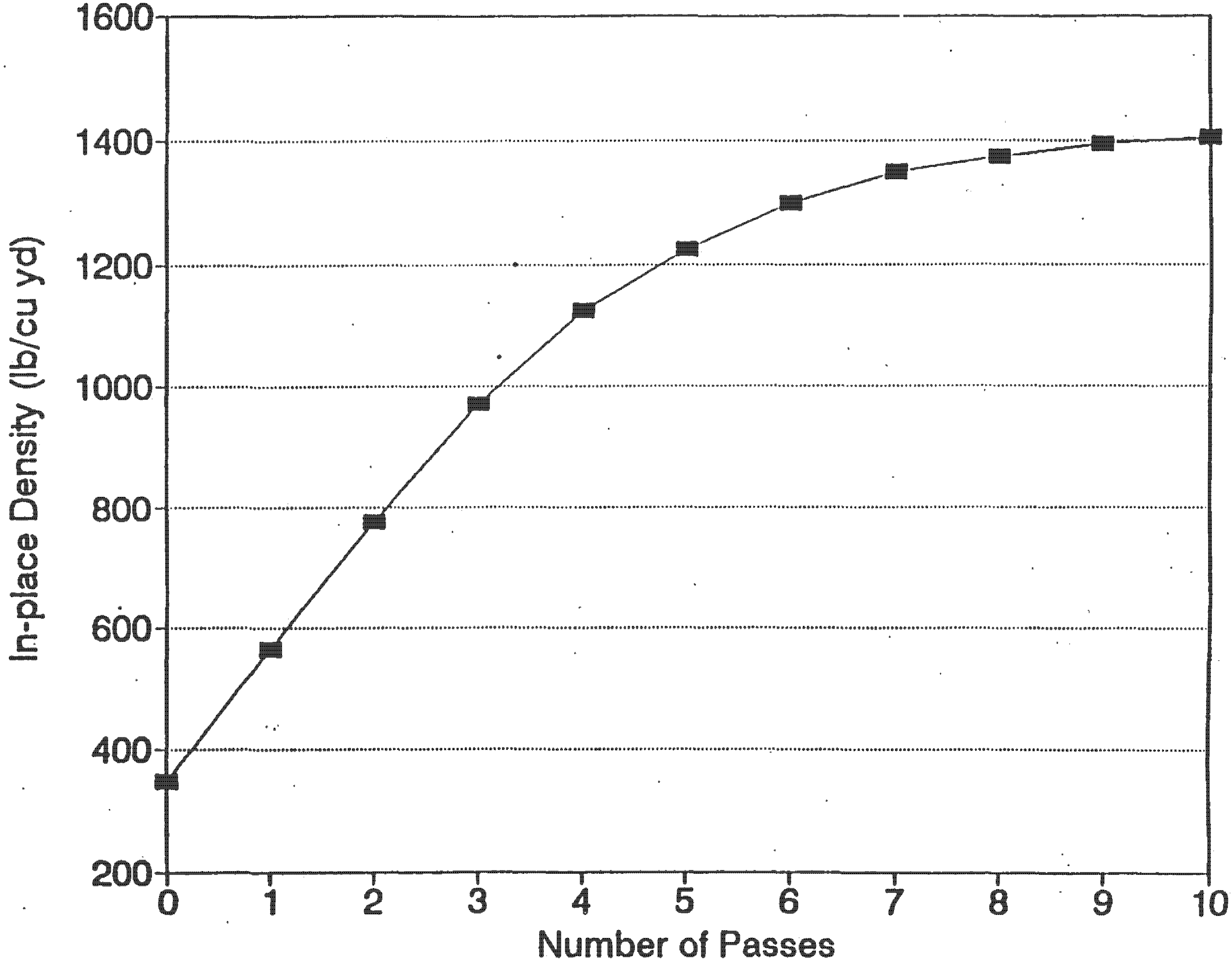

Figure 2-3. Influence of Number of Passes on In-place Density.
(zero slope)

Notice, also, that equation (8) does not allow for variation in the composition or as-delivered density of the waste stream. It was estimated based on published data, assuming average or default values for waste stream composition and density. Two further extensions of the model, allowing its integration with the in-truck model, and allowing for variation in the incoming waste stream composition, are presented in Section 3.

After the in-place density (in lb/cu yd) has been calculated, the user can use the density value to compute the volume of landfill occupied by a given weight of solid waste, i.e., volume (in cu yd) of a specified landfill space occupied = weight of solid waste (tons) divided by average in-place density (in lb/cu yd) multiplied by 2000 lb/ton.

Data Collection and Model Testing

A telephone survey of California landfills was conducted for the purpose of acquiring in-place compaction data. The landfills which reported on their compaction equipment, together with their responses, are listed in Table 2-4. The 31 reported values for in-place density are reported in Table 2-4. Data were incomplete or inferred from partial information for many of the reporting locations. Eighteen of the data were judged representative for the purpose of checking the validity of the model. As a point of information, the reported in-place densities were almost always rounded off to the nearest 100 lb/cu yd, introducing rounding errors of up to 5%.

For the 18 points, the average reported actual density was 1165 lb/cu yd, while the model represented by equation (8) predicted an average of 1375 lb/cu yd. The average error was 210, or 19%; the standard deviation of the errors was 181. A better fit can be obtained by modifying some of the parameters in equation (8) above.

A curve fit to the 18 points of data was performed in order to provide an alternative set of values of the constants used in the in-place density model. The alternative values are listed in the spreadsheet for the landfill compaction model described in Appendix B-2 (Examples of the Three Models). The alternative values of course yield more accurate results than the default values. The predicted in-place densities using the alternative values of the constants are compared to the reported densities in the results section of Appendix B-3 (Test Results of the Three Models). The average error using the in-place model with the alternative constants is about 9%. The alternative values are used in the in-place density modeling calculations in Appendix B. However, the default values are included for reference in the model. (The default values represent curve fit constants based on rigorous landfill compaction tests.) The alternative values have been selected for use since they provided greater accuracy in the estimated in-place density based on the field survey than do the default values.

Table 2-4. Summary Data from California Landfill Compaction Survey

LF - County	Compaction Equipment Model	Year	Weight	Passes	Slope of Cell	In place density (lb/cu yd)
Durham Rd - Alaimeda	D9H dozer	n/a	74,900	5	2.75:1	1350
Durham Rd - Alaimeda	Cat 826C			5	2.75:1	
Durham Rd - Alaimeda	I/R 750LF			5	2.75:1	
Altamont - Alameda	D9L dozer	n/a	109,200	5	3.0:1	1500
Altamont - Alameda	Cat 826C			5	3.0:1	
Amador City Sanitary - Amador	Cat D8	1968		3		
Rock Creek - Calaveras	Bomag BC60	1990	66,230	5	3.5:1	1200
West Contra Costa- Contra Costa	Cat 826B	1972	66,230	3.5	3.0:1	1000
West Contra Costa- Contra Costa	Cat 826C	1981		3.5	3.0:1	
West Contra Costa- Contra Costa	Cat 826C	1983		3.5	3.0:1	
West Contra Costa- Contra Costa	Intl TD25 doz	1986		3.5	3.0:1	
West Contra Costa- Contra Costa	Kom 155A do	1984		3.5	3.0:1	
West Contra Costa- Contra Costa	Kom D65 P	1984		3.5	3.0:1	
West Contra Costa- Contra Costa	Kom TD 15E	1987		3.5	3.0:1	
Acme - Contra Costa	Rex	1971				1250
Union M ine - El Dorado	Cat 816	1979	39,800	9	slope : "fla	1200
Union M ine - El Dorado	Cat 826	1985		9	flat	
Chateau Fresno - Fresno	Cat 825			4.5	3.0:1	
American Ave - Fresno	Cat 826	1986	66,845	5	3.5:1	1200
Orange Ave - Fresno	Rex 350				flat	
Orange Ave - Fresno	Cat D9				flat	
Chestnut Ave - Fresno	Cat 826			4.5	3.0:1	
China Grade - Kern	Cat 826C	n/a	66,845	3.5	3.0:1	1200
China Grade - Kern	Cat D8K doze	n/a		3.5	3.0:1	
China Grade - Kern	Kom D355 do	n/a		3.5	3.0:1	
China Grade - Kern	Cat 637D scra	n/a		3.5	3.0:1	
Arvin Sanitary - Kern	Cat D9H doze	n/a	74,900	3.5	3.0:1	1200
Arvin Sanitary - Kern	Cat 826B			3.5	3.0:1	
Arvin Sanitary - Kern	Cat 623B scraper			3.5	3.0:1	
Hanford Sanitary - Kings	I/R LS750	1987	79,000	6	3.0:1	1200
Western Regional - Placer	CAT826	n/a	66,845	5	3.0:1	1100
Highgrove Sanitary - Riverside	I/R LF750 300	1989	81,000	2.5	3.0:1	1200
El Sobrante - Riverside	Cat826C	1986	66,845	7	2.0:1	1224
El Sobrante - Riverside	REX390	1990	66,845	7	2 to 1	
Sacramento County - Sacramento	Cat826	1991	66,845	4	5.0:1	1200
Sacramento County - Sacramento	Cat826	1988		4	5 to 1	
Sacramento County - Sacramento	Cat826	1986		4	5 to 1	
Sacramento City - Sacramento	Cat826	1983	66,845	6	0.13:1	1100
Milliken Sanitary - San Bernardino	Cat 826 w/spikes		66,845	6		1000
Colton Refuse - San Bernardino	Cat826	n/a	66,845	6	3.0:1	1000
Miramar - San Diego	Cat826	1988	66,845	2	3.0:1	1280
Miramar - San Diego	D9Trak Dozer	1988	66,845	2	3.0:1	
North County - San Joaquin	Cat826	1988	66,845	6	3.0:1	1100
Harney Lane - San Joaquin	Cat826	1988	66,845	6	2.0:1	1100
City of Paso Robles - San Luis Obispo	D9 dozer		66,845		2.0:1	
Tajiquas - Santa Barbara	Cat826C	1989	66,845	9	2.5:1	1275
Tajiquas - Santa Barbara	D9H doz w/ca	1990	84,900	9	2.5:1	1275
City of Lompoc - Santa Barbara	Ingersoll	1988	81,000	4.5	3.0:1	1000
Newby Island - Santa Clara	Cat826	1988	66,845	5	3.0:1	1750

Table 2-4. Summary Data from California Landfill Compaction Survey

LF - County	Compaction Equipment: Model	Year	Weight	Passes	Slope of Cell	In place density (lb/cu yd)
Buena Vista - Santa Cruz	D9 dozer	1990	74,900	3.5	3.0:1	1050
Buena Vista - Santa Cruz	Cat826C	1990		3.5	3 to 1	
Potrero Hills - Solano	C4 826C	1983	66,845	3.5	3.0:1	1300
Potrero Hills - Solano	C5 826C	1989		3.5	3.0:1	
Central - Sonoma	Cat826	1990	66,845	5	3.0:1	1200
Central - Sonoma	Cat826	1990		5	3.0:1	
Fink Road - Stanislaus	Cat	1980		5	3.0:1	1000
Tuolumne Cty - Tuolumne	Cat816	n/a	39,800	5	3.0:1	1200
Simi Valley - Ventura	Cat 826	1989	66,845	5	3.0:1	1200
U.C. Davis - Yolo	Deere646 w/c	1982	42,230	6	3.0:1	898

Section 3

THE GENERAL MODEL

The variable and physical effects described in the preceding sections may be combined into a single, general, unified model in order to estimate in-truck densities and to subsequently estimate in-place landfill densities.

INTEGRATION OF IN-TRUCK AND IN-PLACE DENSITY MODELS: USE OF THE SPREADSHEET VERSION

The spreadsheet submitted with this report combines both the in-truck and in-place compaction models presented previously. The models may be used separately, either with the supplied (default) parameters or with user-specified changes in the parameters. For example, the user can specify a waste composition for a specific location or add or delete material types with appropriate additions or deletions to the compacted and uncompacted densities. Addition of other material types and densities would involve the acquisition of uncompacted and compacted densities either by field tests or interpolating from the density data reported herein or in other references.

The models may also be combined into a joint model of compaction throughout the waste collection and disposal process. The user may enter waste composition in the in-truck model, then allow that waste stream to flow through to the in-place model.

Two additional parameters are required for joint, or sequential, use of the models in a single analysis. First, the in-place model requires an estimate of the as-delivered density for a load of waste received at a landfill; this can either be derived as the uncompacted density of the waste stream, or entered separately.

Second, the in-place model requires an estimate of the relative compactability of the particular waste load, relative to the compactability of the California default waste stream. (That is, compactability is an index number k, defined as $k = 1.0$ for the California default waste composition, and as $k = 0.0$ for materials which cannot be compacted.) The verification of compactability requires that determinations of compacted density and of loose density be made for different waste compositions. Such studies are relatively easy to conduct. Since the accuracy of the complex in-truck density model is very sensitive to waste composition, as indicated previously, compactability is also very sensitive to waste composition. The great sensitivity of the model indicates that composition and compactability data be collected locally in order to provide the user of the model with site-specific information for calibrating the model to his or her specific application.

The user may enter an independent estimate of compactability for a waste load, or the in-truck density model can be used to calculate k:

(9) $k = \dfrac{\text{(truck-compacted density / curbside density for current waste stream)}}{\text{(truck-compacted density / curbside density for default waste stream)}}$

Then, letting

S = as-delivered density

x = subscript for current waste stream

def = subscript for default waste stream

and recalling that the calculation of default waste stream in-place density, D_{def}, is given by equation (8), the complete model calculates

(10) $D_x = S_x (D_{def}/S_{def})^k$

Note that when $k=0$, $D = S$ – that is, in-place density equals as-delivered density, since there is no compaction. On the other hand, when $k=1$, $D_x/S_x = D_{def}/S_{def}$ – that is, compaction of waste stream x is exactly proportional to the compaction of the default waste stream.

An example of the printout of the General Model is presented in the examples section of Appendix B.

The unified model is a complex model that combines a number of variables to describe waste compaction in different situations. The model is amenable to user modifications based on site-specific conditions and to new data as they become available.

These observations concerning the behavior of glass containers undergoing compaction in a matrix of other waste types suggest an extension of the first order model to a second order model. For each waste material, define the "zero compaction percentage" as:

z_i = maximum value of p_i at which no compaction of material i occurs in mixed waste

Based on observation in the field, a value of $z_i = .3$ (i.e., 30%) for glass containers, and 0 for most other materials is deemed accurate. The reason is that glass is a brittle material that exhibits a large and very steep discontinuity in the bulk density versus applied load relation at the point where the applied load fragments the glass objects, i.e., the bulk density increases dramatically as the objects break. The only material type of consequence in MSW that exhibits this phenomena is glass.

For a waste type such as glass containers, c_i, the compacted density of the homogeneous waste type, does not accurately reflect the compacted density of glass in mixed waste. Instead, when $p_i < z_i$, the uncompacted density d_i is the accurate density value (cushioning is complete, and no compaction occurs). When $p_i > z_i$, the compacted density increases toward a limit of c_i when $p_i = 1$. For $z_i < p_i \leq 1$, the compacted density is a weighted average of d_i and c_i.

To express this relationship, a scaling variable is defined and is used only for those material types that behave like glass under compression, i.e., the variable ranges from 0 at $p_i = z_i$ to 1 at $p_i = 1$.

$$q_i = \begin{cases} 0 & \text{if } p_i < z_i \\ (p_i - z_i) / (1 - z_i) & \text{if } p_i \,\hat{}\, z_i \end{cases}$$

The parameter q_i designates the fraction of possible compaction of glass (or other materials with $z_i > 0$) which occurs in a given load of mixed waste.

Defining the mixed-compaction density m_i of waste type i in a a mixed waste batch,

$$(2) \quad m_i = \begin{cases} c_i & \text{if } z_i = 0 \quad \textit{(use compacted density except for glass)} \\ (1 - q_i)d_i + q_i c_i & \text{if } z_i > 0 \quad \textit{(for glass, use weighted average of compacted, uncompacted densities)} \end{cases}$$

Finally, substitution into equation (1) yields,

$$(3) \quad D = 1/(R_i\, p_i/m_i)$$

Equation (3) differs from (1) only for those wastes for which $z_i > 0$. In those cases, the compacted density of material type i, c_i, is replaced by a weighted average of c_i and the uncompacted density d_i; q_i, as defined above, is the fraction of the complete compaction of waste type i. A high value of z_i, through its influence on q_i, implies a high degree of cushioning, and a relatively low degree of compaction, of waste type i in a mixture of waste types.

Appendix A

TEST PLAN

MIXED WASTE AS RECEIVED DENSITY STUDY

REFUSE COLLECTION VEHICLES

Purpose: To determine the as received density of municipal solid waste collected by various types of refuse and self-haul vehicles.

Test Plan: Refuse Collection Vehicles

In cooperation with Marin Sanitary Service, a variety of refuse collection vehicles will be randomly selected after completing collection runs and weighed on the Marin Resource Recovery scales. The vehicles will be representative of solid waste generated in Marin County and delivered to California landfills. Tare weights for each truck will be determined prior to the test. Using information supplied by each manufacturer, the capacity of each truck type will be noted.

Procedure:

Five to ten randomly selected collection vehicles of specific manufacturers from the following general waste source categories will be sampled: rear loaders, front and/or side loaders, and roll-off boxes. For example, Marin Sanitary Service owns three types of rear loaders (Heil, Dempster, Garwood). Therefore, Heil, Dempster, and Garwood vehicles will be selected for weight determinations. In cases where there are less than 5 actual vehicles in operation of a particular manufacturer and model, multiple loads for that vehicle type will be weighed.

After the driver has completed his collection run, he will be instructed to weigh the truck before going to the transfer station. For each vehicle selected for weighing, the manufacturer, model number, vehicle design volumetric capacity, tare weight, and waste source (i.e., residential, commercial or industrial) will be noted by CalRecovery personnel.

The driver will also be asked to estimate what volume of the vehicle is occupied by waste (e.g., 70%, 80%, 90%, etc.). The driver will be asked also to define the waste source of the load (i.e., residential, commercial, industrial, or mixed).

Criteria for waste stream determination for this study will be:

- Residential: collection from single family households. A load must contain no less than 90% residential generated waste to be considered residential;

- Commercial: collection from multi-family and commercial businesses. A load must contain no less than 90% commercial generated waste to be considered commercial;
- Industrial: collection from generators generally considered by Marin Sanitary Service to be industrial in nature and/or debris box waste;
- Mixed: loads that do not meet the residential, industrial or commercial definitions.

All of the information will be entered on a data sheet which is attached to this test plan.

SELF-HAUL VEHICLES

In cooperation with the Marin Resource Recovery Facility, a selection of self-haul vehicles will be weighed and the waste type categorized before entering the Resource Recovery Facility. This aspect of the study will produce information about non-compacted self-haul waste.

Procedure:

Using the scale at the Marin Resource Recovery Facility, random weighings of incoming self-haul vehicles will be made. A minimum of twenty residential and twenty commercial vehicles will be weighed. Vehicles will be weighed before entering the facility: the volume of the load will be estimated visually by a trained observer and type of waste will be noted on the data sheet. After dumping the load, the vehicle will be weighed again to obtain the tare weight.

For this study, self-haul waste is classified into one of four categories: yard waste, construction/demolition debris, dirt/rubble, or miscellaneous (e.g., household refuse). For example, if a load is estimated by visual observation to contain a majority of yard waste, it will be designated a yard waste load. The categories are defined as follows:

- Yard waste: loads typically consisting of residential yard clean-up and maintenance debris;
- Construction/demolition: loads resulting from construction, repairs, remodeling, and demolition projects;
- Dirt/rubble: loads consisting of debris-filled dirt and, on occasion, clean dirt for use as landfill cover;
- Miscellaneous: loads which cannot be classified into one of the categories listed above.

Self-Haul Conversion Factor Study
Data Entry Sheet

Date___________

Type of Generator							Types of Vehicles: Truck Types								Waste Categories			
Resid.	Comm.	Indust.	Incoming Wt. (lbs)	Tare Wt. (lbs)	Est. Total Volume of vehicle	Est. Volume of waste	Mini-pickup	Full-Size pickup	Dump	Flatbed	Trailer	Car Trunk	Station Wagon	Van	Yard Waste	C & D	Dirt/ Rubble	Misc.

Marin Sanitary Service
Truck Conversion Study
Data Work Sheet

Date:__________

Truck No. & Type of Truck	Manufacturer	Model	Capacity cubic yds	Tare wt. lbs.	Incoming Weight lbs.	Incomin Capacity %	Waste Stream					
										Mixed		
							Resid.	Commer	Indust.	Res.	Comm.	Indust.
front	Heil	z20	20	20000	40000	100		x				

Appendix B

AN IN-DEPTH EXAMINATION OF HOW THE MODELS WORK: TEXT, EXAMPLES, AND TEST RESULTS

Appendix B-1

THE THREE MODELS

In this report, three models were previously presented: two to evaluate the in-truck density of waste, and one to calculate the in-place density of waste at a landfill. The two in-truck density models are named the Simple Model and Model-2. The third model, the In-Place Density Model, works independently from the two in-truck density models but information from Model-2 may by selected for use in the In-Place Density Model. The three models will be explained in detail below.

THE SIMPLE MODEL

The Simple Model estimates the weight of incoming waste entering the facility over a given period of time. It does this by taking into account the following information: the truck type and its capacity, percent of capacity utilized, and an average in-truck waste density for each truck type. This model is also capable of modeling self-haul by simply including the self-haul vehicle type and density values in the spreadsheet model. (Observe the difference between the Redwood Sanitary Landfill example and the Rural Landfill example.) The Simple Model is useful when a facility does not have information about the local waste stream; it allows use of California default values for in-truck densities. In the examples, the incoming and tare weights of the trucks are included; one does not need this information to run the model. The advantage of the Simple Model is that it requires very little information to make an estimate of the tonnage entering a facility.

MODEL-2

Model-2 estimates in-truck density by combining regional waste composition information and materials density data to calculate the average regional waste density per vehicle. The model works in a two step manner. First, the model utilizes the waste composition information and density data to calculate an average in-truck waste density. Second, the model uses the average in-truck waste density value to estimate the total weight of the waste entering a facility on any given day. To do this, one must know the capacity of the truck or vehicle and the percent of the capacity utilized, but one does not need to know the type of truck or vehicle used. (Please refer to the Redwood Sanitary Landfill example for a detailed example of how the spreadsheet model is set up.) Incoming and tare weights are reported in the example, but are not needed for model application.

THE IN-PLACE DENSITY MODEL

The In-Place Density Model has been developed to estimate the amount of space that waste will occupy in a landfill. There is some speculation that, since waste arrives in trucks, it is already partially compacted upon arrival. Thus, one should consider the in-truck density in the calculation of in-place density. There is also a counter-argument that waste arrives at a landfill in trucks but then fluffs up again after it is dumped at the landfill and manipulated by landfill compaction equipment, and thus the important arrival density is the uncompacted density of the waste. The In-Place Density Model has been designed to allow the user to choose either of these points of view for use in calculation. The model uses input information on the weight of the compaction vehicle used at the landfill, the number of passes the compaction vehicle makes over the waste, and the slope of the fill, to calculate in-place density. (The reader is referred to the example of 18 California landfills.)

Appendix B-2

HOW THE SPREADSHEET MODELS WORK

Each of the following three sections examines a specific example for each spreadsheet model. The text discusses how the data is input and how the models calculate the results.

EXAMPLE 1: THE SIMPLE MODEL

Imagine a small rural landfill operator who does not have truck scales and does not know the composition of the waste stream in his/her region, or desires a reasonably accurate estimation of incoming tonnage using a simple and easy to use model. Then, the easiest way for this person to determine the number of tons entering the facility in a given time period is to use the Simple Model. To use the Simple Model the following pieces of information are needed:

1. Truck or Vehicle Types Entering the Facility
2. Capacity of Trucks or Vehicles
3. Percent of Capacity Utilized
4. Average Density of Waste in each Truck Type

To obtain the first set of information it is necessary to have someone stationed at the facility entrance recording the type of vehicle entering, its capacity, and percent full, or to set up a system where the drivers would record this information themselves and put it in a common collection box. The driver is often the best source of information as to type of vehicle, capacity, and especially percent full. The estimation of percent full is important to the accuracy of the estimations of the model. These estimates should be performed by trained and knowledgeable personnel. The accuracy calculated for the model indicates that drivers of refuse collection equipment provide accurate estimates of percent of full capacity. As mentioned in Section 1, the error of the Simple Model based on field verification (where percent of capacity was reported) can be expected to be in the range of 8% to 14%.

Once the data is collected, the next step is to input the data into the Simple Model spreadsheet (e.g., as illustrated on page B-13). The first column allows the user to number the entry, i.e., 1, 2, 3. The second column asks for truck type. In this column it is essential that the proper code is entered for each truck since the model depends on recognizing the truck code in that cell and calculating by the correct in-truck density value. The third column requests that the volumetric capacity of the vehicle be entered in units of cubic yards. The fourth column requires the user to input the data describing how full the truck is as it enters the facility, i.e., for a 20-cu yd vehicle filled to 15 cu yd, 75% is entered in this column. After the user completes all the data input, the model calculates the estimated weight in the truck in the fifth and final column. The equation the model uses in doing this is as follows:

estimated in-truck weight = truck density value x truck capacity x percent full

Looking specifically at the Rural Landfill example, the following text examines four data entries and provides a step-by-step process for using the Simple Model. These data entry lines have been highlighted on the spreadsheet to make it easier to follow the example.

First, in the Rural Example, it is assumed that there are four types of vehicles entering the facility: mini-pickups, full-sized pickups, rear loaders, and front loaders. The legend to the model provides the average in-truck density values which are used to estimate the waste entering the facility. If one desires to change these values based on information which is specifically relevant to a particular landfill, one enters the new value in the value column of the legend box next to the appropriate truck code.

In the first example, enter the entry number (1), the truck type (i.e., RL), the truck capacity (20 cu yd), and the percent of the capacity utilized by the incoming truck (i.e., 100%). The model computes the weight of the waste in the vehicle. The following four equations describe the calculations for entries 1, 14, 26, and 39.

1. RL(525 lb/cu yd) x (20 cu yd) x (100%) = 10,500 lb

14.FL(480 lb/cu yd) x (30 cu yd) x (75%) = 10,800 lb

26.FP(316 lb/cu yd) x (2.5 cu yd) x (100%) = 790 lb

39.MP(294 lb/cu yd) x (1.25 cu yd) x (100%) = 367.5 lb

EXAMPLE 2: MODEL-2

Imagine a large urban landfill operator who does not have truck scales, but does know the composition of the waste stream in his/her region. Then, the easiest way to determine the number of tons entering the facility in a given time period is to use Model-2. To use Model-2, one needs the following pieces of information:

1. Waste Composition of the Jurisdiction being Served
2. Capacity of Trucks or Vehicles Entering Facility
3. Respective Percent of Capacity Utilized

To obtain information on the jurisdiction's waste composition, county and city solid waste departments may be contacted. As a requirement of AB 939, all cities and counties in California are to determine their waste compositions by at least residential, commercial, and industrial waste sources. In the use of the model, the composition of each waste source (i.e., residential, etc.) is used for the type of vehicle carrying wastes generated by that particular waste source. To collect the second set of information, it is necessary to have someone stationed at the facility entrance recording the entering vehicle's capacity and percent full, or again to set up a system where the drivers would record this information themselves upon entering.

After the data is collected, the next step is to input the data into the Model-2 spreadsheets. The first spreadsheet requires the user to input the jurisdiction's waste composition. Since the example is from the Redwood Sanitary Landfill in Marin County, the waste composition for Marin County from a 1991 study was used as input data. Note that the only place the user inputs information on this sheet is in the second column titled "Waste Stream Percent by Weight" (denoted by p in the formulas). The third column lists the uncompacted waste density values (denoted by d in the formulas) which the model uses to calculate the average in-truck density. The fourth column lists the compacted waste density values (denoted by c in the formulas). The fifth column, "Zero Compaction Percentage" (denoted by z in the formulas), represents the critical percentage for each waste type below which this material will not compact in a truck. Based on examination of the mixed waste studies conducted by the project team, it was determined that this percentage is only relevant for glass. Thus all other materials are assumed to compact in a truck regardless of their contribution to the total load. Glass is assumed to compact in a truck only if it comprises 30% or more by weight of the total load in the truck, otherwise the uncompacted glass density is used in the model calculations.

In order to understand how Model-2 calculates the average in-truck density for Marin County, let us examine the rows describing corrugated containers (at the top of the spreadsheet), and recyclable glass (in the middle of the spreadsheet).

Corrugated Containers

p = 5.90%

d = 33 lb/cu yd

c = 360 lb/cu yd

z = 0

For this material q (the waste stream composition percent expressed as a decimal) = .06; m (the appropriate density to be used for the calculation, uncompacted or compacted) = 360 (lb/cu yd). In this case we use the compacted density because the z value is 0. Thus regardless of the amount of this material in the truck, the waste will compact normally.

p x m = (.06) x (360 lb/cu yd) = 21 lb/cu yd

Recyclable Glass

p = 2.9%

d = 455 lb/cu yd

c = 1258 lb/cu yd

z = 30% (Since recyclable glass only comprises 2.9% of the waste composition, much below the critical zero compaction percentage of 30%, the correct density to use for the calculation is the uncompacted density.)

q = 0

m = 455 lb/cu yd (as opposed to 1258 (lb/cu yd) which would be used if $p > 30\%$.)

p x m = (.03) x (455 lb/cu yd) = 13 lb/cu yd

The second spreadsheet of Model-2, incorporates the average in-truck density calculated in the first spreadsheet to evaluate the total weight of waste entering the facility over a given period of time. The next example examines data for the Redwood Sanitary Landfill on December 12, 1991.

In the first column, the user inputs the entry number, e.g., 1. In the second column, the user inputs the capacity in cubic yards of the entering vehicle. The third column requires the user to input the data describing how full the truck is as it enters the facility, i.e., for a 20-cu yd vehicle filled to 18 cu yd, 90% is entered. After the user has completed all the data input, the model calculates the estimated weight in the truck in the fourth and final column. The equation the model uses is as follows:

estimated in-truck weight = (average in-truck density value [calculated in the previous spreadsheet]) x (truck capacity) x (percent full)

Looking specifically at the Redwood Sanitary Landfill example, let us follow step by step the process of using the second spreadsheet of Model-2 by examining the first data entry. The data input boxes described have been highlighted on the spreadsheet to make following the example easier.

First, the average in-truck density for Marin County in the first spreadsheet was calculated; this value (724 lb/cu yd) appears in the second spreadsheet of Model-2 in a box at the top of the spreadsheet. If the spreadsheets are not linked automatically or if the average in-truck density of your waste stream is known, the proper value may be typed in this box.

In the first example, the entry number is 1, the truck capacity is 20 cu yd, and the percent of the capacity utilized by the incoming truck is 90%. The model computes the weight of the waste in the vehicle using the following equation:

1. (724 lb/cu yd) x (20 cu yd) x (90%) = 13,032 lb

To determine the total number of tons entering the facility on this day, all of the data in columns 1, 2, and 3 were entered and totalled in the fourth column, for a total throughput of 652,779 tons.

EXAMPLE 3: IN-PLACE DENSITY MODEL

The In-Place Density Model is based on a more sophisticated set of equations than those previously discussed, but it is still easy to use. The simplest way to explain how this model functions is to look at an example and to explain each equation as it is utilized in the model.

This model requires the user to input three pieces of data:

1. The Weight of the Compacting Vehicle

2. The Number of Passes the Vehicle Will Make Over the Waste
3. The Slope Angle of the Surface or Finished Grade of the Fill

The In-Place Density Model provides certain default data if data is not readily available.

To implement the model, the user inputs an entry number in the first row, in our example it is the XYZ Landfill. In the second row, the user is requested to input the weight of the compacting vehicle in pounds. If the type of vehicle used is known, but not the weight of the vehicle, please refer to Section 2, Table 2-1 of this report for a list of machine weights. In the third row, the user inputs the number of passes the vehicle will make over the waste. In the fourth and fifth rows the user inputs the slope of the finished grade of the fill either as a ratio or as an angle.

The following calculations pertain to the fictitious example of the XYZ landfill:

entry number = "XYZ Landfill"

vehicle weight = 66,845 lb

number of passes = 7

slope angle of finished grade = 3:1 ratio

The model makes the following calculations in determining the in-place density of the waste, employing five estimated constants in doing so:

K1 = 1635

K2 = 3.4

K3 = 4.2E-05

K4 = .55

K5 = .25

The model relationship is characterized by the following equation:

$$\frac{K1}{(1 + K2 \times e^{-K3 \times \cos(\text{slope angle}) \times \text{vehicle weight}}) \times (1 + K4 \times e^{-K5 \times \text{number passes}})}$$

First the model calculates the angle in radians. If the user has entered the slope as a ratio the model uses this formula:

angle in radians = arctangent of 1/slope ratio

In our example, angle in radians = arctangent of 1/3 = 0.32 radians.

If the user has entered the slope in degrees, the model transforms the angle from degrees to radians:

$$\text{angle in radians} = \frac{\text{angle in degrees} \times \text{Pi}}{180}$$

Next the model takes the cosine of the angle as it is expressed in radians:

cos = cos (angle in radians)

In our example, cos = cos (0.32) = 0.95

Then the model calculates the two exponentials used in the characterization equation above:

$$\text{first exponential} = 1 + K2 \times e^{-K3 \times \cos(\text{slope angle}) \times \text{vehicle weight}}$$

In our example, first exponential $= 1 + 3.4 \times e^{-4.2E\text{-}05 \times .95 \times 66{,}875} = 1.24$

$$\text{second exponential} = 1 + K4 \times e^{-K5 \times \text{number passes}}$$

In our example, second exponential $= 1 + .55 \times e^{-.25 \times 7} = 1.10$

The final equation combines all of this information to calculate the in-place density:

$$\text{in-place density} = \frac{K1}{\text{first exponential} \times \text{second exponential}}$$

In our example, in-place density = 1635/(1.24 x 1.10) = 1206 lb/cu yd

(Note: Due to rounding errors, the calculation shown in the text appears to yield 1199; the model, retaining more significant figures, calculates the result of 1206)

EXAMPLE 4: THE GENERAL MODEL (COMBINED MODEL-2 AND IN-PLACE DENSITY MODEL)

Both Model-2 and the In-Place Density Model have been demonstrated in detail. The combination of the two models is straightforward. There is an example utilizing waste from ABC County going to landfill XYZ in the tables of the examples. The tables have explanatory text to assist in user comprehension of the model.

Appendix B-3

TESTING THE MODELS

Information collected at two landfills was utilized in testing the Simple Model and Model-2. Data from over a two-day period were collected, respectively, from Redwood Sanitary Landfill and Bee Canyon Landfill. The actual weight of the waste for each vehicle was calculated in the spreadsheet by subtracting the tare weight of the truck from the incoming weight of the truck:

actual weight = incoming weight - tare weight

To test the accuracy of the Simple Model, the truck type, the capacity, and percent full were entered into the model spreadsheet. Then based on the values determined for each truck type the model calculates the estimated weight of the materials in the truck:

weight of waste in truck = (truck type density) x (capacity) x (percent full)

To test the accuracy of the Model-2, the jurisdiction's average waste density was first calculated based on that region's waste composition. Then this information was used to estimate the weight of the incoming waste over a given period of time. In the first spreadsheet of the model, the waste composition was entered, and in the second spreadsheet, the truck's capacity and percent full were entered. Based on the average density value determine in the first spreadsheet of the model, the model calculated the estimated weight of the materials in the truck:

weight of waste in truck = (average in-truck density) x (capacity) x (percent full)

In order to test the In-Place Density Model, California landfills were surveyed to gather data on compactor types, number of passes made by compactors, slope angles, and estimated in-place densities. Eighteen observations were obtained, as shown in the in-place density table. Unfortunately, most of the observations were estimates made by landfill operators, and were not based on actual measurements of in-place density. Many of the reported densities were rounded off to the nearest 100 lb/cu yd, introducing rounding errors of up to ±5%.

The In-Place Density Model was used to estimate densities for these 18 sites; the results are shown in the In-Place Density Model table and the accompanying graph. While there is a qualitative correspondence between model estimates and landfill operator estimates, precise quantitative comparison does not appear justified, in light of the inherent imprecision in the field data available to date.

LIMITATIONS OF THE MODELS

There are several limitations to the in-truck density models shown in this report. First, composition of the waste in the individual trucks was not known; the wide range of calculated densities clearly implies substantial variation in the range of materials being delivered. Some trucks reported densities of under 200 lb/cu yd, while others reported close to or over 1000 lb/cu yd.

Second, the calculations necessarily rely on the landfill's estimates of the percent of full capacity in each delivered truckload. These percentages were almost always rounded off to the nearest 5% or 10%; moreover, they likely involve a substantial component of qualitative judgment. Most of the trucks for which the highest densities calculated were reported 75% or less filled, while most other trucks reported 80% or more filled. If the "high-density" trucks were actually cases of accidental under-reporting of percent full, then the density differences may be artifacts of reporting, rather than actual observations.

How accurate are the in-truck models likely to be in a specific field application? Errors can enter in any stage of data collection:

- Truck capacities might be reported incorrectly; this seems unlikely, and may be ignored.
- Percent full might be estimated incorrectly at the landfill; this is a potentially serious problem in any application.
- Waste-stream related errors may enter: The average compacted density for all solid waste (in the Simple Model) or for a particular waste type (in Model-2) might be incorrect; and the waste composition for a particular truckload (explicitly used in Model-2, implicitly used to derive the average density in the Simple Model) might differ from the average used in the model.

There is no simple way to determine "how much" data is needed for accurate estimation. The more important question is whether errors are random or systematic; in the latter case, no amount of data will help. If errors in estimating percent full, or errors related to waste stream composition and compaction, are randomly distributed, then more observations will lead to more accurate estimates, on average. However, if systematic errors are being made in either estimates of truck loading or in estimates of waste stream composition, then additional observations will only reinforce these errors. A key aspect for accurate model use is that field testing is required to acquire data under local conditions and to confirm that unbiased estimates are, on average, being made.

Examples of the Three Models:

1. Simple Model - Rural Example
2. Model 2 - Redwood Sanitary Landfill Example
3. In-Place Model - XYZ Landfill Example
4. Combination In-Truck and In-Place Density Model (The General Model) - ABC Waste Source and XYZ Landfill Compaction Data

IN-TRUCK DENSITY MODEL: Simple Model

A Rural County: 50% Self Haul, 25% Rear Loaders, 25%Front Loaders(Commercial)

Truck Type	Legend Code	Value (lb/cu yd)
Mini Pick-up	MP	294
Full Pick -up	FP	316
Rear Loader	RL	525
Front Loader	FL	480
Compacting Roll-Off	CRO	680
Open Top Roll-Off	OTR	400

Input Information in the First Four Columns

Entry #	Truck Type	Capacity (cu yd)	% Full	Simple Model Estimated weight (lb)
1	RL	20	100%	10,500
2	RL	20	75%	7,875
3	RL	25	60%	7,875
4	RL	18	75%	7,088
5	RL	16	100%	8,400
6	RL	15	80%	6,300
7	RL	18	100%	9,450
8	RL	10	100%	5,250
9	RL	18	80%	7,560
10	RL	20	80%	8,400
11	RL	15	100%	7,875
12	RL	20	100%	10,500
13	RL	25	80%	10,500
14	FL	30	75%	10,800
15	FL	30	95%	13,680
16	FL	35	50%	8,400
17	FL	35	60%	10,080
18	FL	39	80%	14,976
19	FL	39	100%	18,720
20	FL	39	25%	4,680
21	FL	40	100%	19,200
22	FL	39	100%	18,720
23	FL	35	100%	16,800
24	FL	2.5	90%	1,080
25	FL	40	90%	17,280
26	FP	2.5	100%	790
27	FP	2	75%	474

Entry #	Truck Type	Capacity (cu yd)	% Full	Simple Model Estimated weight (lb)
28	FP	2.5	60%	474
29	FP	2.5	80%	632
30	FP	2	62%	392
31	FP	2	50%	316
32	FP	2	100%	632
33	FP	2.5	100%	790
34	FP	1.75	100%	553
35	FP	2.5	20%	158
36	FP	2	75%	474
37	FP	2	100%	632
38	FP	2	100%	632
39	MP	1.25	100%	368
40	MP	1.5	66%	291
41	MP	1.25	80%	294
42	MP	1.5	20%	88
43	MP	1.5	100%	441
44	MP	1.5	100%	441
45	MP	2.5	40%	294
46	MP	1.75	86%	442
47	MP	1.5	100%	441
48	MP	1.5	100%	441
49	MP	1.25	100%	368
50	MP	1.5	100%	441
Daily Total Weights				273,287

Conversion Factor Study: In-Vehicle and In-Place Waste Densities, Tables 1-16 and 1-18.

Data for this example was drawn from three sources, Redwood Sanitary Landfill, Bee Canyon Landfill, and self-haul data from the Marin County Transfer Station.

IN-TRUCK DENSITY MODEL 2
Marin County

Estimated density (lb/cu yd): 724

The User Inputs the Jurisdiction's Waste Composition

Material Type	Waste stream Percent by weight	Density uncompacted (lb/cu yd)	Density compacted (lb/cu yd)	Zero Compaction Percentage	Intermediate calculations		
	p	d	c	z	q	m	p*m
Paper:							
Corrugated Containers	5.90%	33	360		0.06	359.75	21
Mixed Paper	4.40%	484	613		0.04	612.50	27
Newspaper	1.30%	323	552		0.01	551.50	7
High Grade Ledger	9.40%	364	644		0.09	644.00	61
Other Paper	9.70%	570	635		0.10	635.00	62
Plastics:							
HDPE	0.30%	35	264		0.00	263.75	1
PET	0.20%	39	182		0.00	182.00	0
Film Plastics	4.00%	23	226		0.04	226.00	9
Other Plastics	4.00%	50	372		0.04	371.62	15
Glass:							
Recyclable	2.90%	455	1258	30%		455.38	13
Non-recyclable	0.20%	566	1258	30%		566.00	1
Metals:							
Aluminum Cans	0.30%	91	399		0.00	399.00	1
Ferrous	2.50%	141	501		0.03	501.00	13
Non-Ferrous	0.60%	1248	1248		0.01	1248.32	7
White Goods		255	255			255.40	
Organics:							
Yardwaste	17.00%	292	584		0.17	584.20	99
Other Bio-organic	11.60%	1013	1080		0.12	1080.00	125
Other Nonbio-organic	6.15%	540	648		0.06	648.00	40
Textiles	1.20%	247	540		0.01	540.00	6
Leather	1.20%	380	759		0.01	759.30	9
Woodwaste	6.80%	333	333		0.07	332.65	23
Other Waste:							
Inert Solids	7.80%	1975	1975		0.08	1974.85	154
HHW	0.40%	1523	1523		0.00	1522.70	6
Special Wastes:							
Sewage Sludge		1294	1294			1293.75	
Ash	1.70%	1350	1350		0.02	1350.00	23
Auto Shredder Waste		800	800			800.00	
Dewatered Sludge		1615	1615			1614.60	
Tannery Sludge		NA					
Drilling Mud		NA					
Mine Tailings		NA					
TOTAL	**99.55%**					**TOTAL COMPACTED DENSITY**	**724**

The Model Calculates the In-Truck Density of the Waste Stream

Source: Marin County Solid Waste Management Plan, Beck & Assoc, Table 2.4, 8/91.

IN-TRUCK DENSITY MODEL 2: Redwood Landfill, Marin County

Day: December 12, 1991

Estimated In-Truck Density: 724

Entry #	Capacity (cu yd)	% Full	Model 2 Estimated weight (lb)
1	20	90%	13,029
2	15	80%	8,686
3	15	90%	9,772
4	30	90%	19,543
5	18	100%	13,029
6	25	80%	14,476
7	15	80%	8,686
8	18	100%	13,029
9	20	100%	14,476
10	25	70%	12,667
11	18	100%	13,029
12	18	90%	11,726
13	20	90%	13,029
14	20	75%	10,857
15	25	90%	16,286
16	20	80%	11,581
17	20	90%	13,029
18	18	90%	11,726
19	20	75%	10,857
20	20	100%	14,476
21	25	80%	14,476
22	20	80%	11,581
23	18	75%	9,772
24	30	100%	21,715
25	20	100%	14,476
26	20	80%	11,581
27	18	100%	13,029
28	20	100%	14,476
29	20	100%	14,476
30	18	100%	13,029
31	25	80%	14,476
32	25	90%	16,286
33	18	100%	13,029
34	25	90%	16,286
35	20	75%	10,857
36	20	75%	10,857

The User Inputs
Entry #
Vehicle Capacity
and Percent Full

The Model Calculates
the Estimated Weight
of the Waste in the
Vehicle

IN-TRUCK DENSITY MODEL 2: Redwood Landfill, Marin County

Day: December 12, 1991

Estimated In-Truck Density: 724

Entry #	Capacity (cu yd)	% Full	Model 2 Estimated weight (lb)
37	25	80%	14,476
38	20	100%	14,476
39	25	80%	14,476
40	30	80%	17,372
41	25	80%	14,476
42	20	80%	11,581
43	20	75%	10,857
44	30	90%	19,543
45	15	75%	8,143
46	18	60%	7,817
47	25	60%	10,857
48	18	80%	10,423
49	20	90%	13,029
50	20	75%	10,857
Daily Total Weights			652,779

IN-TRUCK DENSITY MODEL
California Default Values

Material Type	Density Compacted (lb/cy)	Notes
Paper		
Corrugated Containers	359.75	Field test result, E. Harlem, NYC, 11-14-91
Mixed Paper	612.50	Field test result, E. Harlem, NYC, 11-14-91
Newspaper	551.50	Field test result, E. Harlem, NYC, 11-14-91
High Grade Ledger	644.00	Assume compaction is 1.77 to 1
Other Paper	635.00	Assume compaction is 1.11 to 1
Plastics		
HDPE	263.75	Field test, E. Harlem, NYC, 11-12-91 & 11-13-91, avg of two results
PET	182.00	Field test result, E. Harlem, NYC, 11-12-91
Film Plastics	226.00	Assume 10:1 compaciton ratio
Other Plastics	371.62	Field obs of polypropylene, coiled, Wakefield, MA
Glass		
Recyclable	1258.00	Field test result, E. Harlem, NYC, 11-14-91
Non-Recyclable	1258.00	Field test result, E. Harlem, NYC, 11-14-91
Metals		
Aluminum Cans	399.00	Field studies, California, baled aluminum
Ferrous	501.00	Field test, E. Harlem
Non-Ferrous	1248.32	Assume non-compactable
White Goods	255.40	Assume non-compactable
Organics		
Yard Waste	584.20	Assume 2:1
Other Bio-Organic	1080.00	Assume 1.07:1
Other Nonbio-Organic	648.00	Assume 1.2:1 (between mixed paper and non-recyclable paper)
Textiles	540.00	Garment District, Boston, low-grade compactor, personal comm.
Leather	759.30	Assume 2:1, slightly less than textiles
Wood Waste	332.65	Assume non-compactable
Other Waste		
Inert Solids	1974.85	Assume non-compactable
HHW	1522.70	Assume non-compactable
Special Wastes		
Sewage Sludge	1293.75	Assume non-compactable
Ash	1350.00	Assume non-compactable
Auto Shredder Waste	800.00	Assume non-compactable
Dewatered Sludge	1614.60	Assume non-compactable

IN-TRUCK DENSITY MODEL
California default values

Material Type	Waste stream % by wt.	Density uncompacted (lb/cy)
Paper:		
1. Corrugated Containers	8.00%	33.35
2. Mixed Paper	6.00%	484.00
3. Newspaper	9.00%	322.80
4. High Grade Ledger	1.00%	363.50
5. Other Paper	12.00%	570.40
Plastics:		
6. HDPE	1.00%	34.60
7. PET	0.00%	38.90
8. Film Plastics	2.00%	22.60
9. Other Plastics	3.00%	49.80
Glass:		
10. Recyclable	6.00%	455.38
11. Non-recyclable	1.00%	566.00
Metals:		
12. Aluminum Cans	4.00%	91.40
13. Ferrous	1.00%	141.38
14. Non-Ferrous	1.00%	1248.32
15. White goods	1.00%	255.40
Organics:		
16. Yardwaste	19.00%	292.10
17. Other Bio-organic	8.00%	1013.33
18. Other Nonbio-organic	2.00%	540.00
19. Textiles	2.00%	247.00
20. Leather	1.00%	379.65
21. Woodwaste	3.00%	332.54
Other Waste:		
22. Inert Solids	7.00%	1974.85
23. HHW	1.00%	1522.70
Special Wastes:		
24. Sewage Sludge		1293.75
25. Ash	0.33%	1350.00
26. Auto Shredder Waste	0.33%	800.00
27. Dewatered Sludge	0.33%	1614.60

IN-TRUCK DENSITY MODEL
California Default Values

Notes[a)]

1. Table 5, Task 2 Report[b)], averaged flattened (50.1) and whole (16.6)
2. Field test at Wellsley, MA Recycling drop-off facility
3. Table 5, Task 2 Report, without glossy inserts
4. Table 5, Task 2 Report, without CPO
5. Table 5, glossy paper.

6. Table 5, Task 2 Report, average of both milk/water (22.1) and mixed color (47.1)
7. Table 5, Task 2 Report, average to PET/mixed (43.3) and PET/CRV (34.6)
8. Table 5, film plastic/mixed
9. Table 5, other plastic #3-7

10. Table 5, average of glass/clear CRV (466.5), glass/clear non CRV (437.8), glass/green (456.7), glass/mix brown (439.6), and glass/mix clear (476.3)
11. Assume 2.5:1 compaction ratio

12. Table 5
13. Field (East Harlem)
14. Field (FS) and Literature Studies (LS), average of LS for lead scrap (1603.84) and copper (1070.57). The figure for copper is an average of LS for copper scrap (1093.52) and FS for copper fittings (1047.62).
15. Table 5, Task 2 Report, average of dishwashers (234), dryers (224), refrigerators/freezers (198), washers (321), and stoves/ovens (300)

16. Table 5, Task 2 Report, average of yardwaste items, exc. items prefixed by "compost", incl.: leaves/dry (343.7) grass/fresh (280.2), prunings/dry <4" (36.9), prunings/green <4" (46.7), large limbs and stumps >4" (1080), garden debris (182.8) and pine needles (74.4)
17. Field test, average of cantaloupes (1000), mixed vegetables (1131), and mixed fruit (909), Star Market, Cambridge, MA
18. Table 5, diapers
19. Field test and Table 5 (FS), average of shoes (224), winter coats (241), jeans (285), T-shirts (260), mixed, some dresses, shirts (225). From Table 5 (FS) carpet and padding (84.4)
20. Field test, average of six different semi-compacted figures collected at Columbia Tanning, Brockton, MA, and Berman Leathercraft, Boston, MA (243, 303, 470, 383, 61, 363.42, 524.85)
21. Table 5, Task 2 Report, average of pallets (210), sawdust (375) wood scrap <2' (329.5), and particle board (425.1). All were FS.

22. Field test and Table 5, Task 2 Report, incl. rock 2" - 12" (2570.96), rock/red lava 5/16" (1325.9), concrete/<8"scrap (1855.2), brick/red-broken <8" (1614.1), ceramic tile 6"x6" (1213.9), sand (2441.3), average of 2 soils (2392, 2385.5)
23. 32% latex paint (1836); 23% enamel paint(1653); 20% oil (1524.94); 25% other (1000 (midpoint of range of other))

24. Table 5, 14.7% solids
25. Table 5, 50% water, trucked
26. Table 5, shredder fluff
27. Table 5, 38% solids

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a) All amounts are lb/cu yd unless otherwise noted.

b) Conversion Factors For Individual Material Types, Final Report, Cal Recovery Inc., December, 1991.

IN-PLACE DENSITY MODEL

Entry Number	XYZ Landfill
INPUTS:	
Vehicle weight (lbs)	66,845
Number of passes	7
Slope angle of surface or finished grade	
enter either as ratio X:1 = = >	3
or in degrees = = >	
CALCULATIONS:	
angle (radians)	0.32
cosine	0.95
first exponential	1.24
second exponential	1.10
in-place density	1206

The User Inputs:
Facility Name or Reference
Weight of Compaction Vehicle
and Slope of Fill,
either in a ratio form or as an angle

The Model calculates:
The Estimated In-Place Density

ESTIMATED CONSTANTS	ALTERNATIVE VALUES
K1	1635
K2	3.40
K3	4.20E-05
K4	0.55
K5	0.25

Waste stream compaction model:

Estimates a) compaction of a waste stream in a packer truck
b) compaction in a landfill

Truck compaction based on measured loose and compacted densities, and on the observation that glass does not compact if it accounts for less than a critical ("zero compaction") percentage of the waste stream.

Landfill compaction base.. on weight of compacting vehicle, number of passes, surface slope angle, and on loose density and relative compactibility of waste stream as received.

A: IN-TRUCK COMPACTION MODEL

User enters percentage composition of waste stream, and location, date, and description if desired. Percentage composition must sum to 100%; check calculated percentage below. Results may be used alone, and/or as inputs feeding automatically into the in-place compaction model presented below.

	User entries:
Location:	XYZ Landfill
Date:	3/1/92
Description:	Waste Incoming from ABC County

	Results:
Sum of waste stream %	100.00%
Loose density	521.82
Compacted density	767.11

In-Truck Model 2 and In-Place Density Model Combined Example : THE GENERAL MODEL
Waste Composition for ABC County

Material Type	Waste stream compos.	Density uncompacted (lb/cu yd)	Density compacted (lb/cu yd)	Zero Comp. %	Intermediate calculations			
	p	d	c	z	q	m	p*m	p*d
Paper:								
Corrugated Containers	8.00%	33.35	359.75	0.00%	0.08	359.75	28.78	2.67
Mixed Paper	6.00%	484.00	612.50	0.00%	0.06	612.50	36.75	29.04
Newspaper	9.00%	322.80	551.50	0.00%	0.09	551.50	49.64	29.05
High Grade Ledger	1.00%	363.50	581.60	0.00%	0.01	581.60	5.82	3.64
Other Paper	12.00%	570.40	627.44	0.00%	0.12	627.44	75.29	68.45
Plastics:								
HDPE	1.00%	34.60	263.75	0.00%	0.01	263.75	2.64	0.35
PET	0.00%	38.90	182.00	0.00%	0.00	182.00	0.00	0.00
Film Plastics	2.00%	22.60	226.00	0.00%	0.02	226.00	4.52	0.45
Other Plastics	3.00%	49.80	371.62	0.00%	0.03	371.62	11.15	1.49
Glass:								
Recyclable	6.00%	455.38	1258.00	30.00%	0.00	455.38	27.32	27.32
Non-recyclable	1.00%	566.00	1415.00	30.00%	0.00	566.00	5.66	5.66
Metals:								
Aluminum Cans	1.00%	91.40	399.00	0.00%	0.01	399.00	3.99	0.91
Ferrous	4.00%	141.38	501.00	0.00%	0.04	501.00	20.04	5.66
Non-Ferrous	1.00%	1248.32	1248.32	0.00%	0.01	1248.32	12.48	12.48
White Goods	1.00%	255.40	255.40	0.00%	0.01	255.40	2.55	2.55
Organics:								
Yardwaste	19.00%	292.10	584.20	0.00%	0.19	584.20	111.00	55.50
Other Bio-organic	8.00%	1013.33	2026.66	0.00%	0.08	2026.66	162.13	81.07
Other Nonbio-organic	2.00%	540.00	648.00	0.00%	0.02	648.00	12.96	10.80
Textiles	2.00%	247.00	540.00	0.00%	0.02	540.00	10.80	4.94
Leather	1.00%	379.65	759.30	0.00%	0.01	759.30	7.59	3.80
Woodwaste	3.00%	332.65	332.65	0.00%	0.03	332.65	9.98	9.98
Other Waste:								
Inert Solids	7.00%	1974.85	1974.85	0.00%	0.07	1974.85	138.24	138.24
HHW	1.00%	1522.70	1522.70	0.00%	0.01	1522.70	15.23	15.23
Special Wastes:								
Sewage Sludge		1293.75	1293.75	0.00%	0.00	1293.75	0.00	0.00
Ash	0.33%	1350.00	1350.00	0.00%	0.00	1350.00	4.50	4.50
Auto Shredder Waste	0.33%	800.00	800.00	0.00%	0.00	800.00	2.67	2.67
Dewatered Sludge	0.33%	1614.60	1614.60	0.00%	0.00	1614.60	5.38	5.38
Tannery Sludge		not available						
Drilling Mud		not available						
Mine Tailings		not available						
TOTAL	100.00%						**767.11**	**521.82**

We seek to estimate the in-place density InPlace(WS, EffWt, NPass), where

WS	= waste stream identifier
EffWt	= effective weight of compaction vehicle exerted on in-place waste
NPass	= number of passes by compaction vehicle

The effective weight, based on geometry and elementary physics, is the weight of the vehicle multiplied by the cosine of the slope angle (the angle of the finished surface).

The modeling proceeds in two steps. First, based on published data and landfill reports, we model in-place density for an average mixed municipal solid waste stream; this involves logistic functions in both effective weight and in number of passes, reflecting the existence of saturation effects. There are five constant parameters required, K1 through K5:

DefaultInPlace(EffWt, NPass) = K1/[(1+K2*EXP(-K3*EffWt)*(1+K4*EXP(-K5*NPass))]

Second, to allow variation for different waste streams, we add two further parameters:

AsDelivered(WS)	= Waste stream density when dumped at landfill
Compact(WS)	= Relative compaction (where default waste stream compaction = 1.0)

Both parameters can if desired be estimated by the in-truck compaction model presented above. AsDelivered(WS) can be assumed to equal the uncompacted density for a given waste stream composition; this assumes either no in-truck compaction, or expansion back to uncompacted density when dumped, neither of which is perfectly realistic. Compact(WS) can be derived as the ratio of truck-compacted to loose density for a waste stream, relative to the same ratio for the default waste stream; however, the model user may also experiment with other values.

Then the complete model is:
InPlace(WS, EffWt, NPass) =
AsDelivered(WS) * [DefaultInPlace(EffWt, NPass)/AsDelivered(Default)]^Compact(WS)

Note that when Compact=0, no compaction can occur, and in-place density equals as-delivered density. When Compact=1, the estimated in-place density is proportional to the DefaultInPlace estimate, scaled up or down for changes in as-delivered density.

Prompt	User entries:
Does as-delivered density equal uncompacted density? (Y/N)	Y
If N, enter as-delivered density (lb/cu yd)	
Weight of compacting vehicle (enter in lb, no commas)	66845
Number of passes made by compacting vehicle (default = 5)	7
Express angle of slope or finished surface as X:1 (i.e., enter X)	3
Calculated compactibility relative to default value	0.87
Use calculated compactibility (Y/N)?	Y
If N, enter compactibility relative to default waste stream = 1.0	

Constants for landfill density model:

	ALTERNATIVE VALUES	DEFAULT VALUES*
K1	1635	1680
K2	3.40	3.50
K3	4.20E-05	6.30E-05
K4	0.55	3.00
K5	0.25	0.60

Intermediate calculations

Cosine of slope angle	0.95
First term (weight, angle effects)	1.24
Second term (number of passes)	1.10
Default in-place density	1206.43
Default as-delivered density	391.00
Actual as-delivered density	521.82
Compactibility	0.87
Estimated in-place density	1391.75

*Default Values are for reference only.

Test Results of the Three Models:

1 Simple Model & Model 2 - Redwood Sanitary Landfill
2 Simple Model & Model 2 - Bee Canyon Landfill
3 Simple Model & Model 2 - Rural Landfill
4 In-Place Model - 18 California Landfills

IN-TRUCK DENSITY MODEL
Marin County

Estimated density (lb/cu yd): 724

Material Type	Waste stream Percent by weight	Density uncompacted (lb/cu yd)	Density compacted (lb/cu yd)	Zero Compaction Percentage	Intermediate calculations		
	p	d	c	z	q	m	p*m
Paper:							
Corrugated Containers	5.90%	33	360		0.06	359.75	21
Mixed Paper	4.40%	484	613		0.04	612.50	27
Newspaper	1.30%	323	552		0.01	551.50	7
High Grade Ledger	9.40%	364	644		0.09	644.00	61
Other Paper	9.70%	570	635		0.10	635.00	62
Plastics:							
HDPE	0.30%	35	264		0.00	263.75	1
PET	0.20%	39	182		0.00	182.00	0
Film Plastics	4.00%	23	226		0.04	226.00	9
Other Plastics	4.00%	50	372		0.04	371.62	15
Glass:							
Recyclable	2.90%	455	1258	30%		455.38	13
Non-recyclable	0.20%	566	1258	30%		566.00	1
Metals:							
Aluminum Cans	0.30%	91	399		0.00	399.00	1
Ferrous	2.50%	141	501		0.03	501.00	13
Non-Ferrous	0.60%	1248	1248		0.01	1248.32	7
White Goods		255	255			255.40	
Organics:							
Yardwaste	17.00%	292	584		0.17	584.20	99
Other Bio-organic	11.60%	1013	1080		0.12	1080.00	125
Other Nonbio-organic	6.15%	540	648		0.06	648.00	40
Textiles	1.20%	247	540		0.01	540.00	6
Leather	1.20%	380	759		0.01	759.30	9
Woodwaste	6.80%	333	333		0.07	332.65	23
Other Waste:							
Inert Solids	7.80%	1975	1975		0.08	1974.85	154
HHW	0.40%	1523	1523		0.00	1522.70	6
Special Wastes:							
Sewage Sludge		1294	1294			1293.75	
Ash	1.70%	1350	1350		0.02	1350.00	23
Auto Shredder Waste		800	800			800.00	
Dewatered Sludge		1615	1615			1614.60	
Tannery Sludge		NA					
Drilling Mud		NA					
Mine Tailings		NA					
TOTAL	99.55%		TOTAL COMPACTED DENSITY				724

Source: Marin County Solid Waste Management Plan, Beck & Assoc. Table 2.4, 8/91.

IN-TRUCK DENSITY MODEL: Redwood Landfill, Marin County

Day: December 11, 1991

	RL	FL	CRO	OTR	Units
Estimated In-Truck Density:	724 | 525	480	680	400	(lb/ cu yd)

#	Truck Type	Capacity (cu yd)	% Full	Actual weight (lb)	Simple Model Estimated weight (lb)	Model 2 Estimated weight (lb)	Incoming weight	Tare weight
1	RL	20	100%	11,520	10,500	14,476	38,080	26,560
2	OTR	30	80%	6,180	9,600	17,372	30,820	24,640
3	FL	42	100%	36,480	20,160	30,401	55,260	18,780
4	RL	18	75%	7,320	7,088	9,772	27,860	20,540
5	RL	16	100%	6,960	8,400	11,581	26,460	19,500
6	OTR	20	75%	27,620	6,000	10,857	54,000	26,380
7	RL	18	100%	5,820	9,450	13,029	28,180	22,360
8	RL	10	100%	2,720	5,250	7,238	18,540	15,820
9	RL	18	80%	6,080	7,560	10,423	27,200	21,120
10	RL	20	80%	14,260	8,400	11,581	45,120	30,860
11	RL	15	100%	7,880	7,875	10,857	28,460	20,580
12	FL	42	100%	3,580	20,160	30,401	40,020	36,440
13	RL	25	80%	13,540	10,500	14,476	42,340	28,800
14	FL	38	80%	11,240	14,592	22,004	43,680	32,440
15	OTR	18	80%	2,060	5,760	10,423	23,680	21,620
16	RL	25	80%	12,940	10,500	14,476	41,900	28,960
17	RL	20	80%	11,620	8,400	11,581	37,700	26,080
18	RL	20	80%	3,300	8,400	11,581	24,340	21,040
19	RL	20	100%	8,180	10,500	14,476	34,700	26,520
20	RL	25	80%	14,960	10,500	14,476	45,240	30,280
21	RL	20	100%	15,300	10,500	14,476	45,580	30,280
22	RL	25	80%	7,820	10,500	14,476	40,020	32,200
23	OTR	15	100%	9,900	6,000	10,857	36,220	26,320
24	OTR	15	90%	2,640	5,400	9,772	23,780	21,140
25	OTR	20	100%	5,020	8,000	14,476	29,860	24,840
26	RL	25	80%	13,020	10,500	14,476	44,860	31,840
27	OTR	40	0.8	7,340	12,800	23,162	33,720	26,380
28	RL	25	80%	14,000	10,500	14,476	44,060	30,060
29	CRO	15	100%	11,560	10,200	10,857	40,140	28,580
30	RL	20	75%	14,380	7,875	10,857	44,900	30,520
31	CRO	20	80%	9,440	10,880	11,581	38,080	28,640
32	FL	42	100%	15,920	20,160	30,401	52,500	36,580
33	CRO	20	80%	8,620	10,880	11,581	37,620	29,000
34	RL	20	80%	11,020	8,400	11,581	39,620	28,600
35	RL	20	100%	13,220	10,500	14,476	41,820	28,600
36	RL	20	80%	5,480	8,400	11,581	34,320	28,840

N-TRUCK DENSITY MODEL: Redwood Landfill, Marin County

ay: December 11, 1991	RL	FL	CRO	OTR	Units
stimated In-Truck Density: 724	525	480	680	400	(lb/ cu yd)

#	Truck Type	Capacity (cu yd)	% Full	Actual weight (lb)	Simple Model Estimated weight (lb)	Model 2 Estimated weight (lb)	Incoming weight	Tare weight
37	RL	15	75%	10,600	5,906	8,143	37,400	26,800
38	RL	20	75%	9,280	7,875	10,857	36,660	27,380
39	RL	25	60%	15,260	7,875	10,857	48,120	32,860
40	RL	15	80%	4,660	6,300	8,686	24,100	19,440
41	RL	20	100%	13,480	10,500	14,476	41,940	28,460
42	RL	20	75%	9,420	7,875	10,857	39,960	30,540
43	RL	25	80%	13,900	10,500	14,476	45,500	31,600
44	RL	20	100%	7,460	10,500	14,476	35,760	28,300
45	RL	18	75%	6,900	7,088	9,772	28,320	21,420
46	RL	20	80%	7,900	8,400	11,581	31,080	23,180
47	RL	20	75%	10,060	7,875	10,857	38,440	28,380
48	RL	20	75%	8,820	7,875	10,857	34,360	25,540
49	RL	20	80%	11,080	8,400	11,581	36,340	25,260
50	RL	25	60%	13,940	7,875	10,857	45,580	31,640
51	OTR	48	100%	11,720	19,200	34,743	38,380	26,660
52	RL	25	100%	15,540	13,125	18,096	45,800	30,260
53	FL	38	80%	12,220	14,592	22,004	44,760	32,540
54	RL	18	0.75	8,720	7,088	9,772	29280	20560
55	RL	18	1	9,500	9,450	13,029	31780	22280
56	RL	18	100%	10,560	9,450	13,029	33,020	22,460
57	OTR	50	100%	16,520	20,000	36,191	43,200	26,680
58	RL	18	100%	11,040	9,450	13,029	32,280	21,240
59	OTR	20	80%	4,020	6,400	11,581	30,140	26,120
60	RL	25	90%	10,520	11,813	16,286	39,780	29,260
61	OTR	15	100%	1,900	6,000	10,857	24,580	22,680
62	OTR	15	80%	2,680	4,800	8,686	24,000	21,320
aily Total Weights				636,640	607,300	886,212		
ERCENT ERROR					-4.61%	39.20%		

onversion Factor Study: In-Vehicle and In-Place Waste Densities, Table 1-18.

IN-TRUCK DENSITY MODEL: Redwood Landfill, Marin County

Day: December 12, 1991

		RL	FL	CRO	OTR	Units
Estimated In-Truck Density:	724	525	480	680	400	(lb/ cu yd)

#	Truck Type	Capacity (cu yd)	% Full	Actual weight (lb)	Simple Model Estimated weight (lb)	Model 2 Estimated weight (lb)	Incoming weight	Tare weight
1	OTR	15	80%	1,280	4,800	8,688	23,060	21,780
2	RL	20	75%	10,470	7,875	10,860	40,990	30,520
3	RL	15	75%	10,360	5,906	8,145	37,280	26,920
4	RL	20	75%	7,020	7,875	10,860	35,380	28,360
5	RL	20	100%	11,900	10,500	14,480	40,520	28,620
6	RL	25	70%	7,740	9,188	12,670	44,440	36,700
7	RL	15	80%	4,300	6,300	8,688	23,740	19,440
8	RL	20	75%	10,420	7,875	10,860	37,800	27,380
9	RL	20	75%	11,360	7,875	10,860	36,920	25,560
10	RL	18	80%	16,200	7,560	10,426	42,200	26,000
11	RL	25	80%	14,020	10,500	14,480	45,660	31,640
12	RL	20	100%	14,420	10,500	14,480	42,900	28,480
13	RL	20	80%	8,660	8,400	11,584	31,820	23,160
14	RL	20	80%	9,060	8,400	11,584	38,040	28,980
15	RL	25	60%	15,400	7,875	10,860	48,620	33,220
16	RL	20	80%	11,820	8,400	11,584	37,560	25,740
17	CRO	25	80%	14,560	13,600	14,480	41,680	27,120
18	RL	18	75%	7,340	7,088	9,774	27,960	20,620
19	RL	18	100%	10,320	9,450	13,032	32,560	22,240
20	RL	18	100%	11,000	9,450	13,032	33,260	22,260
21	RL	18	100%	12,320	9,450	13,032	33,540	21,220
22	FL	30	90%	21,320	14,175	19,548	56,540	35,220
23	OTR	15	90%	2,280	5,400	9,774	24,000	21,720
24	RL	20	100%	10,180	10,500	14,480	35,420	25,240
25	RL	20	100%	11,860	10,500	14,480	33,040	21,180
26	RL	18	100%	6,580	9,450	13,032	27,200	20,620
27	RL	18	100%	4,480	9,450	13,032	25,660	21,180
28	OTR	20	75%	19,240	6,000	10,860	43,640	24,400
29	RL	18	100%	8,080	9,450	13,032	30,260	22,180
30	RL	18	90%	7,280	8,505	11,729	26,740	19,460
31	RL	20	90%	540	9,450	13,032	22,900	22,360
32	RL	20	90%	21,394	9,450	13,032	45,080	23,686
33	RL	20	100%	7,960	10,500	14,480	28,520	20,560
34	RL	20	100%	11,280	10,500	14,480	42,180	30,900
35	RL	25	90%	14,540	11,813	16,290	43,360	28,820
36	RL	18	90%	8,140	8,505	11,729	29,160	21,020
37	RL	20	90%	8,140	9,450	13,032	34,220	26,080
38	RL	25	90%	15,460	11,813	16,290	46,080	30,620
39	RL	20	90%	9,020	9,450	13,032	34,220	25,200
40	FL	30	80%	17,500	11,520	17,376	52,660	35,160
41	RL	25	80%	12,640	10,500	14,480	44,400	31,760
42	RL	20	75%	7,600	7,875	10,860	28,680	21,080
43	RL	20	80%	7,660	8,400	11,584	32,860	25,200
44	RL	25	80%	14,600	10,500	14,480	45,860	31,260
45	RL	25	80%	10,540	10,500	14,480	42,720	32,180

IN-TRUCK DENSITY MODEL: Redwood Landfill, Marin County

Day: December 12, 1991

		RL	FL	CRO	OTR	Units
Estimated In-Truck Density:	724	525	480	680	400	(lb/ cu yd)

#	Truck Type	Capacity (cu yd)	% Full	Actual weight (lb)	Simple Model Estimated weight (lb)	Model 2 Estimated weight (lb)	Incoming weight	Tare weight
46	RL	25	80%	6,960	10,500	14,480	37,100	30,140
47	FL	18	60%	10,100	5,184	7,819	45,200	35,100
48	OTR	30	90%	5,760	10,800	19,548	28,840	23,080
49	RL	25	90%	10,680	11,813	16,290	39,980	29,300
50	OTR	30	100%	16,800	12,000	21,720	43,040	26,240
	Daily Total Weights			528,584	462,818	652,939		
	PERCENT ERROR				-12.44%	23.53%		
	Two Day Totals (1000's)			1,165	1,070	1,539		
	PERCENT ERROR				-8.16%	32.09%		

Conversion Factor Study: In-Vehicle and In-Place Waste Densities, Table 1-18.

N-TRUCK DENSITY MODEL- Model 2

:ALIFORNIA DEFAULT

Estimated density (lb/cu yd): 688

Material Type	Waste stream Percent by weight	Density uncompacted (lb/cu yd)	Density compacted (lb/cu yd)	Zero Compaction Percentage	Intermediate calculations		
	p	d	c	z	q	m	p*m
'aper:							
Corrugated Containers	8.00%	33	360	0%	0.08	359.75	29
Mixed Paper	6.00%	484	613	0%	0.06	612.50	37
Newspaper	9.00%	323	552	0%	0.09	551.50	50
High Grade Ledger	1.00%	364	644	0%	0.01	644.00	6
Other Paper	12.00%	570	635	0%	0.12	635.00	76
lastics:							
HDPE	1.00%	35	264	0%	0.01	263.75	3
PET	0.00%	39	182	0%	0.00	182.00	0
Film Plastics	2.00%	23	226	0%	0.02	222.88	4
Other Plastics	3.00%	50	372	0%	0.03	222.88	7
ilass:							
Recyclable	6.00%	455	1258	30%	0.00	455.38	27
Non-recyclable	1.00%	566	1258	30%	0.00	566.00	6
letals:							
Aluminum Cans	1.00%	91	399	0%	0.01	399.00	4
Ferrous	4.00%	141	501	0%	0.04	501.00	20
Non-Ferrous	1.00%	1248	1248	0%	0.01	1248.32	12
White Goods	1.00%	255	255	0%	0.01	255.40	3
rganics:							
Yardwaste	19.00%	292	584	0%	0.19	584.20	111
Other Bio-organic	8.00%	1013	1080	0%	0.08	1080.00	86
Other Nonbio-organic	2.00%	540	648	0%	0.02	648.00	13
Textiles	2.00%	247	540	0%	0.02	540.00	11
Leather	1.00%	380	759	0%	0.01	759.30	8
Woodwaste	3.00%	333	333	0%	0.03	332.65	10
ther Waste:							
nert Solids	7.00%	1975	1975	0%	0.07	1974.85	138
HHW	1.00%	1523	1523	0%	0.01	1522.70	15
pecial Wastes:							
Sewage Sludge		1294	1294	0%	0.00	1293.75	0
Ash	0.33%	1350	1350	0%	0.00	1350.00	5
Auto Shredder Waste	0.33%	800	800	0%	0.00	800.00	3
Dewatered Sludge	0.33%	1615	1615	0%	0.00	1614.60	5
Tannery Sludge		NA					
Drilling Mud		NA					
Mine Tailings		NA					
OTAL	100.00%		TOTAL COMPACTED DENSITY				688

IN-TRUCK DENSITY MODEL: Bee Canyon Landfill, Orange County

Day: January 15-16, 1992		RL	FL	CRO	OTR	Units
Estimated In-Truck Density:	688	525	480	680	400	(lb/ cu yd)

#	Truck Type	Capacity (cu yd)	% Full	Actual weight (lb)	Simple Model Estimated weight (lb)	Model 2 Estimated weight (lb)	Incoming weight	Tare weight
73	FL	36	50%	11,180	8,640	12,391	42,480	31,300
74	FL	36	75%	14,400	12,960	18,586	45,460	31,060
75	FL	36	75%	16,860	12,960	18,586	51,480	34,620
76	OTR	40	100%	9,300	16,000	27,535	37,540	28,240
77	OTR	30	100%	24,820	12,000	20,651	49,260	24,440
78	FL	30	75%	14,720	10,800	15,489	48,580	33,860
79	OTR	40	50%	5,620	8,000	13,768	31,280	25,660
80	OTR	30	50%	6,060	6,000	10,326	36,680	30,620
81	OTR	30	90%	2,640	10,800	18,586	29,540	26,900
82	OTR	20	100%	27,140	8,000	13,768	62,760	35,620
83	FL	36	100%	20,480	17,280	24,782	55,640	35,160
84	FL	36	95%	19,140	16,416	23,543	54,720	35,580
85	FL	36	55%	13,620	9,504	13,630	43,760	30,140
86	FL	30	60%	17,260	8,640	12,391	50,860	33,600
87	OTR	40	20%	7,340	3,200	5,507	34,720	27,380
88	OTR	35	10%	3,820	1,400	2,409	31,340	27,520
89	OTR	40	40%	9,340	6,400	11,014	38,840	29,500
90	OTR	21	30%	6,860	2,520	4,337	33,640	26,780
91	OTR	35	30%	9,740	4,200	7,228	36,960	27,220
92	OTR	40	10%	2,560	1,600	2,754	31,100	28,540
93	OTR	21	110%	28,400	9,240	15,902	54,200	25,800
94	OTR	40	40%	8,120	6,400	11,014	36,120	28,000
95	FL	36	100%	22,260	17,280	24,782	56,880	34,620
	Daily Total Weights			1,239,560	1,070,252	1,651,979		
	PERCENT ERROR				-13.66%	33.27%		

Conversion Factor Study: In-Vehicle and In-Place Waste Densities, Table 1-18.

IN-TRUCK DENSITY MODEL: Simple Model and Model 2

A Rural County: 50% Self Haul, 25% Rear Loaders, 25%Front Loaders(Commercial)

		MP	FP	RL	FL	CRO	OTR	Units
Estimated In-Truck Density:	688	294	316	525	480	680	400	(lb/cu yd)

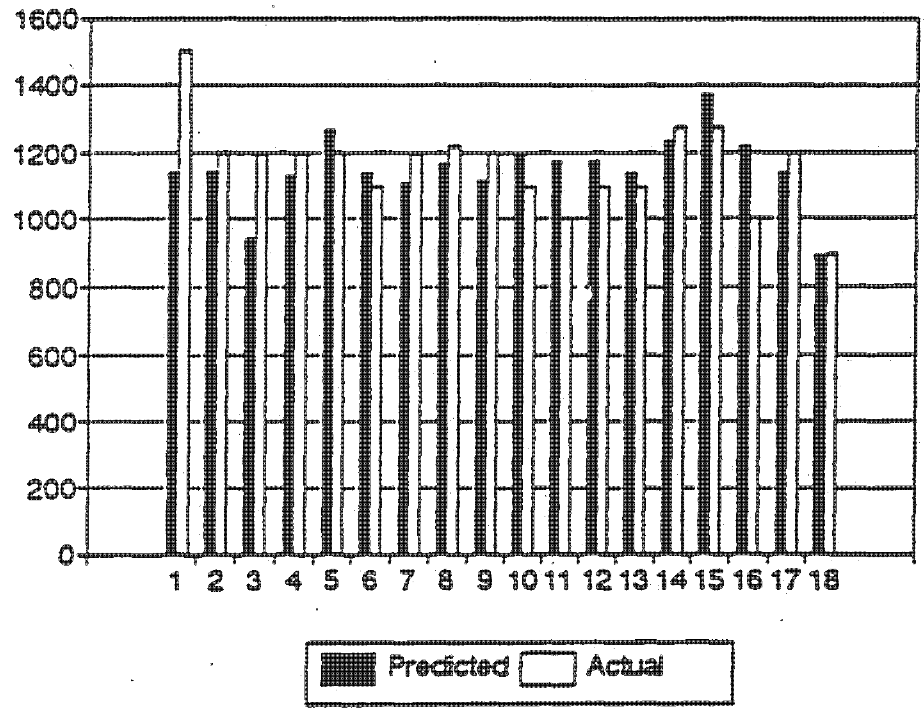
#	Truck Type	Capacity (cu yd)	% Full	Actual weight (lb)	Simple Model Estimated weight (lb)	Model 2 Estimated weight (lb)	Incoming weight	Tare weight
1	RL	20	100%	11,520	10,500	13,768	38,080	26,560
2	RL	20	75%	9,280	7,875	10,326	36,660	27,380
3	RL	25	60%	15,260	7,875	10,326	48,120	32,860
4	RL	18	75%	7,320	7,088	9,293	27,860	20,540
5	RL	16	100%	6,960	8,400	11,014	26,460	19,500
6	RL	15	80%	4,660	6,300	8,261	24,100	19,440
7	RL	18	100%	5,820	9,450	12,391	28,180	22,360
8	RL	10	100%	2,720	5,250	6,884	18,540	15,820
9	RL	18	80%	6,080	7,560	9,913	27,200	21,120
10	RL	20	80%	14,260	8,400	11,014	45,120	30,860
11	RL	15	100%	7,880	7,875	10,326	28,460	20,580
12	RL	20	100%	13,480	10,500	13,768	41,940	28,460
13	RL	25	80%	13,540	10,500	13,768	42,340	28,800
14	FL	30	75%	14,920	10,800	15,489	48,780	33,860
15	FL	30	95%	19,060	13,680	19,619	52,920	33,860
16	FL	35	50%	9,240	8,400	12,047	40,940	31,700
17	FL	35	60%	12,740	10,080	14,456	44,880	32,140
18	FL	39	80%	18,640	14,976	21,478	52,500	33,860
19	FL	39	100%	10,300	18,720	26,847	45,240	34,940
20	FL	39	25%	15,780	4,680	6,712	49,640	33,860
21	FL	40	100%	20,240	19,200	27,535	52,380	32,140
22	FL	39	100%	16,900	18,720	26,847	50,100	33,200
23	FL	35	100%	17,120	16,800	24,093	48,980	31,860
24	FL	2.5	90%	21,100	1,080	1,549	52,080	30,980
25	FL	40	90%	14,880	17,280	24,782	46,280	31,400
26	FP	2.5	100%	800	790	1,721	6,200	5,400
27	FP	2	75%	380	474	1,033	6,140	5,760
28	FP	2.5	60%	2,140	474	1,033	7,460	5,320
29	FP	2.5	80%	720	632	1,377	5,740	5,020
30	FP	2	62%	380	392	854	4,760	4,380
31	FP	2	50%	600	316	688	4,500	3,900
32	FP	2	100%	1,740	632	1,377	6,400	4,660
33	FP	2.5	100%	800	790	1,721	5,340	4,540
34	FP	1.75	100%	2,640	553	1,205	7,000	4,360
35	FP	2.5	20%	610	158	344	6,170	5,560

Calculates in-place density as function of compaction vehicle weight, number of passes, and slope angle. *This model uses the Alternative values for the curve-fit constants as explained in the body of the report.* The Default Values that are listed are for the reference of the user.

ESTIMATED CONSTANTS	ALTERNATIVE VALUES	DEFAULT VALUES
K1	1635	1680
K2	3.40	3.50
K3	4.20E-05	6.30E-05
K4	0.55	3.00
K5	0.25	0.60

DIAGNOSTICS	
Average error	12.73
Standard deviation	136.85
Ave abs % error	8.90%

Predicted vs. Actual In-place Densities



IN-PLACE DENSITY MODEL

Entry Number	1	2	3	4	5	6	7	8	9
INPUTS:									
Vehicle weight (lbs)	66,845	66,230	39,800	74,900	79,000	66,845	81,000	66,845	66,845
Number of passes	5	5	9	3.5	6	5	2.5	7	4
Slope angle of surface or finished grade									
enter either as ratio X:1 ==>	3	3.5	0	3	3	3	3	2	5
or in degrees ==>									
CALCULATIONS:									
angle (radians)	0.32	0.28	0.00	0.32	0.32	0.32	0.32	0.46	0.20
cosine	0.95	0.96	1.00	0.95	0.95	0.95	0.95	0.89	0.98
first exponential	1.24	1.23	1.64	1.17	1.15	1.24	1.13	1.28	1.22
second exponential	1.16	1.16	1.06	1.23	1.12	1.16	1.29	1.10	1.20
in-place density - Predicted	1142	1144	943	1135	1271	1142	1113	1170	1118
Actual	1500	1200	1200	1200	1200	1100	1200	1224	1200
Difference	358	56	257	65	-71	-42	87	54	82
% Difference ((A-O)/A)	24%	5%	21%	5%	-6%	-4%	7%	4%	7%
	24%	5%	21%	5%	6%	4%	7%	4%	7%

Entry Number	10	11	12	13	14	15	16	17	18
INPUTS:									
Vehicle weight (lbs)	66,845	66,845	66,845	66,845	66,845	84,900	81,000	66,845	42,230
Number of passes	6	6	6	6	9	9	4.5	5	6
Slope angle of surface or finished grade									
enter either as ratio X:1 ==>	7.7	3	3	2	2.5	2.5	3	3	3
or in degrees ==>									
CALCULATIONS:									
angle (radians)	0.13	0.32	0.32	0.46	0.38	0.38	0.32	0.32	0.32
cosine	0.99	0.95	0.95	0.88	0.93	0.93	0.95	0.95	0.95
first exponential	1.21	1.24	1.24	1.28	1.25	1.12	1.13	1.24	1.63
second exponential	1.12	1.12	1.12	1.12	1.08	1.08	1.18	1.16	1.12
in-place density	1203	1177	1177	1141	1235	1375	1222	1142	892
Actual	1100	1000	1100	1100	1275	1275	1000	1200	898
Difference	-103	-177	-77	-41	40	-100	-222	58	6
% Difference ((A-O)/A)	-9%	-18%	-7%	-4%	3%	-8%	-22%	5%	1%